Design And Specification of Power Distribution And Protection Systems In Buildings

(1st Edition)

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Design and Specification of

Power Distribution and Protection Systems in Buildings

(1st Edition)

The design, installation and maintenance of electrical distribution and protection system are essential to the reliability, safety and security of supply to buildings. The contents of this book aim at familiarize the readers and designers with the technique in design and specifications of electrical distribution and protection systems in the buildings, whether it is residential, commercial or industrial buildings. Case studies and exercises have been used to provide an insight to the principle and technical information for design and installation of the electrical distribution and protection system.

The contents of this book will certainly benefit those who are involved in design, installation and maintenance of electrical systems, consulting engineers, building services engineers, electrical maintenance engineer, facilities engineers, contractors, developers, technical officers from industries, government and statutory bodies, etc.

About the Author

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Mr Tan is a practising consulting engineer and lecturer with extensive experience in the design, operation and maintenance of M & E systems. Specific experience includes the planning and design of M & E services for various major industrial, commercial & residential projects.

Mr Tan has more than 27 years of working experience as a Consultant and Professional Engineer. His early experience includes many years in the planning, installation and maintenance of extensive electrical distribution system for a power utilities company. He has also gained wide practical experience with M&E Consulting firms, Ewbank Preece Engineers Pte Ltd, Peter Teo & Associates, Oscar Faber Consultants Pte Ltd and Maunsell Consultants (Singapore) Pte Ltd in the design and installation of M&E Services. Mr Tan is now a Licensed Electrical Engineer and an Authorised H.T. Switching & Testing Engineer and currently a Technical Director of Maunsell Consultants (Singapore) Pte Ltd.

Mr Tan is also an established trainer and adjunct lecturer at a local tertiary institution. He has delivered many public seminars and in-house courses such as Effective Maintenance Management of M&E Services; Design & Specification of M&E Services; Lightning Protection for Electronics, Computer and telecommunication Equipment; High Voltage System Design, Operation & Maintenance; Electrical Safety; Power System Harmonics; Earthing and Power Supply Quality problems, Design & Installation of Standby Generators, Design & Specification of Electrical Power & Distribution for Data Processing & Communication Centres.

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CHAPTER 1
INTRODUCTION TO ELECTRICITY SUPPLY SYSTEM

1.1 ELECTRICITY DISTRIBUTION SYSTEM

Electricity Distribution System in the buildings receive bulk electrical power from the high voltage networks of the electricity supply company and step down the voltage to utilisation voltage through the distribution transformers.

A typical electricity distribution system in a building is illustrated in Figure 1.1.

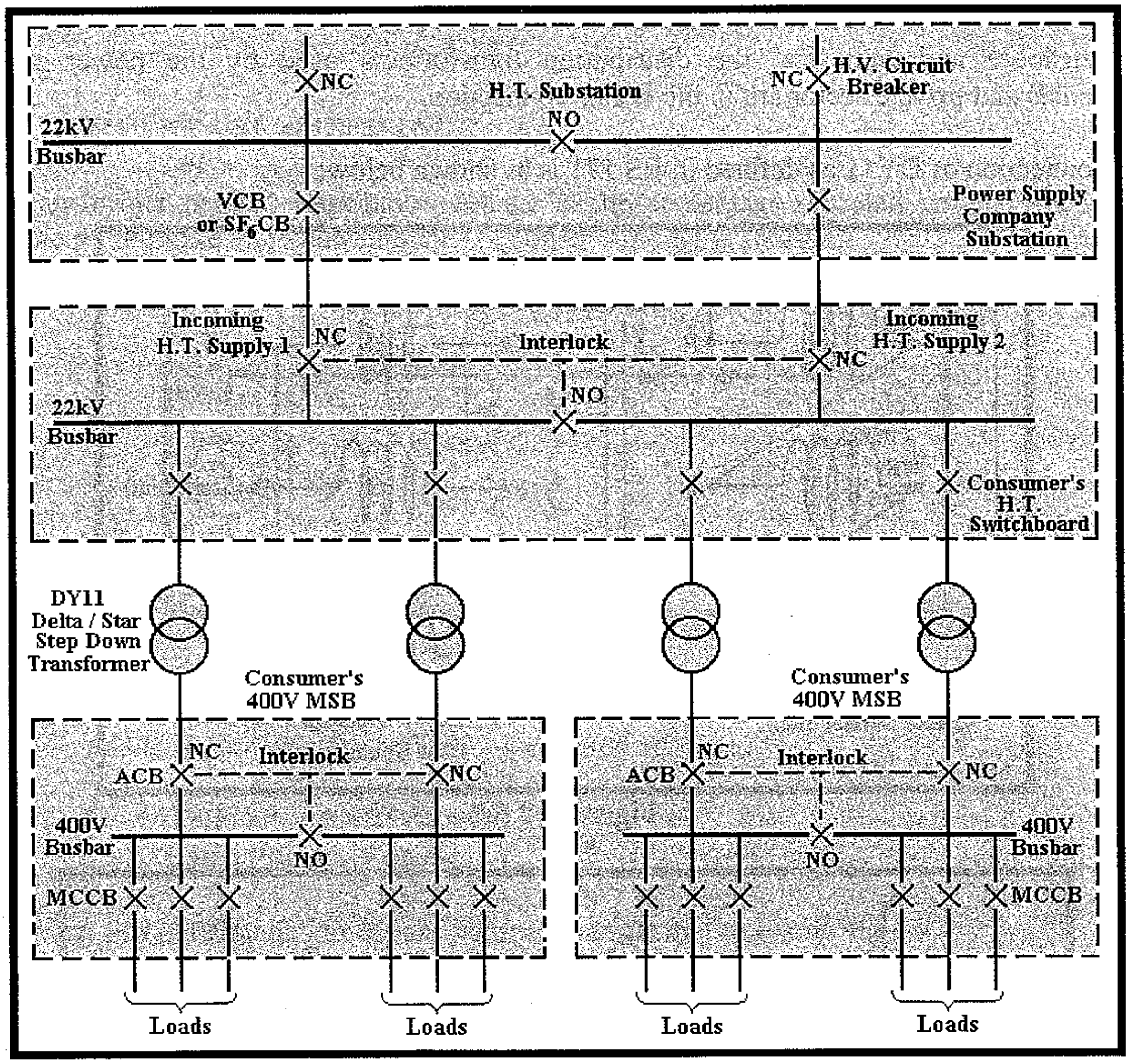


Figure 1. 1 22 kV Supply System

Electrical power is normally distributed at voltage level in the range of 6.6kV, 11kV, or 22kV, and step down to the utilisation voltage at 400V (3-phase) / 230V (single phase) through the 22kV/400V or 6.6kV/400V distribution transformers. The power rating of the distribution transformers may be 1000kVA (1MVA), 1500kVA (1.5MVA), 1600kVA (1.6MVA), 2000kVA (2MVA) or 2500kVA (2.5MVA).

1.2 DY 11 DISTRIBUTION TRANSFORMER – WINDING CONNECTIONS

Medium voltage distribution systems (400V phase to phase, and 230V phase to neutral) are supplied by the secondary windings of the distribution transformers. As single phase voltage (230 V phase to neutral) has to be made available to consumers and the neutral (N) has to be maintained close to earth potential (0 V), secondary windings of the distribution transformers have to be star connected to allow for neutral point or star point to be connected to earth.

For the satisfactory elimination of the 3rd harmonic frequency in the distribution system, the primary windings of the distribution transformers have to be delta connected.

The most common winding connections are therefore DY1, DY5, DY7 or DY11 with DY11 being used widely throughout the world.

In Singapore and Malaysia, the distribution transformers used by the power supply companies and private sector are in the DY11 connection.

The connection of DY11 as defined in BS 171 is as shown below:

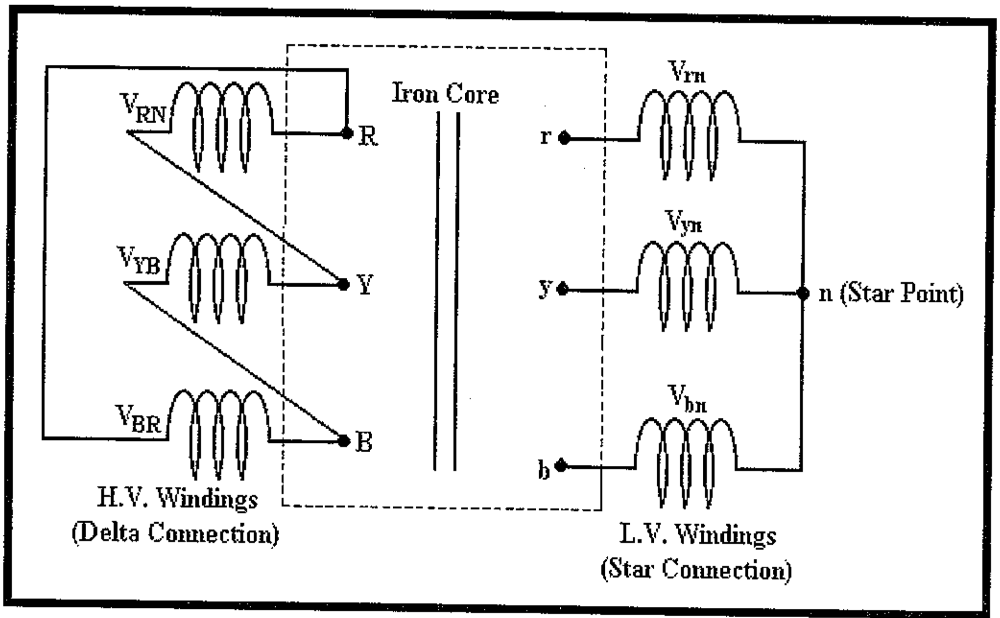


Figure 1. 2 (a)

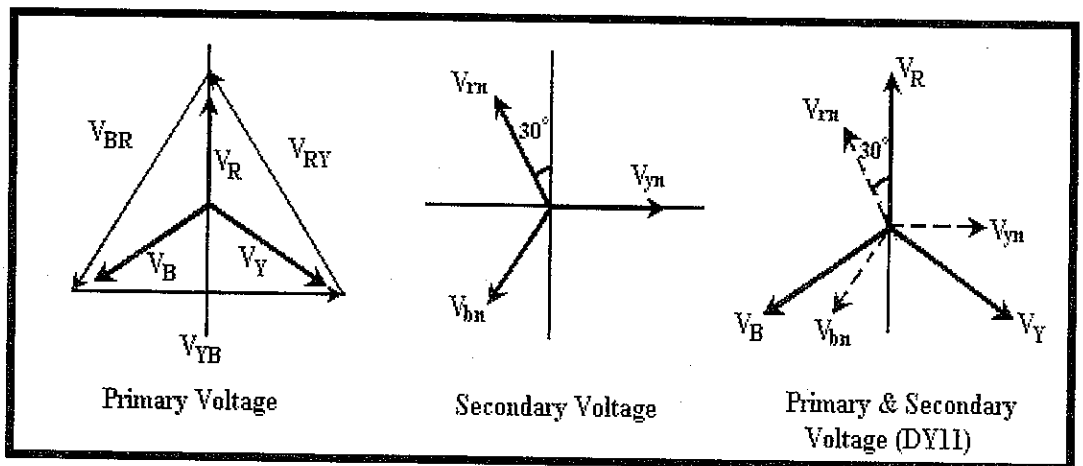


Figure 1.2 (b)

The phasor diagrams of the primary and secondary voltage are as shown:
DY11 indicates that the voltage of the secondary star windings lead the primary phase voltage by 30° and it corresponds to 11 o'clock.

1.3 TRANSFORMER IMPEDANCE

The reactance of power transformers are usually 6 to 30 times greater than the resistance. In design and comparison of transformers it is useful to express the Z, R and X in percent or p.u. of MVA rating rather than the ohmic value.

$$Z_T = R_T + jX_T$$

where X_T is about 5 to 6 times larger than R_T in transformer of 1MVA to 2.5MVA.

1.4 PERCENTAGE IMPEDANCE

The transformer percent impedance voltage is the percentage of rated voltage needed to circulate three-phase rated current when the other winding is shorted.

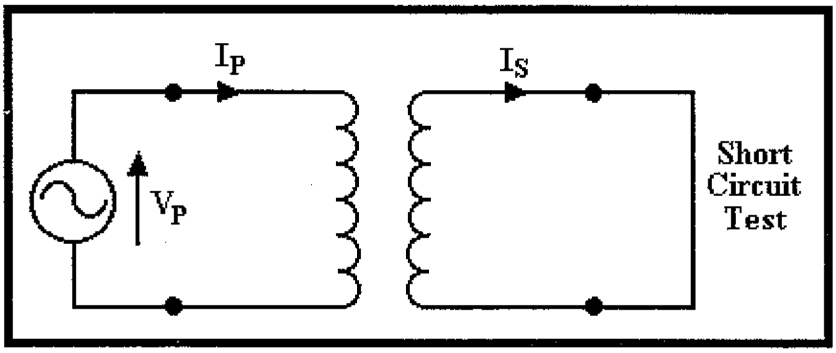


Figure 1. 3

Ip and Is are the primary and secondary rated current.

$$\% Z = \left(\frac{\text{Applied Primary Voltage}}{\text{Rated Primary Voltage}}\right) \text{x } 100\%$$

To convert this percentage impedance value of transformer to ohmic value:

$$Z_T\,(\text{ohm}) = \left(\frac{\% Z}{100}\right) \text{x} \left(\frac{V^2}{MVA}\right)$$

The impedance of distribution transformer Z_T (%) has two effects:

(a) It limits the fault current or short circuit current.

(b) It causes voltage drop or voltage dip in the winding of the transformer.

Therefore a small Z_T (%) lead to larger fault current but help to minimise voltage changes at the output of transformers caused by fluctuation of the loads.

In accordance with British Standard BS171 for distribution transformers, the typical value of Z_T (%) are as follows:

Distribution Transformers:	631 kVA to 1250kVA	$Z_T = 5.0\%$
	>1250kVA	$Z_T = 6.25\%$
Large Power Transformers:	>15MVA	$Z_T = 10$ to 15%

1.5 LOW VOLTAGE 3-PHASE 4-WIRE SYSTEM

Low Voltage (L.V.) system refers to distribution voltage below 1000V. In Singapore, a L.V. system refers to 3-phase 4-wire (R, Y, B and neutral conductors) system of rated line to line voltage (or phase to phase voltage) at 400V, and rated phase to neutral voltage at 230V. In Malaysia and the United Kingdom (UK), the rated phase to phase voltage is 415V (R.M.S value), whereas the rated phase to neutral voltage is 240V (R.M.S value).

A typical 3-phase 4-wire system obtained from a H.V./L.V. DY 11 Distribution Transformer is shown in Figure 1.4.

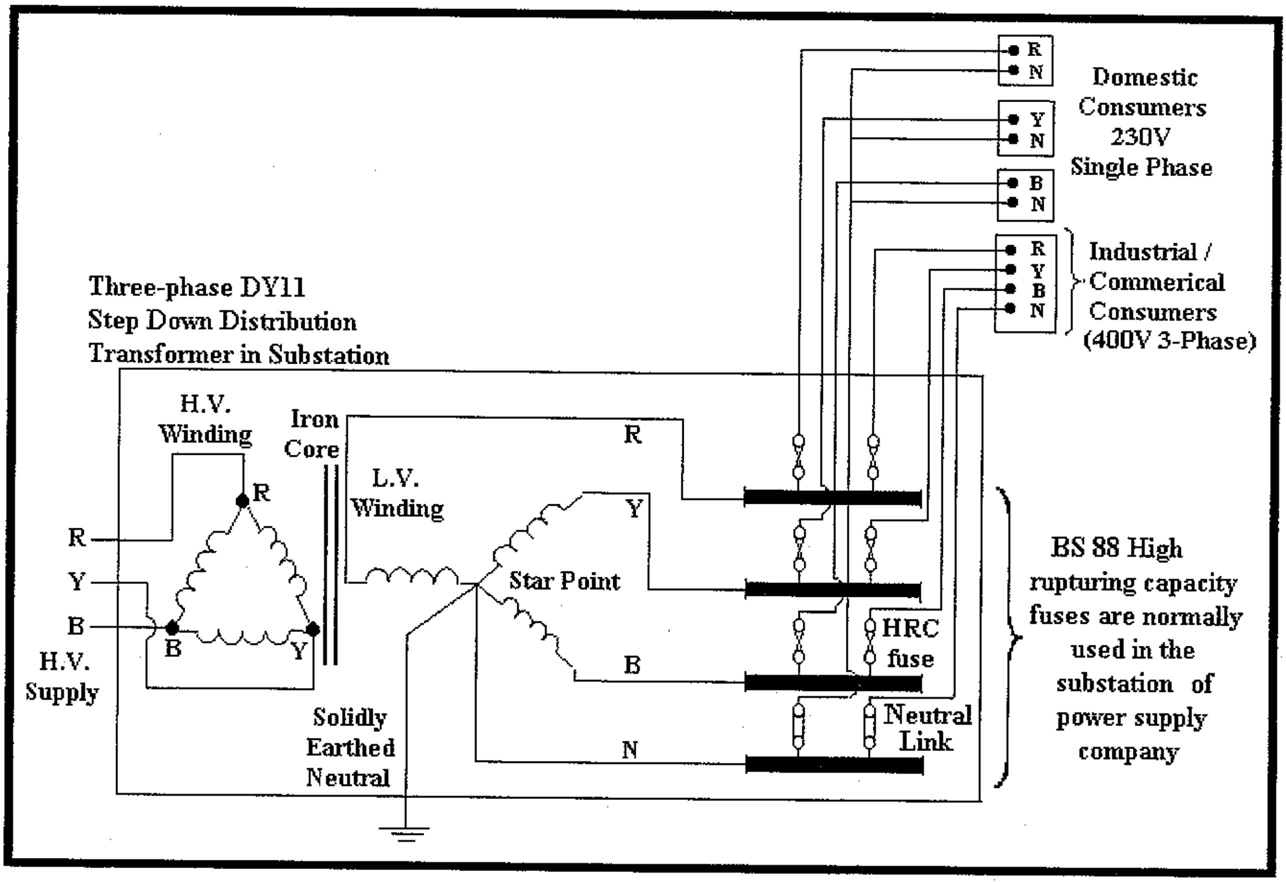


Figure 1. 4 A Typical 400V / 230V Distribution System

Neutral of 3-phase 4-wire System

The star point or neutral point of the L.V. star winding of the distribution transformers is solidly connected to earth for the following purposes:

(a) To maintain the potential (or voltage) of the neutral conductor to be close to earth potential so that the R.M.S value of phase voltages V_{RN}, V_{YN} & V_{BN} can be maintained at 230V (in Singapore) or 240V (in Malaysia and UK).

(b) To enable the phase to earth fault current on the electrical installation system can return safely to the star point (or neutral point) of the L.V. winding of the distribution transformer.

Relationships Between Phase Voltages & Line Voltages of the L.V. 3-phase, 4-wire System

If the R.M.S values of the phase voltages of the L.V. distribution system are given as:

$$V_{RN} = 230 \angle 0°$$
$$V_{YN} = 230 \angle{-120°}$$
$$\text{and } V_{BN} = 230 \angle{-240°}$$

It can be proven that the R.M.S value of the line voltages are:

$$V_{RY} = \sqrt{3} \text{ x } 230 \angle 30° = 400 \angle 30°$$
$$V_{YB} = \sqrt{3} \text{ x } 230 \angle{-90°} = 400 \angle{-90°}$$
$$\text{and } V_{BR} = \sqrt{3} \text{ x } 230 \angle{-210°} = 400 \angle{-210°} = 400 \angle 150°$$

1.6 RATED FULL LOAD CURRENT & RATED TRIP RATING OF CIRCUIT BREAKER

Circuit breaker such as Miniature Circuit Breaker (MCB), Moulded Case Circuit Breaker (MCCB) and Air Circuit Breaker (ACB) are provided in L.V. electrical installation system to offer protection against overloading and short circuit.

Rated full load current or rated trip rating of circuit breaker is the maximum load current that may pass continuously through the circuit breaker without causing the circuit breaker to be overloaded or overheated.

Example 1.1

The full load current of the 1 MVA (or 1000 kVA) 22 kV / 400 V distribution transformer is calculated to be:

$$I_{F.L.} = \frac{1000 \text{ kVA}}{\sqrt{3} \text{ x } 0.4 \text{ kV}} = 1443\text{A}$$

Therefore a 1500AF/1400AT 4-pole Air Circuit Breaker (ACB) is used as the main circuit breaker for the 400 V main switchboard.

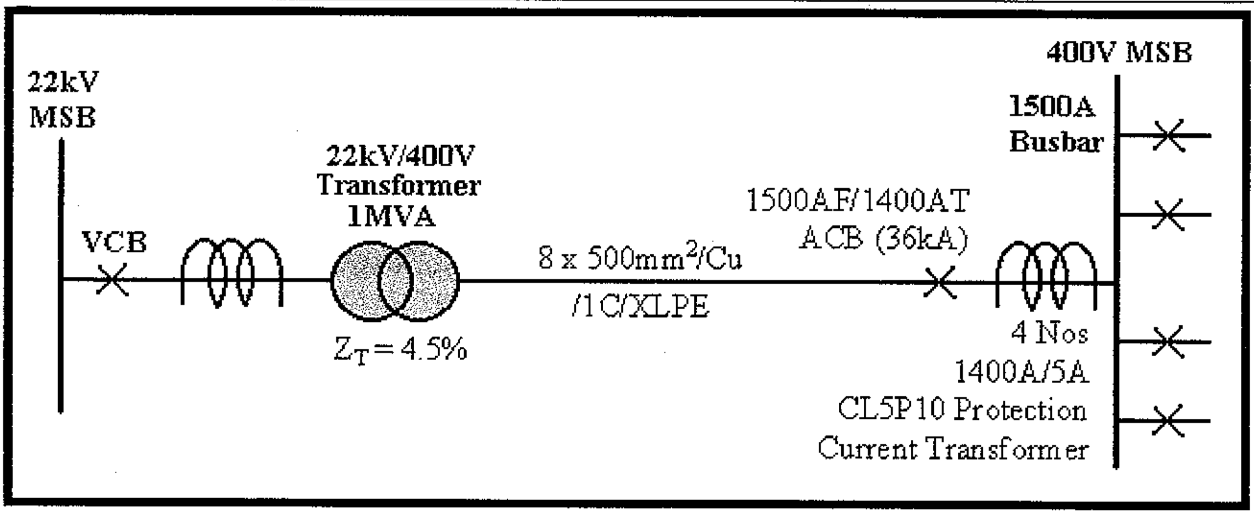


Figure 1. 5 L.V. Supply Fed Directly From Transformers

The incoming circuit breaker / disconnector and the main busbars of the switchboard (SB) or distribution boards (DB) will usually be rated at the same current. This value is obtained normally by adding all the loads of individual outgoing circuits, and multiply by a load diversity factor (DF). The factor which is smaller than one has to be determined carefully be the designer.

L.V. Main switchboards (MSBs) are usually designed for standard sizes at 200A, 250A, 300A, 400A, 600A, 800 A, 1000A, 1400A, 1500A, 2100A, 2500A, 2800A, 3000A.

Copper busbars are often selected based on load capacity at 1.55 Ampere per mm^2 by switchboard manufacturer:

The current carrying capacity of busbar = width x thickness x $1.55A/mm^2$.

Distribution boards (DB) are often designed for standard sizes at 30A, 40A, 60A, 80A, 100A (single phase or 3-phase).

1.7 FAULT CURRENT AND RATED SHORT CIRCUIT BREAKING CAPACITY OF CIRCUIT BREAKER.

The fault current or short circuit current that a circuit breaker can break safely is not determined by the load connected to it, but the impedances of the upstream source transformers, impedances of the main, submains connected to the circuit breakers.

Electrical short circuit may occur due to breakdown of the insulation materials between phase conductors or between a phase to neutral or phase to earth. These different types of faults are illustrated in Figure 1.6.

Rated short circuit breaking capacity (in kA, R.M.S value) is the maximum short circuit current (expressed in R.M.S value) that the circuit breaker is capable of breaking safely without causing damage to itself.

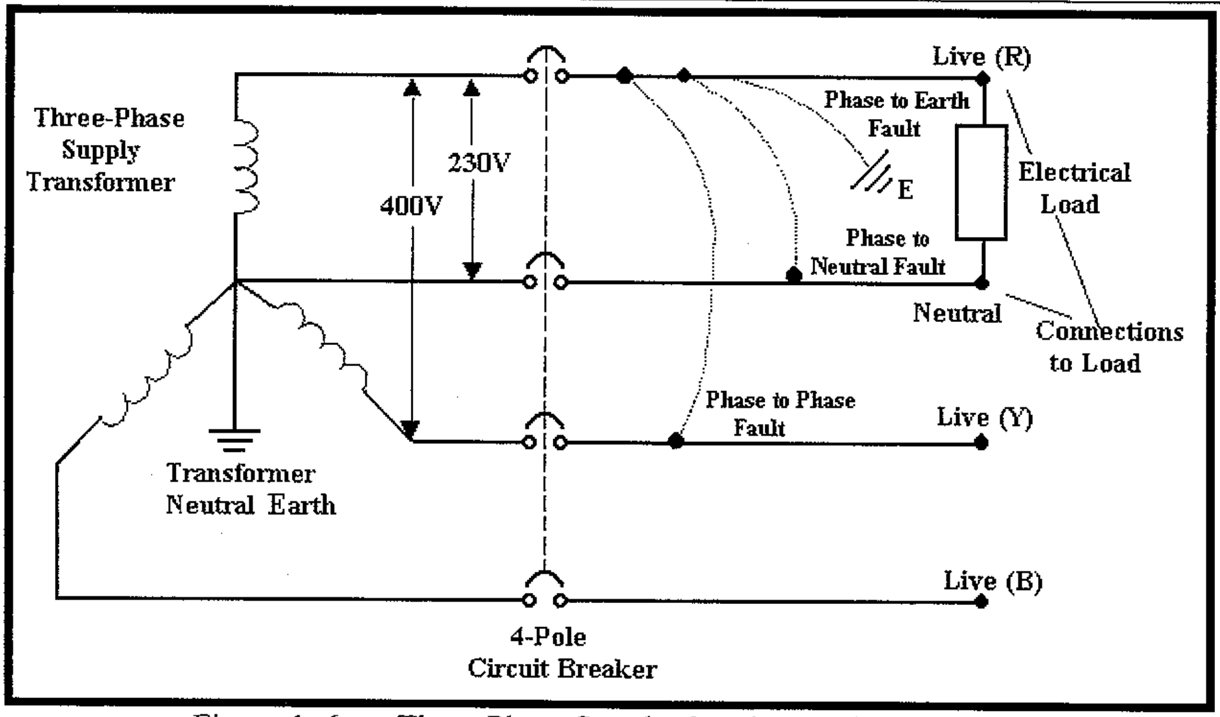


Figure 1. 6 Three-Phase Supply showing Fault Conditions

The relationships of transformer sizes, L.V. circuit breaker rated trip ratings and short circuit fault levels on the secondary side of the transformers are determined as followed:-

22 / 0.4 kV Transformer	Impedance Z (%)	ACB Trip Rating I_n	Prospective 3-phase Short Circuit Current (kA)	CT Ratio for L.V. Side
1000	4.75	1400 A	30	1400 A / 5 A
1250	5	1750 A	35	1750 A / 5 A
1500 / 1600	5.5	2100 A	40	2100 A / 5 A
2000	5.5	2800 A	50	2800 A / 5 A

Table 1.1

$$\textbf{Fault Level} = \frac{\textbf{Base MVA}}{\left(\begin{array}{c}\textbf{Impedance of the Source}\\ \textbf{Transformer } Z_T \textbf{ in per unit}\end{array}\right)}$$

$$\textbf{Prospective 3-phase Short Circuit Current} = \left(\frac{\textbf{Fault Level}}{\sqrt{3} \textbf{ x Rated Line Voltage}}\right)$$

Circuit breakers must be selected to have rated short circuit breaking capacity bigger than the prospective 3-phase short circuit current at the point of installation.

1.8 DECLARED PROSPECTIVE SHORT CIRCUIT CURRENT OF POWER SUPPLY COMPANY

The Power Supply Company in Singapore has declared that the prospective maximum short circuit current at their power supply incoming are as follows:

400V/230V Supply

(a) 9kA for approved load > 15kVA and up to 75kVA from PowerGrid at 230V single phase supply.
(b) 25kA for approved load > 75kVA and up to 180kVA from PowerGrid at 400V 3-phase supply.
(c) 36kA for approved load > 180kVA and up to 1000kVA from PowerGrid at 400V 3-phase supply.

These values must be checked and confirmed with Power Supply Company.

High Voltage Supply

(a) 20kA for 3sec for 6.6kV supply from PowerGrid.
(b) 25kA for 3sec for 22kV supply from PowerGrid.

These values must be checked and confirmed with Power Supply Company.

1.9 METERING OF ELECTRICITY CONSUMPTION

Single Consumer

For premises occupied by a single consumer, the electricity supply is metered at one point and the appropriate tariff in accordance with the use of electricity is charged.

For electricity supply rated at 100A (single phase or 3-phase), direct meter for recording of electricity consumption as shown in Figure 1.7 (a) is used. Whereas for electricity supply more than 100A, C.T. meter as shown in Figure 1.7 (b) is used.

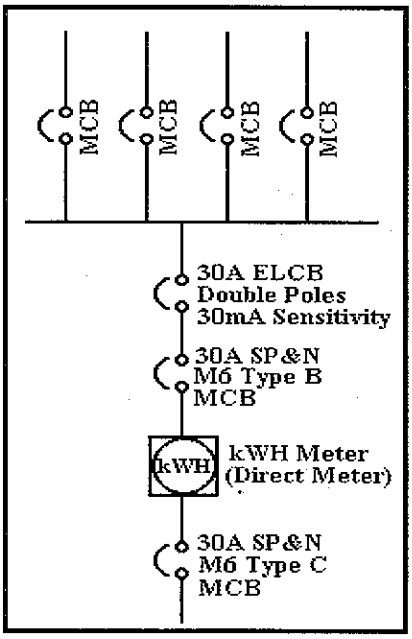


Figure 1. 7 (a) 230V Single Phase Supply not Exceeding 100A

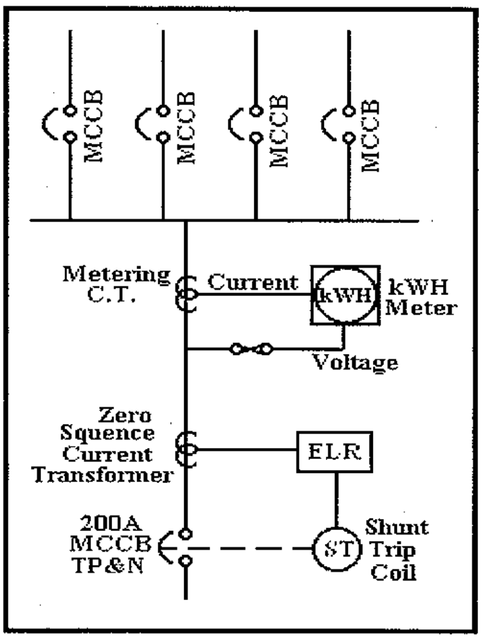


Figure 1.7 (b) 400V 3-Phase Supply Exceeding 100A

Multi-Tenanted Premises
Metered & Unmetered Scheme

In the case of condominium housing or flatted factory development where the consumption for common service is minor, the electricity supply to development is delivered at low tension. The supplies to the landlord and tenants are separately metered and billed under their respective accounts.

To enable the electricity supply company to know that the electricity supply to a tenant is to be taken from unmetered submain or switchboard, the consumers who plan to take electricity supply is such a manner has to be indicated in Form CS/3 to inform the power supply company accordingly.

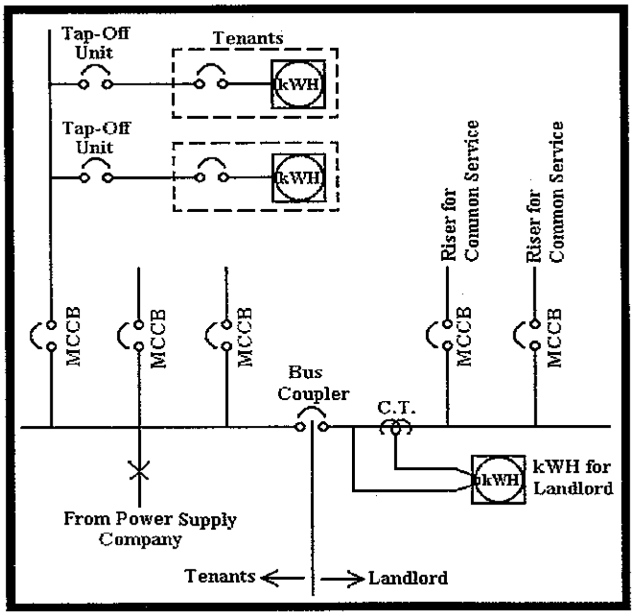


Figure 1. 8 (a) Metered & Unmetered System for Multi-Tenanted Premises

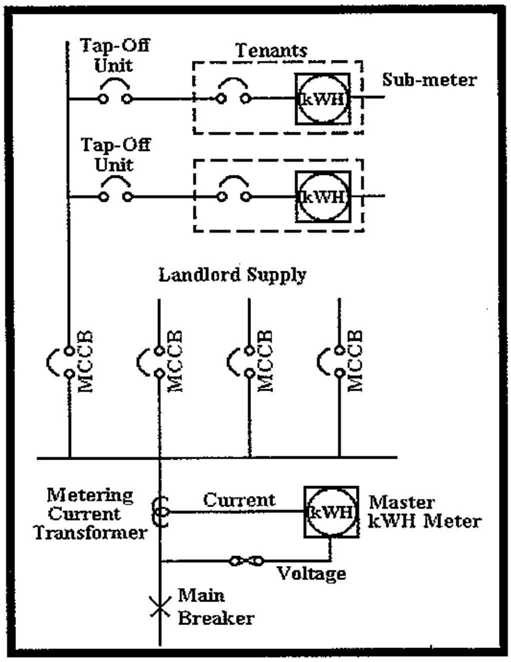


Figure 1.8 (b) Master & Sub-metering scheme for Multi-tenanted buildings

Metered & Sub-metering scheme

In commercial buildings where the supply for common services accounts for the bulk of consumption, the "master / sub-metering scheme" is adopted. Master meters are installed at the intake switchboard with the tenants' consumption separately metered and billed under their respective accounts. The landlord / management corporation pays for the consumption registered at the master meters after deducting the units billed to the tenants.

To enable the deduction of sub-meters' readings from the landlord's master meter by the electricity supply company, consumers (tenants in the buildings) who plan to take electricity supplies from the main switchboard or submains which have already been metered by master meter, has to submit the account number of the master meter via Form CS/3 (as shown in Figure 1.9).

FORM CS/3

To: Power Supply Ltd
111 Somerset Road
Singapore 238164

ELECTRICITY SUPPLY TO ______________________________
(Full Address of the Customer)

FOR ______________________________
(Name of Customer)

TOTAL LOAD ALLOWED FOR: ____________________ AT ____________ VOLTS

PART I

1 I have checked the loading of the electrical installation of the abovementioned building/complex and hereby confirm that the abovementioned load requirement can be catered for from the rising/horizontal mains system/main switchboard of the building/complex, and the total approved load to the entire building/complex will not be exceeded.

2 I have no objection for the abovementioned load to be connected to the rising/horizontal mains system/main switchboard of the building/complex.

3 The Electrical Installation Licence No. of the building/complex is ____________.

4 The electrical installation of the building/complex from which this load is to be connected is

☐ Unmetered

☐ Metered under Master Account No. ____________.

5 I will check to ensure that the abovementioned installation is compatible with the electrical installation of the building/complex.

____
Signature of Licensed Electrical Worker

Date: ____________

Licence No:

Tel No:

Name:

Address:

PART II

I hereby give consent for the abovementioned customer to tap electricity supply of a capacity indicated above from the rising/horizontal mains system/main switchboard of the building/complex.

____
Signature of authorised person

Date: ____________

____
Name Designation

Official Stamp of the
landlord/developer/management corporation

0896

Figure 1. 9 Sample of Form CS/3

A typical arrangement of master kW-HR meter and sub-meter for tenants in a school is shown in Figure 1.10. This fundamental requirements for safety in the design of electrical installation as required by SS CP5:1998 in terms of:

(a) Overcurrent Protection
(b) Earth Fault & Earth Leakage Protection
(c) Isolation for Safety

have also been incorporated in Figure 1.10.

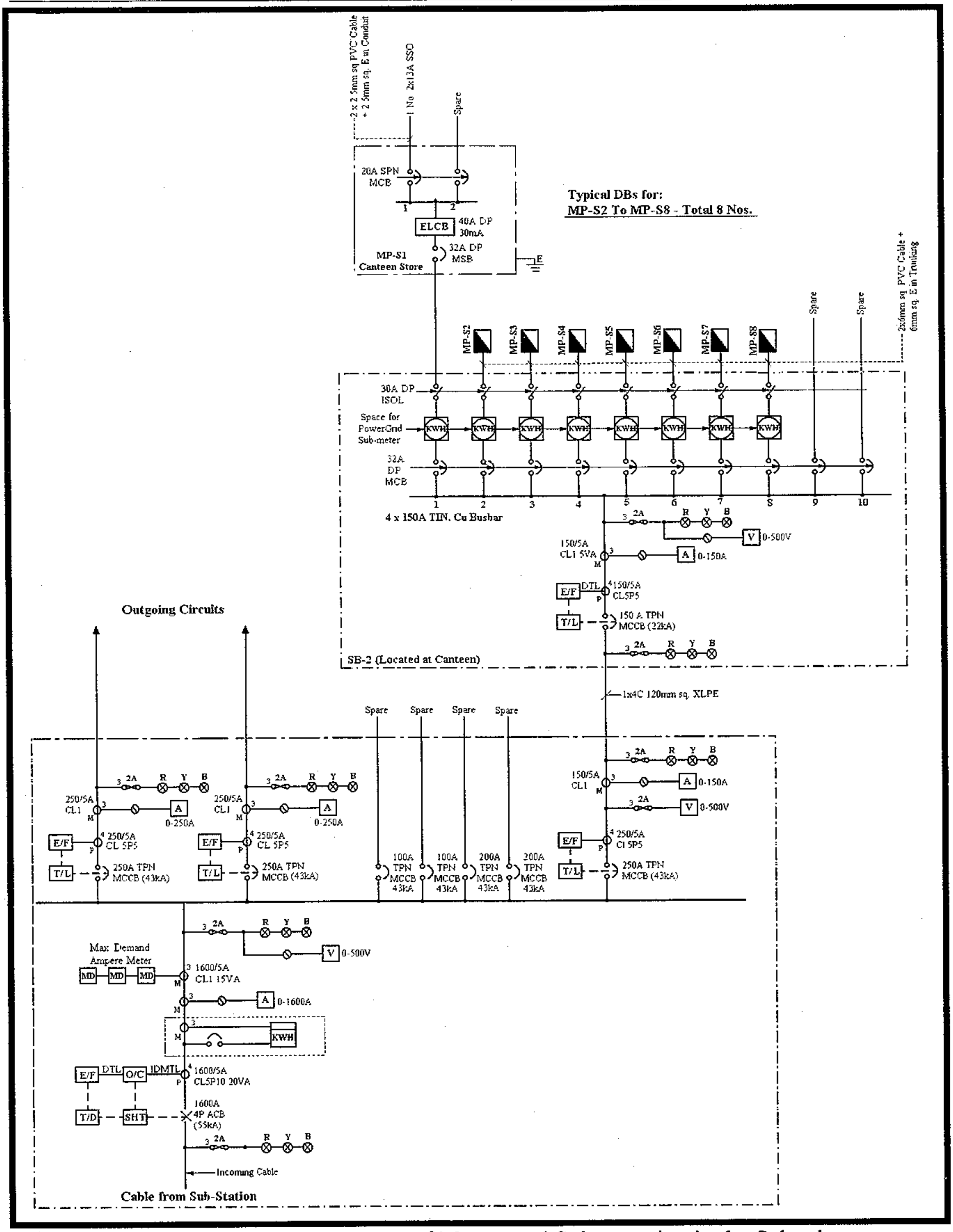


Figure 1. 10 Arrangement of Master and Sub-metering in the Schools

(1) Explain briefly the definition of

(a) Instantaneous Value
(b) Peak or Maximum Value
(c) Root Mean Square Value
(d) Average Value
(e) Crest Factor
(f) Form Factor

of A.C. Voltage and Current

(2) A 3-phase load may be connected in Star or Delta-connection.

If the magnitude of the line voltage is the same in both cases, prove that the magnitude of line current in Star-connection is $^1/_3$ that of the Delta-connection.

(3) Describe briefly the meaning of each of the following markings on a transformer nameplate:

(a) 22kV/400V
(b) 1MVA
(c) DY11
(d) Z = 5%

(4) A 3-phase star connected load with equal impedance $Z_L = (10 + j50)\ \Omega$ in each phase is connected to the star connected secondary winding of a 22 kV / 400 V distribution transformer.

(a) Draw the connection diagram to show the connection of the star connected load and the secondary winding of the transformer. Explain briefly why neutral point of the star connected winding of the distribution transformers has to be solidly connected to earth.

(b) Assuming that the phase voltages of the L.V. transformer windings are:
$V_{RN} = 230 \angle 0°$
$V_{YN} = 230 \angle -120°$
$V_{BN} = 230 \angle -240°$

Show that the line voltages are given by
$V_{RY} = \sqrt{3} \times 230 \angle 30°$
$V_{YB} = \sqrt{3} \times 230 \angle -90°$
$V_{BR} = \sqrt{3} \times 230 \angle 150°$

(c) Calculate the magnitude and phase angle of the current in each phase and hence, determine the magnitude and phase angle of the neutral currents.

(d) Express the equation of instantaneous value of the line currents in function of time.

(5) A 3-phase Delta-connected load with equal impedance of (10 + 50j) Ω in all three phases is connected to the Star-connected secondary of a 22 kV / 400 V distribution transformer.

(a) Draw a diagram to show how the load is connected to the transformer.

(b) Calculate all the three line currents and express them as phasor quantities.

(c) Express the instantaneous value of the line currents.

(6) The star connected secondary winding of a 22 kV / 400 V distribution transformer is connected to a 3-phase, 4-wire unbalanced star connected load. The load impedances are:-

$Z_{RN} = (8 + j50)\ \Omega$
$Z_{YN} = (12 + j40)\ \Omega$
$Z_{BN} = (10 + j60)\ \Omega$

The phase voltage of the transformer windings are

$V_{RN} = 230 \angle 0°$
$V_{YN} = 230 \angle -120°$
$V_{BN} = 230 \angle -240°$

(a) Draw a diagram to show how the load is connected to the distribution transformer. Explain briefly why neutral points of distribution transformers have to be solidly connected to earth.

(b) Using either a mathematical method or a graphical method, prove that the line voltages are: -

$V_{RY} = \sqrt{3} \times 230 \angle 30°$
$V_{YB} = \sqrt{3} \times 230 \angle -90°$
$V_{BR} = \sqrt{3} \times 230 \angle 150°$

(c) Calculate the magnitude and phase angle of the line current and hence, determine the magnitude and phase angle of the neutral current.

(7) The L.V. winding of the 22 kV / 400 V DY 11 distribution transformer is connected to a Star connected load with equal impedance $Z_{L1} = (10+j50)\ \Omega$ in each phase and a Delta connected load with equal impedance $Z_{L2} = (10+j60)\ \Omega$ in each phase.

(a) Draw the connection diagram to show the connection of the transformer L.V. winding and the Star connected load and Delta connected load. Explain briefly why Neutral point of the transformer L.V. winding has to be solidly connected to earth.

(b) Given the phase voltages of the transformer windings as:

$V_{RN} = 230 \angle 0°$
$V_{YN} = 230 \angle -120°$
$V_{BN} = 230 \angle -240°$

and the line voltages as

$V_{RY} = \sqrt{3} \times 230 \angle 30°$
$V_{YB} = \sqrt{3} \times 230 \angle -90°$
$V_{BR} = \sqrt{3} \times 230 \angle 150°$

Determine the total line currents (R, Y & B) at the secondary windings of the distribution transformer and express them in instantaneous value equations.

(8) In the figure shown below, determine the required frame size, rated trip rating & rated short circuit breaking capacity of the Air Circuit Breaker and the appropriate C.T. ratio and the busbar current rating at the 400V MSB.

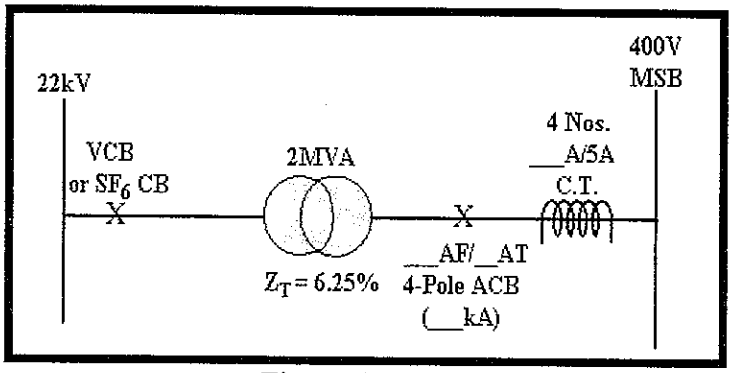


Figure 1. 11 (a)

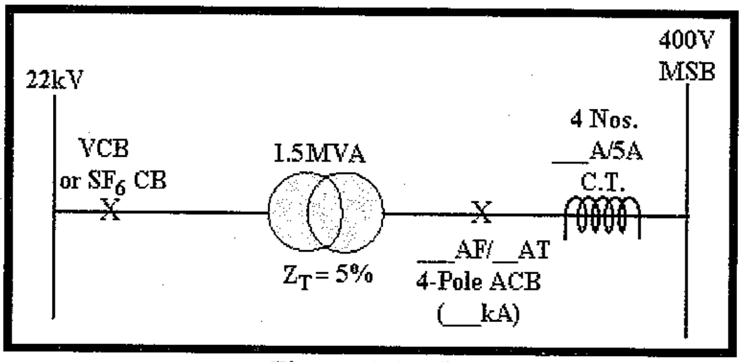


Figure 1.11 (b)

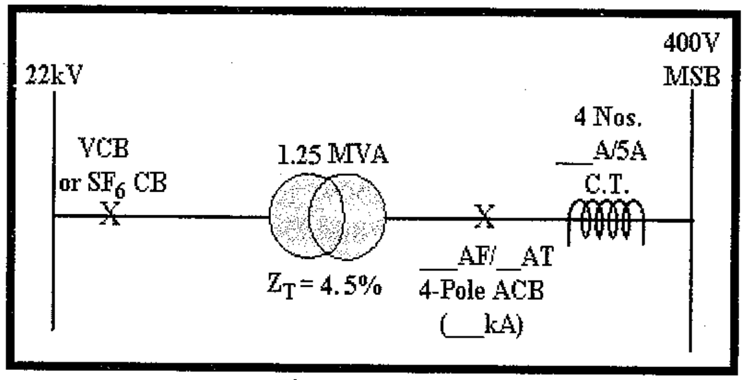


Figure 1.11 (c)

CHAPTER 2
FUNDAMENTAL REQUIREMENTS FOR SAFETY IN DESIGN

2.1 ELECTRICITY – THE HAZARDS

The principal hazards in the use of electricity, as envisaged by statutory regulations such as **Singapore Standard CP5:1998, Code of Practice for Electrical Installations and British Standard, IEE 16th edition of the Wiring Regulations** are as follows:-

- electric shock (direct contact and indirect contact),
- fire,
- burns,
- injury from mechanical movement of electrically actuated equipment, in so far as such injury is intended to be prevented by electrical emergency switching or by electrical switching for mechanical maintenance of non-electrical parts of such equipment.

2.2 PROTECTION AGAINST OVERCURRENT

Overcurrent

An overcurrent is a current greater than the rated current of a circuit. It may occur in two ways:-

(a) As an overload current, or

(b) As a short-circuit or fault current.

These conditions need to be protected against in order to avoid damage to circuit conductors and equipment. In practice, fuses and circuit breakers are used to protect against overloading or short-circuit.

Overload Current

Overload currents occur in circuits which have no faults but are carrying a higher current than the design value due to:-

(a) overloaded machines

(b) an error in the assessment of the loads in the circuit, or

(c) under-design of the circuit conductors.

If overload current is allowed to persist, it will result in an increase in conductor temperature. If the conductor becomes too hot, the insulation of the cable or conductor may be deteriorated and eventually fail.

Short Circuit Current

Short circuit current is an overcurrent resulting from a fault of negligible impedance between 'live' conductors or between 'live' and earthed conductors.

A short circuit may occur due to a direct contact or connection between

(a) a phase conductor to 'neutral' conductor,
(b) a 'phase' conductor to 'earth' conductor or earthed metal frame,
(c) a 'neutral' conductor to 'earth' conductor or earthed metal frame,
(d) a 'phase' to 'phase' short circuit or 3-phase short circuit.

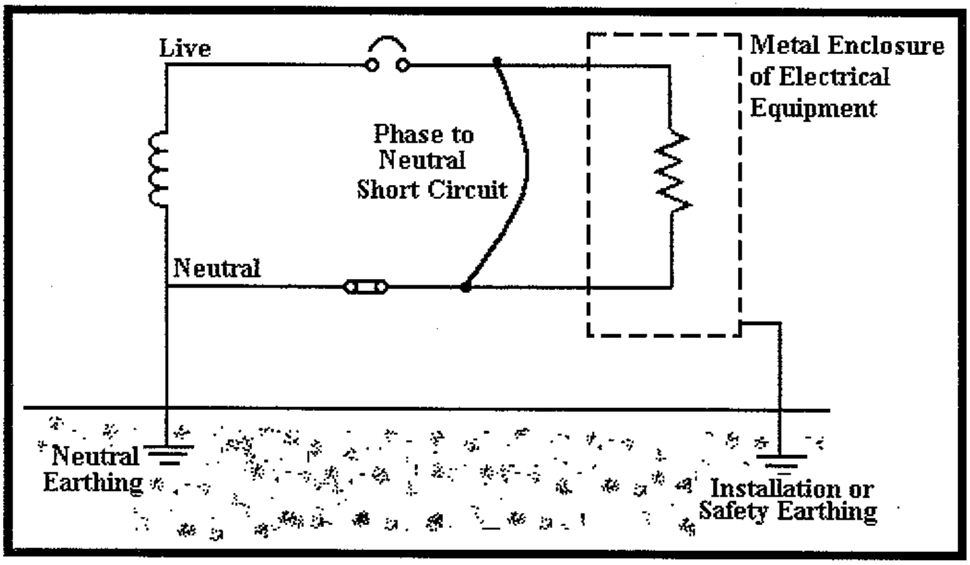


Figure 2.1 Short Circuit between 'Live' and 'Neutral' Wire of a 'Single-Phase' System

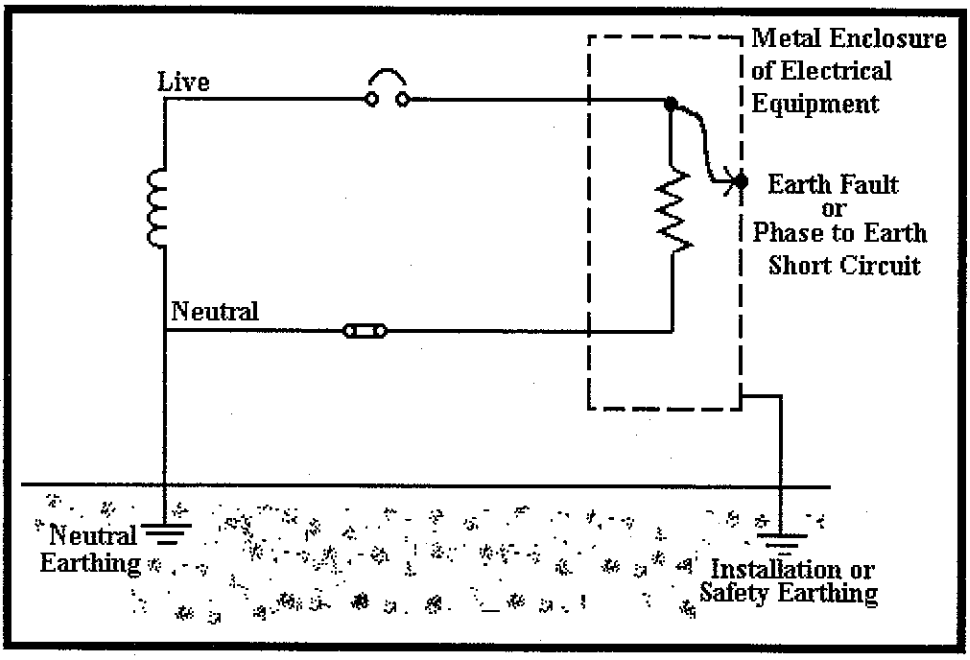


Figure 2.2 Short Circuit between 'Live' Wire and the Earthed Metal Frame of Equipment

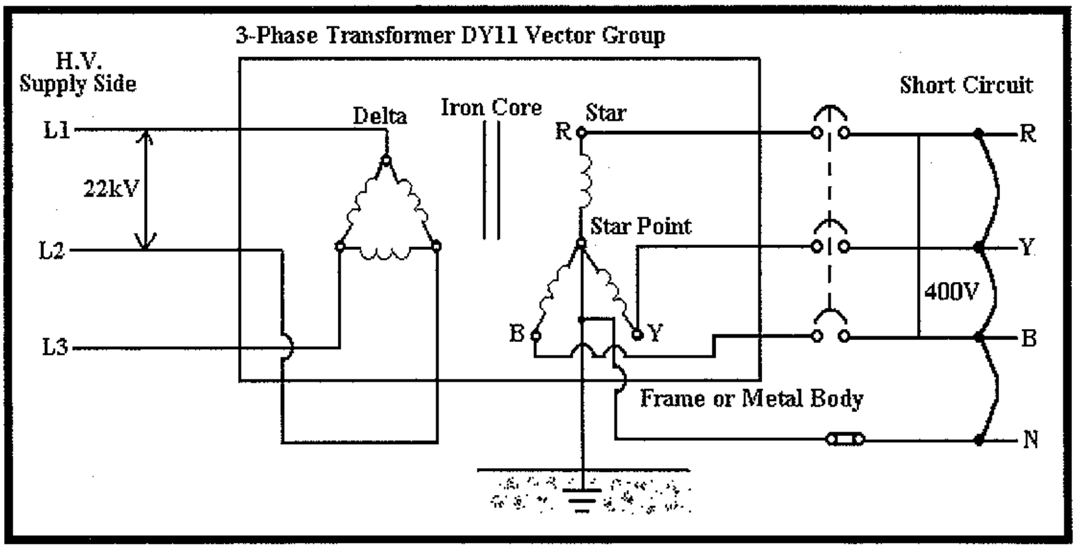


Figure 2.3 3-Phase Short Circuit on a 3 Phase System

2.3 PROTECTION AGAINST OVERCURRENT AND EARTH LEAKAGE PROTECTION

Overcurrent Protection

Singapore Standard CP5:1998, Code of practice for electrical installations and British Standard, IEE Wiring Regulations 16th edition requires that:-

Clause 130-03-01 Where necessary to prevent danger, every installation and every circuit thereof shall be protected against overcurrent by devices which:

i. will **operate automatically** at values of current which are suitably related to the safe current rating of the circuit, and

ii. are of **adequate breaking** capacity and, where appropriate, making capacity, and

iii. are **suitably located** and are constructed so as to prevent danger from overheating, arcing or the scattering of hot particles when they come into operation and to permit ready restoration of the supply without danger.

These requirements are stipulated in Clause 130-03-01 of CP5:1998 and IEEth Wiring Regulation 16th edition.

Earth Leakage Protection

Clause 130-04-01, 130-04-02, 130-04-03 and 130-04-04 of the Singapore Standard CP5:1998 and British Standard; IEE Wiring Regulations 16th edition also require that:-

130-04 Precautions Against Earth Leakage and Earth Fault Currents

130-04-01 Where metalwork of electrical equipment, other than current-carrying conductors, may become charged with electricity in such a manner as to cause danger:

i. the metalwork shall be connected with earth in such a manner as will cause discharge of electrical energy without danger, or

ii. other equally effective precautions shall be taken to prevent danger.

130-04-02 Every circuit shall be arranged so as to prevent the persistence of dangerous earth leakage currents.

130-04-03 Where metalwork is connected with earth in accordance with Clause 130-04-01 (i) the circuits concerned shall be protected against the persistence of an earth fault current by:

i. the overcurrent protective devices required by Clause 130-03-01, or

ii. **a residual current device** or equally effective device.

The method described in item (ii) above shall be used whenever the prospective earth fault current is insufficient to cause prompt operation of the overcurrent protective devices.

130-04-04 Where metalwork of electrical equipment is connected with earth in accordance with Clause 130-04-01(i) and is accessible simultaneously with substantial exposed metal parts of other services, the latter shall be effectively connected to the main earthing terminal of the installation.

2.4 ISOLATION AND SWITCHING

Clauses 130-06-01, 537-02-01 & 537-02-02L of CP5:1998 and IEE 16^{th} edition requires that:-

130-06 Isolation and Switching

130-06-01 Effective means, suitably placed for ready operation, shall be provided so that all voltage may be cut off from every installation, from every circuit thereof and from all equipment, as may be necessary to prevent or remove danger.

537-02 Devices For Isolation

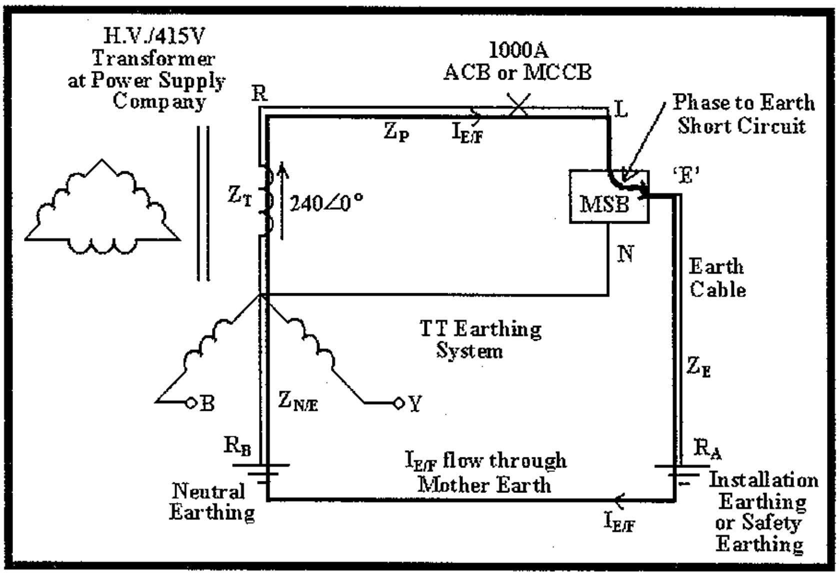
537-02-01 Except as detailed by Clause 460-01-04, the devices for isolation shall effectively isolate all live supply conductors from the circuit concerned. Equipment used for isolation shall comply with Clauses 537-02-02 to 537-02-10.

537-02-02L The isolating distance between contacts or other means of isolating when in the open position shall be not less than that determined for an isolator (disconnector) in accordance with the requirement of IEC 947-3.

IEC 947-3 Standard requires that the isolator be subjected to a 2kV A.C. pressure test at open position and the leakage current shall not be more than 2mA.

2.5 NEED FOR EARTH LEAKAGE AND EARTH FAULT PROTECTION

Phase to Earth Fault can best be represented by the fault impedance diagram as shown in figure 2.4, where a short circuit has occurred from 'phase' or 'live' conductor to metal enclosure (or known as Exposed Conductive part) of electrical equipment.



Z_T – Transformer Impedance in Ohmic value

Z_P – Phase Conductor Impedance in Ohmic value

Z_E – Earth Conductor Impedance in Ohmic value

$Z_{N/E}$ – Neutral / Earth Conductor Impedance in Ohmic value

R_A – Electrode Resistance of Installation Earthing at the Consumer's Installation

R_B – Electrode Resistance of Neutral Earthing at the Power Supply Company's Distribution Transformer

Figure 2.4 Phase to Earth Fault & Earth Fault Loop Impedance

where **Earth Fault Loop Impedance** is defined as the Total Impedance in the path or Loop of phase to Earth fault current and phase to Earth fault current

$$I_{E/F} = \frac{\text{Phase Voltage}}{Z_{EFLI}}$$

$$= \frac{230V}{Z_T + Z_P + Z_E + (R_A+R_B) + Z_{N/E}}$$

and since $Z_{EFLI} = Z_T + Z_P + Z_E + (R_A+R_B) + Z_{N/E}$

$\approx R_A+R_B$

where Z_T, Z_P, Z_E & $Z_{N/E}$ are relatively small

Therefore, $I_{E/F} \approx \dfrac{230V}{R_A+R_B}$

$= \dfrac{230V}{1\Omega + 1\Omega}$ if $R_A = R_B \leq 1\Omega$

$\approx$ 115A to 120A, depending on whether V_{Phase} = 230V or 240V

This current is small and unable to cause the overcurrent protection such as MCB, MCCB or overcurrent relay to operate. This will certainly cause electric shock and electrical hazards. Residual Current Device (RCD) such as RCCB (Residual Current Circuit Breaker), ELR (Earth Leakage Relay) or EFR (Earth Fault Relay) must be used as sensitive phase to Earth fault protection device.

It is also for this reason that a rule by Power Supply Company is imposed to limit the trip current setting of EFR (Earth Fault Relay) to maximum value at 120A (i.e. EFR can be set to 10% to 20% of the rated current of the L.V. switchboard subject to maximum setting at 120A, please see handbook of Power Supply Ltd.)

2.6 INSTALLATION OF OVERCURRENT AND EARTH LEAKAGE PROTECTION DEVICE FOR DB RATED AT 100A OR LESS

For Distribution Board (DB) rated at 100A or less, RCCB (Residual Current Circuit Breaker) or known as ELCB (Earth Leakage Circuit Breaker) are normally used as the protection device against phase to earth fault as shown in Figure 2.5.

As RCCB is not an overcurrent protection device, a Miniature Circuit Breaker (MCB) at an appropriate **Rated Trip Rating I_n** must be installed to provide overcurrent protection. The RCCB with appropriate **Rated Normay Current** rating I_n and **sensitivity** (or operating current) $I_{\Delta n}$ must be selected.

As a safety rule to prevent electrical hazards in domestic premises, RCCB of 30mA sensitivity must be used for protection in domestic residential premises.

The following guidelines are to be compiled with in the design of electrical installation:

(a) Use RCCB of 30mA sensitivity for domestic switch socket outlet and lighting circuits.
(b) Use RCCB of 30mA sensitivity for temporary supply.
(c) Use RCCB of 30mA sensitivity for market and food stall.
(d) Use RCCB of appropriate sensitivity for non-domestic electrical installation.

2.7 PROVISION OF EARTH LEAKAGE RELAY (ELR) AS RESIDUAL CURRENT DEVICE (RCD) FOR SMALL SWITCHBOARD WITH RATED CURRENT LESS THAN 300A.

For small switchboard not more than 300A, Earth Leakage Relay (ELR) of adjustable operating current 0.3A to 3A (primary current) OR 0.3A to 10A (Primary Current) can be used as Residual Current Device (RCD), ELR come with time delay which can be adjustable from 0.04 to 0.5 second.

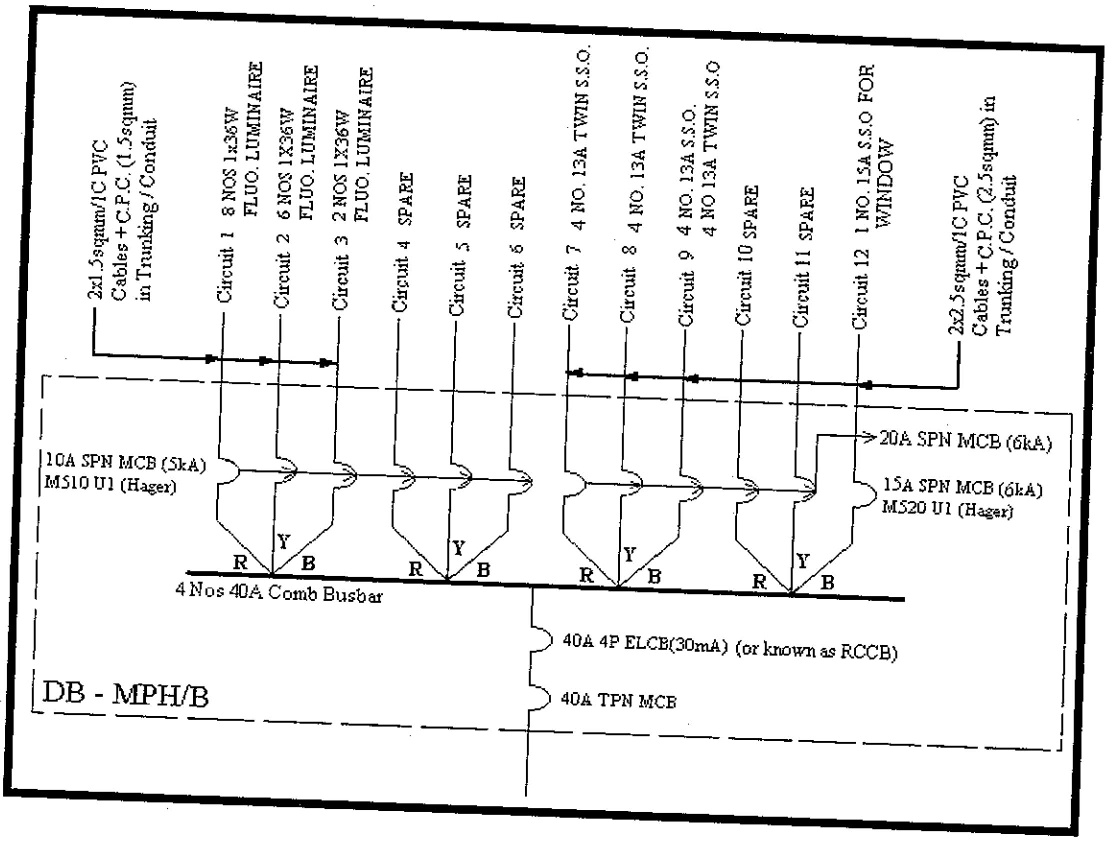


Figure 2.5 30mA RCCB provided as Supplementary Protection against Direct Contact & Protection against Indirect Contact by Automatic Disconnection.

The Earth Leakage Relay (ELR) makes use of a Zero Sequence Current Transformer (ZCT) which couple to all 3 phase conductors and neutral conductor (R, Y, B & N) to check the phasor sum of currents on the 4 conductors and it will operate only if this phasor sum is not zero (i.e. $\vec{I}_R + \vec{I}_Y + \vec{I}_B + \vec{I}_N \neq 0$) and exceed the trip setting current (i.e. $I_R + I_Y + I_B + I_N = I_{E/F} >$ setting).

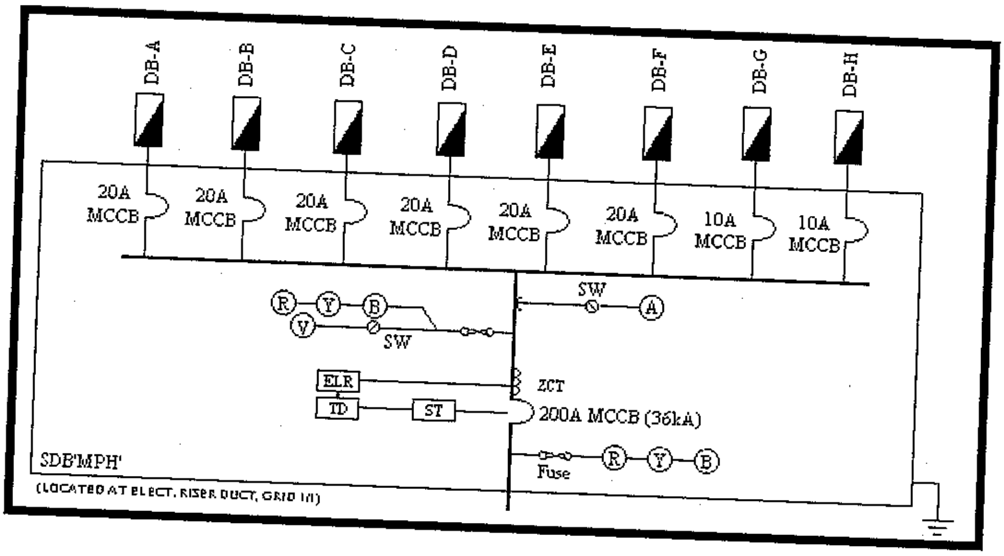


Figure 2.6 ELR (set to operate within 0.4 sec) to provide protection against Electric Shock by indirect contact

2.8 PROVISION OF EARTH FAULT RELAY (EFR) AS RESIDUAL CURRENT DEVICE (RCD) FOR SWITCHBOARD WITH RATED CURRENT 300A OR MORE.

For bigger low voltage (400V, 3-phase) installation with rated normal current 300A or more, Earth Fault Relay (EFR) together with 4 nos. of CL5P10 current transformers are normally used as shown in Figure 2.7.

The 4 nos. of protection current transformers reduce the primary currents on all 4 conductors (R, Y, B & N) to a smaller current by C.T Ratio (for example: 1000A/5A, 500A/5A, 400A/5A, etc.) and check the phasor sum of the secondary currents (i_r, i_y, i_b & i_n), and it will operate only if the phasor sum is not zero (i.e. $i_r + i_y + i_b + i_n \neq 0$) and exceed the relay setting current.

For Example

If Primary Current $I_R + I_Y + I_B + I_N = I_{E/F}$ (Phase to Earth Fault Current)

Then

Secondary Current $i_r + i_y + i_b + i_n = I_{E/F}$ x CT Reduction Ratio

A current will flow into the earth fault relay and cause it to operate.

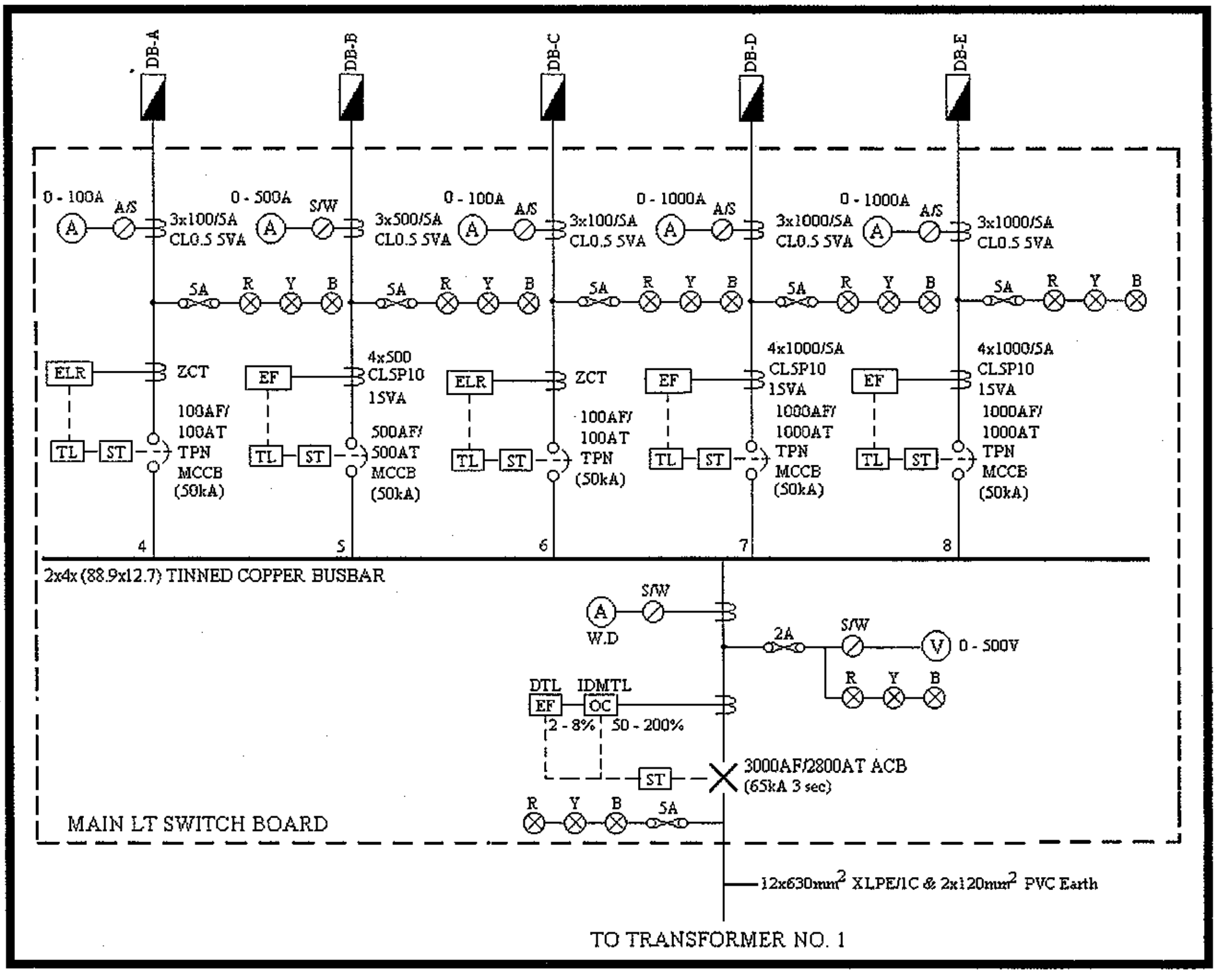


Figure 2.7 Earth Fault Relay on main switchboard with rated current 300A or more

1. Describe briefly the fundamental requirements for safety in the design of electrical installations for buildings as stipulated by Singapore Standard CP 5:1998 & IEE Wiring Regulation (16th Edition).

2. The single-line diagram for a distribution board (DB) as shown in Figure 2.8 contains errors which violate the safety requirements of CP 5:1998. Explain what are these errors and how you would rectify them.

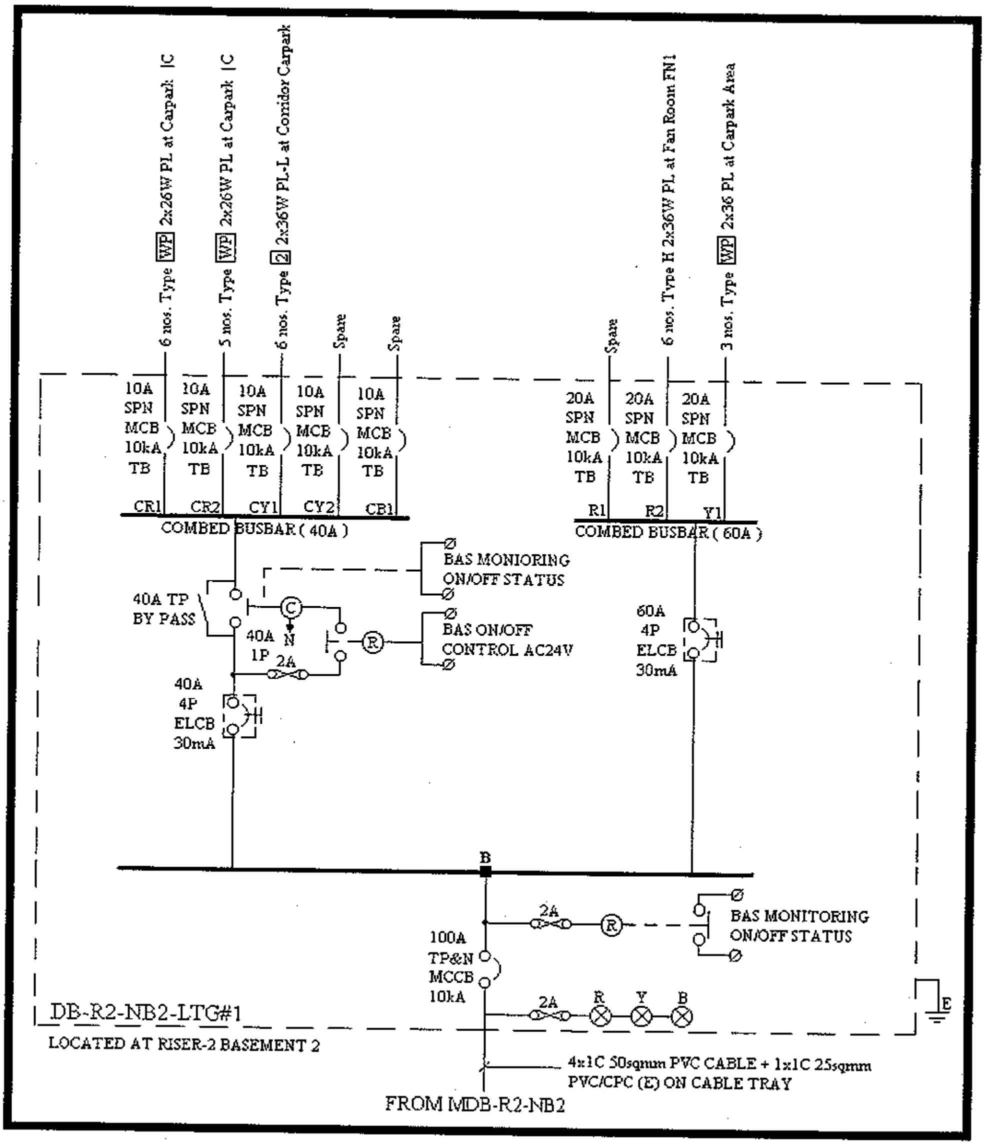


Figure 2.8 The Single-Line Diagram of a Distribution Board (DB) which contains Design Errors

3. The single line diagram of electrical riser tap off unit and meter boards for a high-rise building is shown in Figure 2.9. Explain briefly the requirements of CP5:1998 and IEE regulation (16th edition) pertaining to provision of overcurrent protection.

4. Explain briefly the requirements in provision of Residual Current Device(RCD) as required by CP 5:1998 and the authority.

5. The single line diagram of an electrical riser is shown in Figure 2.10. Explain briefly

(a) Why overcurrent protection device is omitted at the tap-off unit and how overcurrent protection is provided in this example.

(b) How Earth leakage and Earth fault protection are provided in this example.

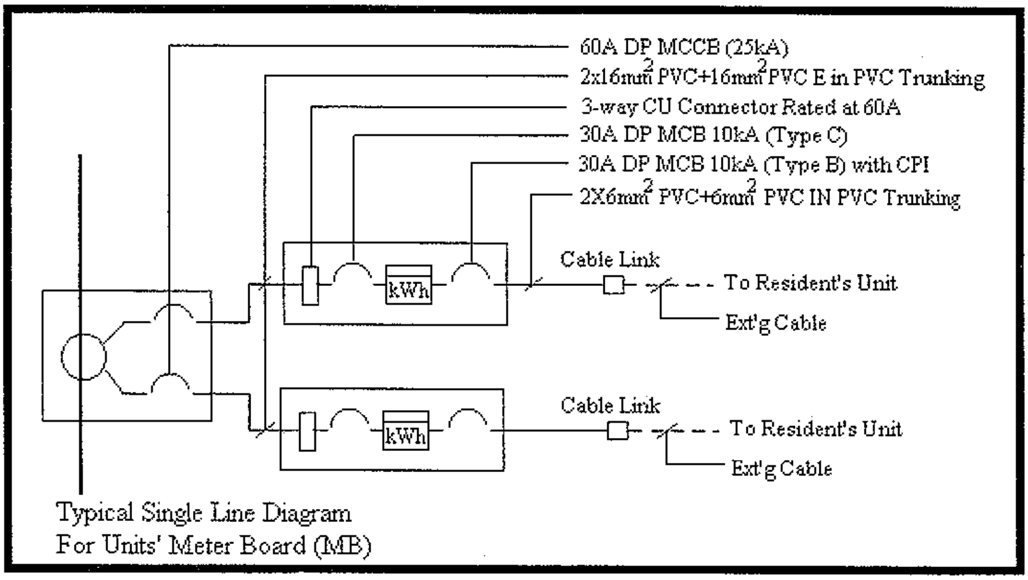


Figure 2.9 Position of Fault Current Protection Device

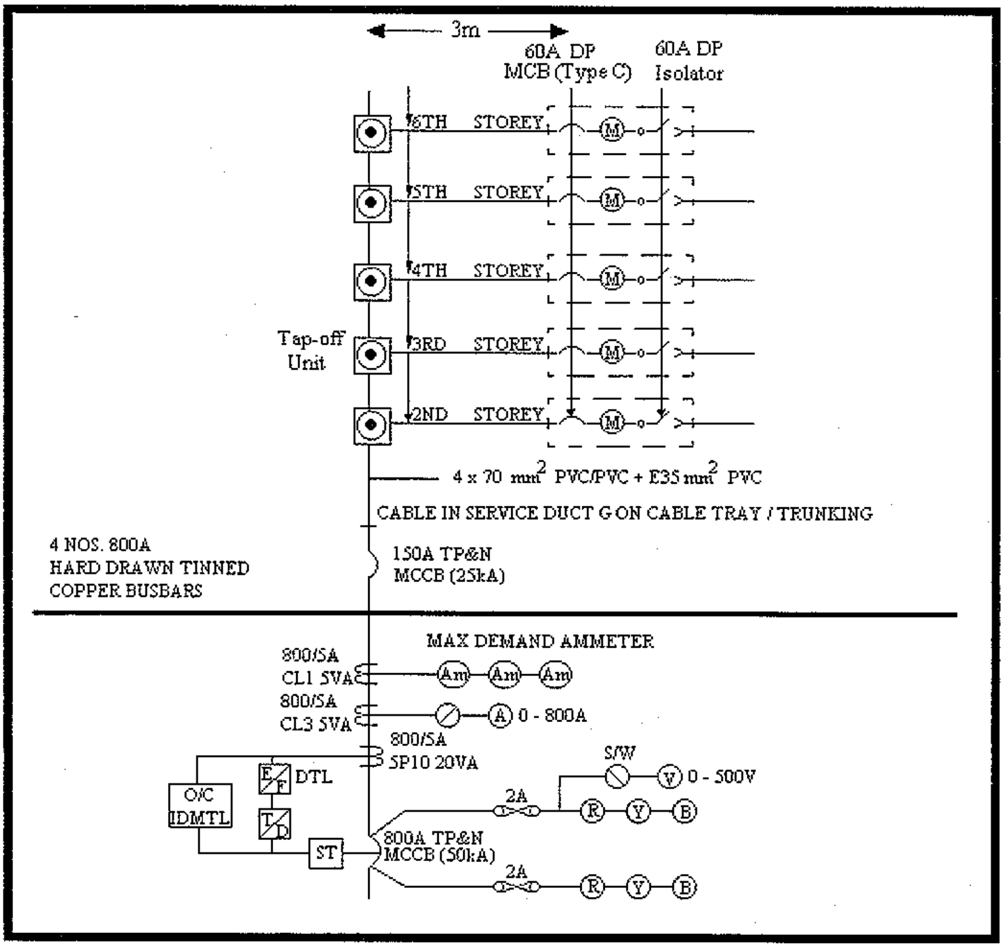


Figure 2.10 Position of fault current protection device

CHAPTER 3
MINIATURE CIRCUIT BREAKER (MCB) - OVERCURRENT PROTECTION DEVICE

3.1 PROTECTION AGAINST OVERLOAD AND SHORT CIRCUIT

It is often possible to use the same device to protect against overload and short circuit, but before doing so it is necessary to determine the design current of the circuit and also to ascertain the prospective short circuit current which is likely to arise.

3.2 NOMINAL CURRENT RATING (OR RATED TRIP RATING) I_n

(a) Nominal current rating or Rated trip rating of the circuit breaker is the current for which the circuit breaker can carry <u>continuously</u> without causing the breaker to trip, overheat or deteriorate.

(b) The nominal current rating is easily identified as the nearest available current rating I_n in amperes (A) equal to or more than the design current I_b of the circuit.

(c) Miniature Circuit Breakers (MCBs) are manufactured in fixed ratings from 5A, 10A, 15A, 16A, 20A, 30A, 32A, 40A, 50A, 60A, 63A, 80A & 100A.

3.3 RATED SHORT CIRCUIT BREAKING CAPACITY OF CIRCUIT BREAKER

(a) Rated short circuit breaking capacity (kA, R.M.S. value) or also known as interrupting capacity of circuit breaker is the root mean square (R.M.S.) value of the a.c. component of current at which the circuit breaker can break <u>safely</u> under the specified conditions of voltage and power factor.

(b) Since short circuit breaking capacity of a protective device is the maximum fault current that the device can interrupt or break safely, it must therefore not be less than the maximum prospective short circuit current at the point of installation.

(c) In British standard BS EN 60898 and Singapore standard SS359 for miniature circuit breaker, MCB may have short circuit breaking capacity from 1kA to 25kA. However, commonly available MCBs are rated at 6kA, 9kA OR 10kA (RMS)

3.4 MINIATURE CIRCUIT BREAKER (SS359 AND BS EN 60898)

Miniature Circuit Breaker (MCB) is the small circuit breaker used for the protection of final circuits at the Distribution Board (DB) of residential and small commercial and industrial installations.

It is used as an alternative to fuse as it can be easily reset and re-closed when the fault in the circuit is cleared.

It will trip on a small sustained overcurrent, but not on a harmless transient overcurrent such as switching surge (For example, on a fluorescent lamp circuit).

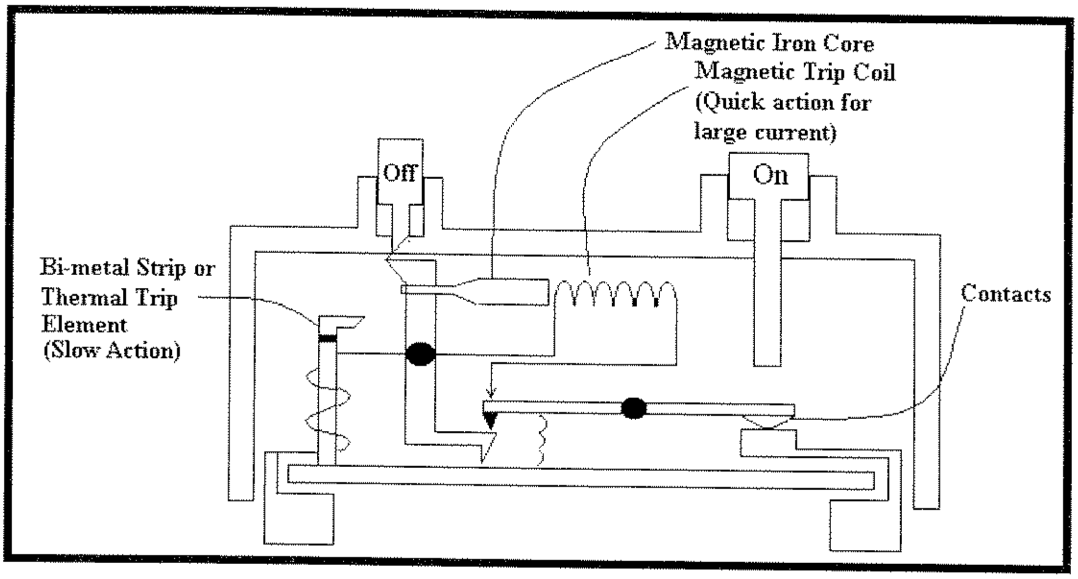


Figure 3. 1 Miniature Circuit Breaker (MCB)

Functions of the Circuit Breaker

As circuit breaker is a protective device, its basic functions are:-

(a) To permit the electrical installations or appliances it protects to be used up to its full rated current capacity.
(b) To detect and to protect equipment against dangerous conditions.
(c) To perform the duties as local circuit control switches and fault-making isolation switches.

Principles of Operation

Miniature Circuit Breakers use one of both of the following principles of operation:-

(a) Thermal Operation

Thermal tripping uses a heat-sensitive bi-metal element. The heat produced by the sustained high current warms the bi-metal strips, which bend to trip the operating contacts.

(b) Magnetic Operation (Instantaneous Trip)

Magnetic operation is due to the magnetic field set up by a coil carrying the fault current, which attracts an iron core to trip the breaker when the fault current becomes large enough.

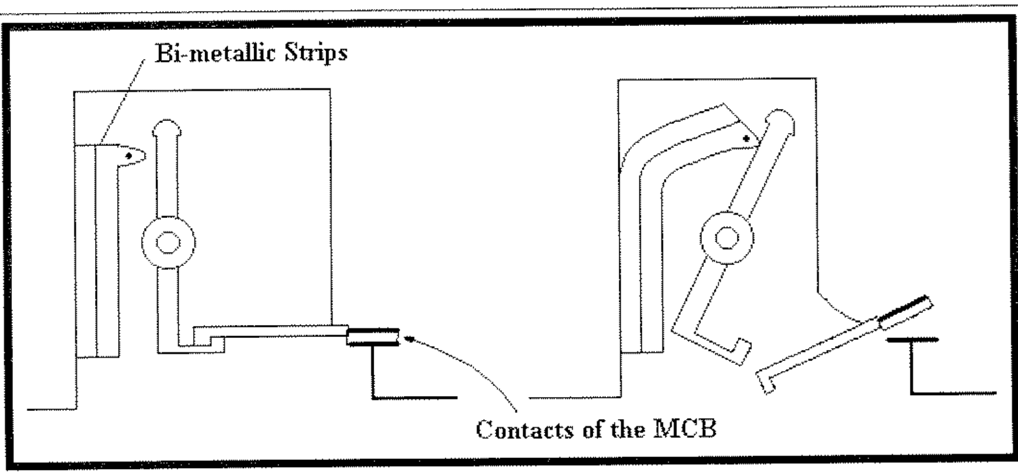


Figure 3. 2 Operation of Thermal element

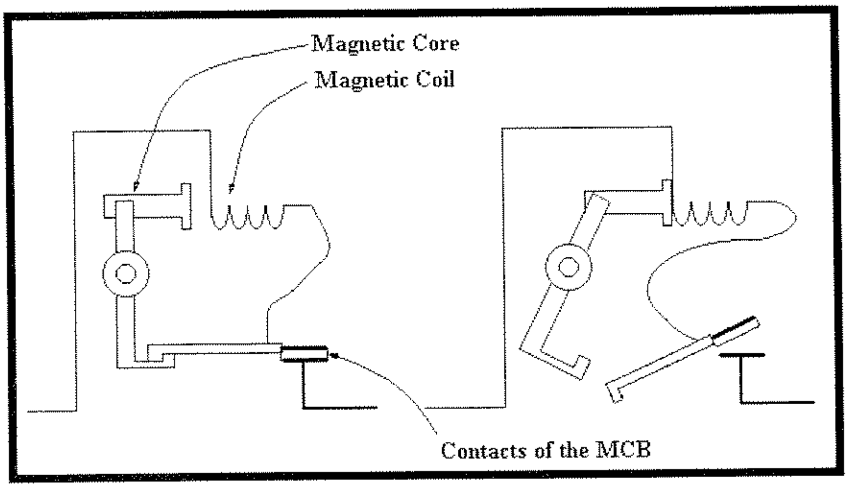


Figure 3. 3 Magnetic Operation

Thermal operation is slow, so it is unsuitable for the speedy disconnection required to clear fault currents. However, it is ideal for operation in the event of small but prolonged overload current.

Magnetic operation can be very fast and so it is used for breaking fault currents; in many cases, both thermal and magnetic operation are combined to make the circuit breaker more suitable for both overload and fault protection.

The mechanical operation of opening the contacts takes a definite minimum time, typically 10ms to 20ms, so there can never be any possibility of truly, instantaneous operation.

3.5 SELECTION OF MCB

There are three important parameters to consider when selecting an MCB:

- The current rating (5A to 100A)
- The instantaneous trip current (represented by Type no.)
- The short-circuit capacity (1kA to 10kA)

Magnetic trip (or Instantaneous trip) & Type no.

As illustrated in Figure 3.4, there are seven types of MCBs currently available. They vary in the magnitudes of current that can cause the magnetic trip element to operate instantaneously (defined as within 100ms) although, with smaller current, their thermal element (or overload characteristic) are the same in all cases.

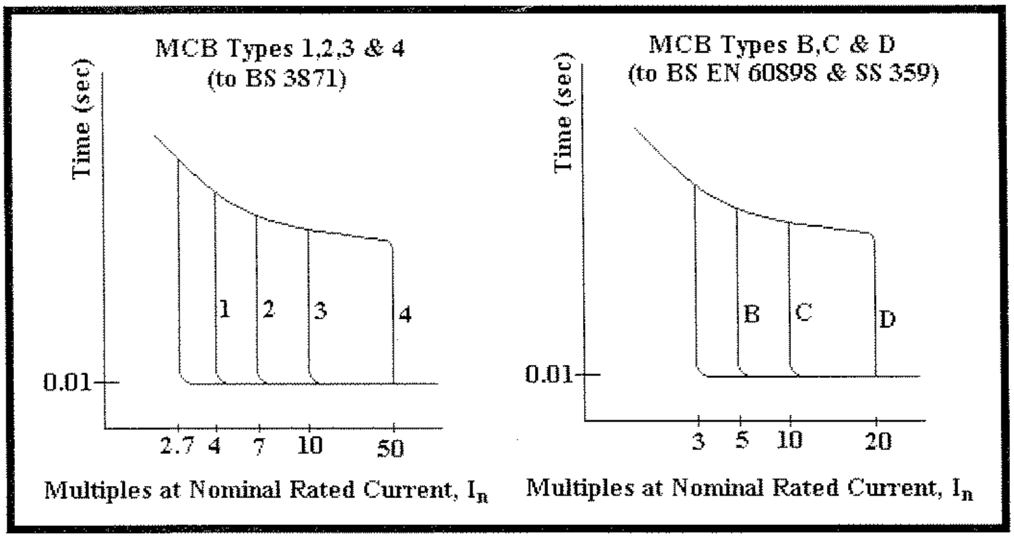


Figure 3. 4 Magnetic trip

Instantaneous Trip Operating Time

Instantaneous trip operating time is therefore defined as being with 100 m-second (0.1 second) and the following table in Table 3.1 show that the range of currents that the MCB will definitely not operate within 100 m-second and the range of currents that the MCB will definitely operate within 100 m-second for various types of MCB:-

Type	Will NOT trip in 100ms at current	Will trip in 100ms at current	Typical Application
1	$I < 2.7 X I_n$	$I < 4 x I_n$	Low Inrush Currents (Domestic Installation)
2	$I < 4 x I_n$	$I < 7 x I_n$	General Purpose Use
3	$I < 7 x I_n$	$I < 10 x I_n$	High Inrush Currents (Motor Circuits)
B	$I < 3 x I_n$	$I < 5 x I_n$	General Purpose Use
C	$I < 5 x I_n$	$I < 10 x I_n$	High Inrush Currents (Motor Circuits)

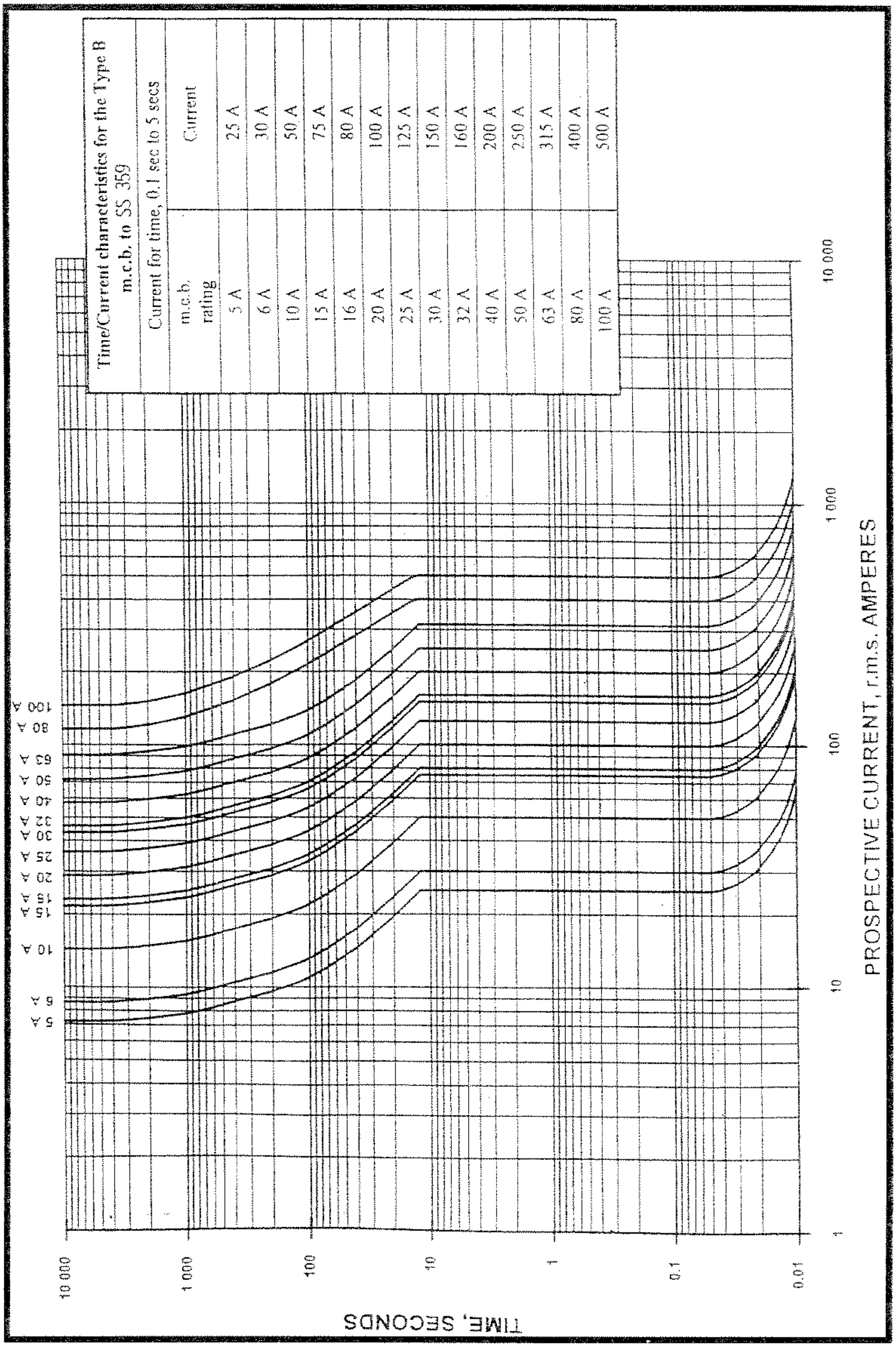
Table 3.1 Where In is the Nominal rating or Thermal trip rating of MCB.

For example, the magnetic trip (or instantaneous trip) of a type C MCB definitely will not trip if fault current is less than 5 x I_n and the same MCB will trip magnetically if fault current is more than 10 x I_n.

Time-Current Characteristic

Time-current characteristic of protection device (MCB, MCCB and Overcurrent Relay) are often plotted in graphs with logarithmic scales.

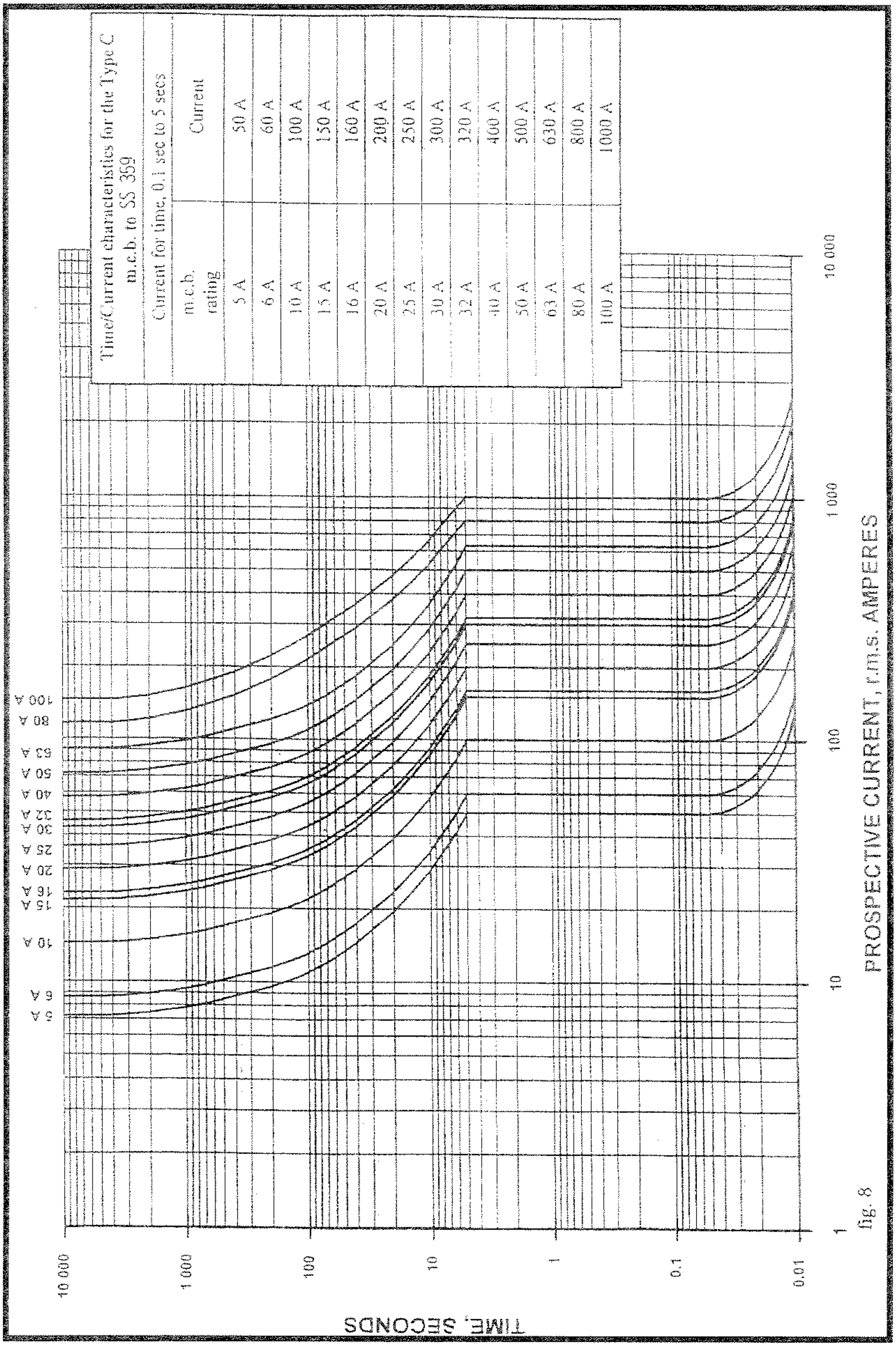
Typical characteristic of MCB with fixed and non-adjustable time / current characteristic calibrated at 30°C for Type 1, 2, 3 and Type B, C, D are available from Singapore Standard CP5:1998.



Time/Current characteristics for the Type B m.c.b. to SS 359

Current for time, 0.1 sec to 5 secs	
m.c.b. rating	Current
5 A	25 A
6 A	30 A
10 A	50 A
15 A	75 A
16 A	80 A
20 A	100 A
25 A	125 A
30 A	150 A
32 A	160 A
40 A	200 A
50 A	250 A
63 A	315 A
80 A	400 A
100 A	500 A

Figure 3. 5 Time-Current Characteristic in Logarithmic Scales – Type B MCB



m.c.b. rating	Current
5 A	50 A
6 A	60 A
10 A	100 A
15 A	150 A
16 A	160 A
20 A	200 A
25 A	250 A
30 A	300 A
32 A	320 A
40 A	400 A
50 A	500 A
63 A	630 A
80 A	800 A
100 A	1000 A

Figure 3. 6 Time-Current Characteristic in Logarithmic Scales – Type C MCB

3.6 EXAMPLES IN SELECTION OF MCB

Example 3.1

For a final circuit feeding four (4) twin 40-watt fluorescent lightings and six (6) 60-watt incandescent lightings (filament lamp), determine the appropriate current rating of the MCB.

Assuming power factor of 0.85 and efficiency of the fluorescent lamp be 65%.

Total load for 4 twin 40-watt Fluorescent lights and 6 nos. 60-watt Incandescent lights:

$$= \left(\frac{4 \text{ x } 2 \text{ x } 40 \text{ W}}{p.f. = 0.85 \text{ x } efficiency = 65\%} \right) + \left(\frac{6 \text{ x } 60\text{W}}{p.f. = 1 \text{ x } efficiency = 100\%} \right)$$

$$= 4 \text{ x } (2 \text{ x } 40\text{W}) \text{ x } \left(\frac{1}{0.85 \text{ x } 0.65} \right) + 6 \text{ x } (60\text{W}) \text{ x } 1$$

$= 4 \text{ x } (2 \text{ x } 40) \text{ x } (1.8) + 360 \text{ x } (1)$, (Please note: Factor = 1.8 for Fluorescent lights
Factor = 1 for Incandescent lights)

$= 576 \text{ VA} + 360 \text{ VA}$

$= 936 \text{ VA}$

Designed Circuit Current $I_b = \frac{937 \text{ VA}}{230 \text{ V}}$

$\approx 4.07 \text{ A}$

Since, Nearest MCB current rating I_n = 5A or 10A

A 10A Type B MCB is preferred in this non-domestic situation.

Example 3.2

For a final circuit feeding a 230V, single-phase 3kW instantaneous water heater, determine the appropriate current rating of the MCB.

Designed Circuit Current $I_b = \frac{3000 \text{ W}}{230 \text{ V}} = 13\text{A}$, because Power Factor =1

Therefore, use the nearest available MCB current rating, I_n = 20A.

A 20A MCB Type B is selected.

A typical design of a small lighting and power distribution board (DB) in a residential unit is shown in Figure 3.7.

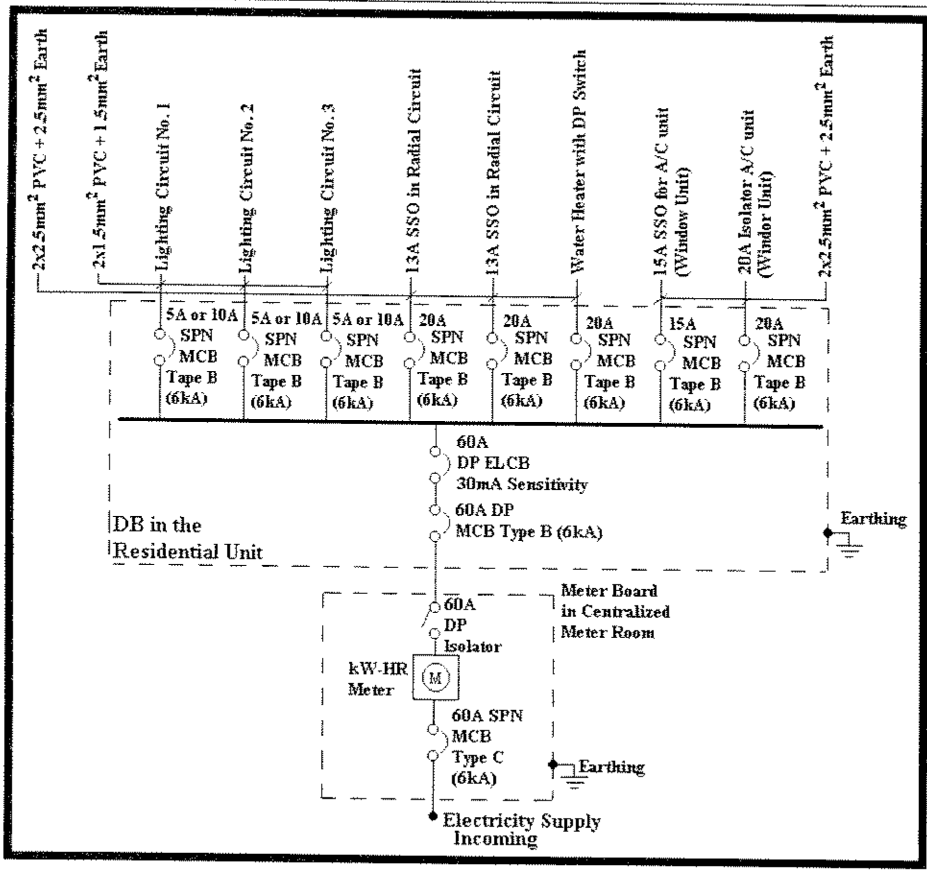


Figure 3.7 A Typical Distribution Board (DB) using MCBs and RCCBs as Protective Devices

3.7 SELECTION OF MCB FOR MOTOR CIRCUITS

Motor Loads present the most complex type of transient inrush current. The starting phenomenon takes place in two stages, a transient and a steady-state stage. Figure 3.8 shows the two stages of the motor starting currents:-

(a) An initial peak Inrush current of 2.8 times the r.m.s. value of the motor's locked rotor current (I_{start}) or 15 times x Full Load Current lasting for less than two main cycles (0.04 sec).

(b) The second stage where the motor starting current decays to about 7.5 times x Full Load Current which may last for 5 to 15 seconds.

The motor finally takes the steady running current at maximum value equal to Full Load Current.

The first stage of in-rush current is due to initial surge of current into a stationary motor which lasts until the field is established.

The second stage of starting current lasts while the motor speeds builds up. In practice, this second stage of starting current is not constant as shown but is generally assumed to be so since it simplifies the problem and assumes the worst case.

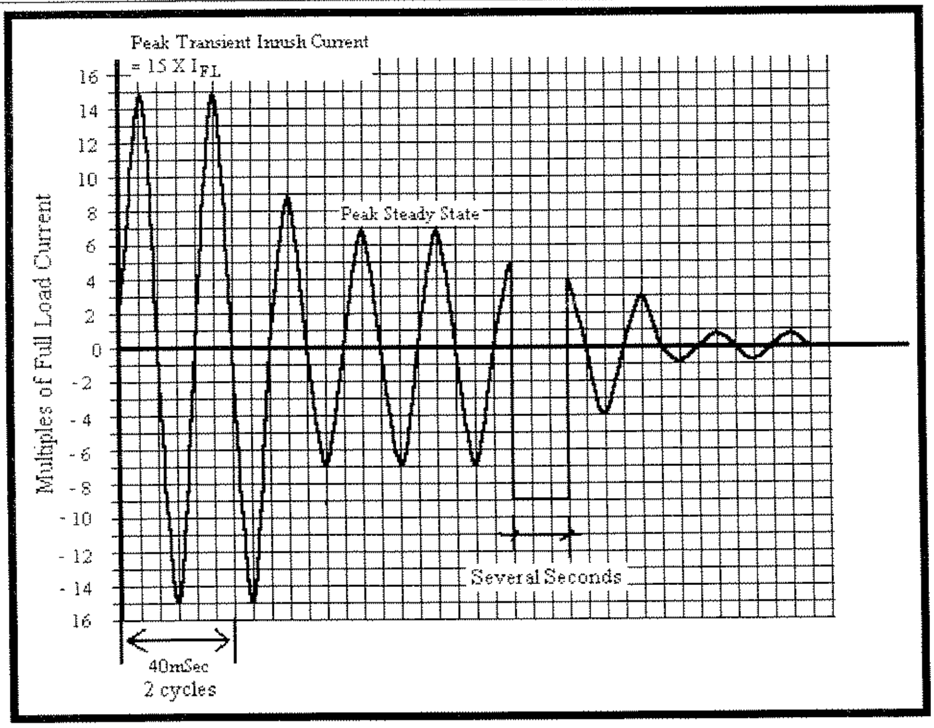


Figure 3. 8 Motor Inrush Current (Shown as Instantaneous Value)

The R.M.S values of motor current in the three (3) stages from initial peak to final running current is shown in Figure 3.9.

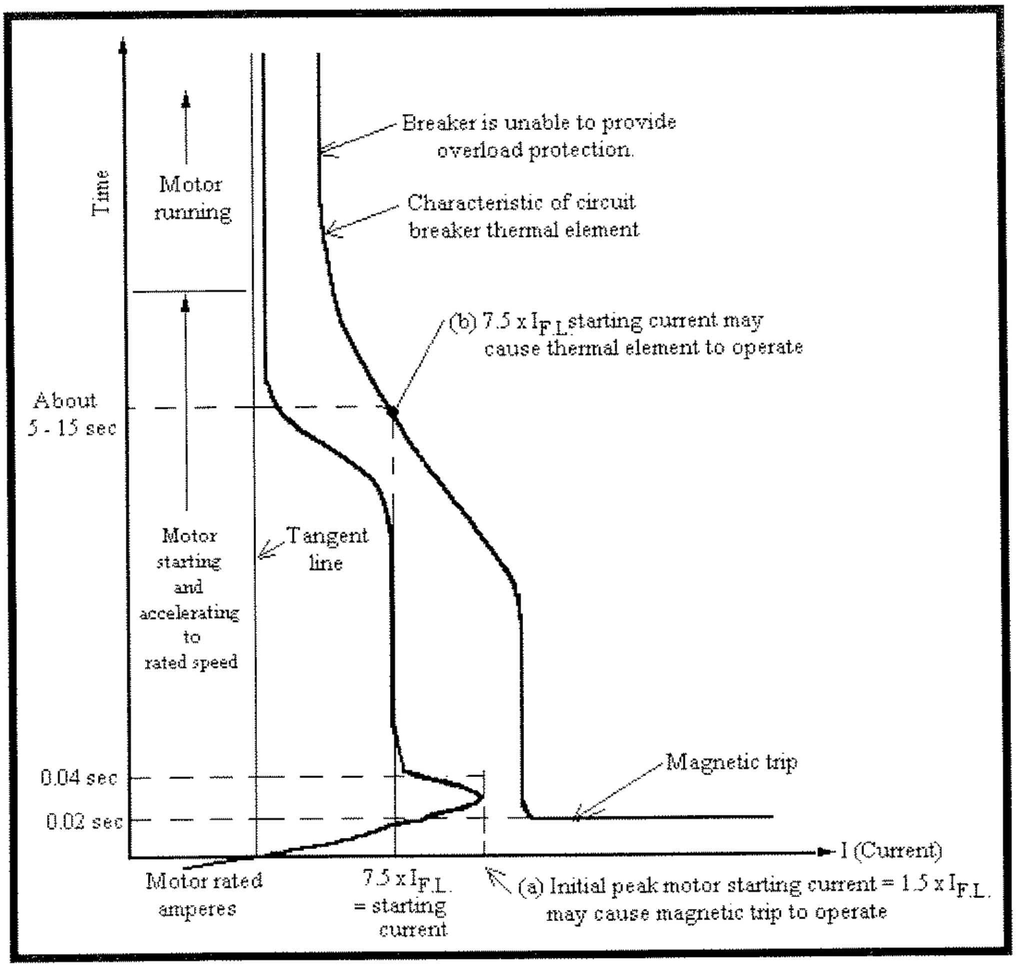


Figure 3. 9 Characteristic of Motor Starting Current with respect to time (R.M.S. Value)

(a) As the initial peak last for about 0.04 seconds, it may cause the magnetic trip to trip.
(b) Whereas the second stage starting current which may last for 5 to 15 seconds and may cause the thermal element to trip.

To overcome these kinds of unnecessary tripping, the following design approach has been used quite satisfactorily:

(a) Rated thermal trip rating or nominal rating (I_n) of circuit breakers are selected larger to avoid unnecessary tripping.

For motor with Full Voltage Starting or Direct-on-line Starting, I_n is select between 2 x $I_{Full\ Load}$ and 2.5 x $I_{Full\ Load}$.
For motor with Reduced Voltage Starting, I_n is selected between 1.5 x $I_{Full\ Load}$ and 2 x $I_{Full\ Load}$.

(b) Magnetic trip element or type no. are selected to ensure that magnetic trip element will not operate at Inrush current.

Example: If $I_{Inrush} < 3 \times I_n$ (or maximum current that will definitely not trip magnetic trip of Type B)
Then Type B will be selected.

If $I_{Inrush} < 5 \times I_n$ (or maximum current that will definitely not trip magnetic trip of Type C)
Then Type C will be selected.

However, the above design rule of thumb should be subjected to further closer analysis with time-current characteristic of the MCB and the characteristic of motor starting currents to ensure appropriate and proper selection.
It is also to be noted that, when the circuit breaker is selected with higher thermal trip rating (I_n) for the motor circuit, the circuit breaker selected is unable to provide appropriate overload protection for the motor cable and the motor itself. Overload relay (which is normally set to 110% to 120% of Full load running current) must be provided at the motor starter for overload protection. The circuit breaker will now provide only short circuit protection.

For motor circuit or motor submain without overload relay (E.g. Fire pumps, essential motor circuit where overload relays have been removed for safety reason), the cable size and motor must be selected carefully to have current carrying capacity equal to (or more than) the Rated trip rating I_n of the circuit breaker.

3.8 IDENTIFICATION OF CIRCUIT BREAKER IN TERMS OF NUMBER OF POLES

Overcurrent devices such as MCB and MCCB are commonly referred to by the number of poles in terms of switching as shown in Figure 3.10. It is to be noted that overcurrent detection is normally provided only in each phase conductor, but not in the neutral conductors, except where it is necessary required as shown in Figure 3.10.

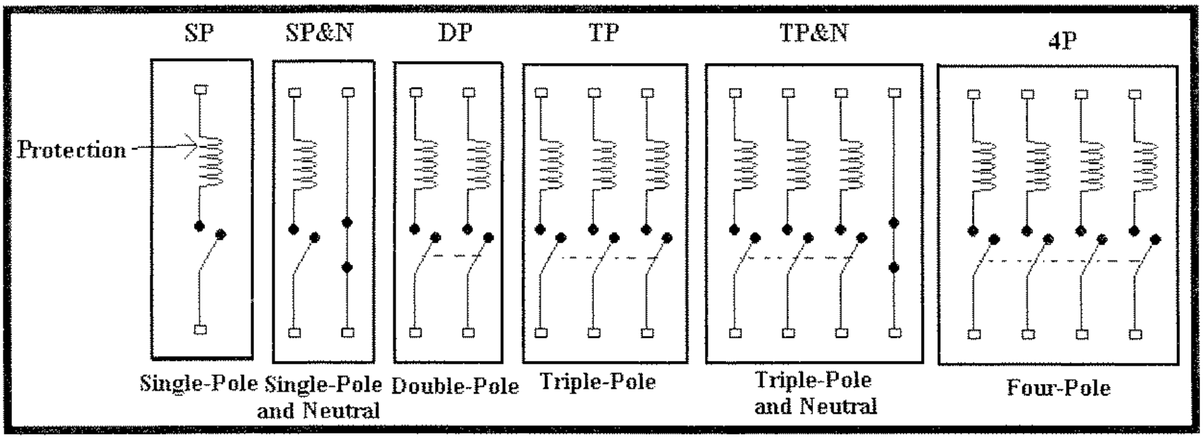


Figure 3. 10 Identification by Number of Poles Example 3.3

Example 3.3

Determine the appropriate current rating of MCB for a 3-phase, 400V, 50Hz 4.5kW Motor with an efficiency 85% and power factor 0.8. Assuming that the motor is started by Direct On-Line starter (D.O.L.).

(a) Input Power (kW) = $\frac{\text{Outpower}}{\text{Efficiency}}$

$$= \frac{4.5\text{ kW}}{85\ \%} = 5.3\text{ kW}$$

Therefore, Designed Circuit Current, $I_b = I_{F.L.} = \frac{P}{1.732 \times V_L \times \text{p.f.}}$

$$= \frac{5300\text{ W}}{1.732 \times 400 \times 0.85}$$

$$= 9.56\text{A}$$

As the motor is started by D.O.L. starter, to allow for the starting current, the MCB current rating is sized larger at 2.5 times x $I_{F.L.}$

2.5 x $I_{F.L.}$ = 2.5 x 9.56A = 23.9A

Since, the next available MCB current rating is I_n = 30A

A 30A triple pole (TP) MCB is selected.

(b) Determination of thermal trip rating

Calculate I_{Inrush} = 15 x $I_{F.L.}$
= 15 x 9.56A
= 143.4A (Peak) which last for 0.04 seconds

$I_{start} = 7.5 \times I_{F.L.}$
$= 7.5 \times 9.56A$
$= 71.7A$ (Second Stage) which last for 5 to 15 seconds

The MCB thermal characteristic, shows that at $I_{start} = 71.7A$

20A MCB will operate in about 28 seconds.
30A MCB will operate in about 42 seconds.
40A MCB will operate in about 350 seconds.

Since the starting current only last for about 15 seconds, a MCB with $I_n = 30A$ (thermal trip rating) is selected.

(c) Determination of magnetic trip and type no.

Since $\dfrac{\text{Inrush Current}}{\text{Trip Rating, } I_n} = \dfrac{143.4\ A}{30\ A} = 4.78$ times

and a 30A Type B MCB may trip on magnetic trip at 3 I_n, Type B is not suitable

and a 30A Type C MCB may trip on magnetic trip at 5 I_n which is larger than 4.78 I_n, a 30A Type C MCB is selected.

(1) (a) Explain briefly the operation of the following tripping elements of a circuit breaker

(i) Thermal Trip
(ii) Magnetic Trip

(2) For a 5A (i.e. current rating, I_n = 5A), type B MCB used as protection device for a lighting circuit in domestic residential premises, determine the operating time of the MCB and state which tripping element operates for the following range of currents:

(a) 10A
(b) 20A
(c) 25A (i.e. 5 x I_n)
(d) 30A
(e) 100A
(f) 1000A
(g) 10,000A

(3) For a 20A (i.e. current rating, I_n =20A), type B MCB used as protection for 20A radial circuit for 13A switch socket outlets, determine the operating time of the MCB and state which tripping element operates for the following range of currents:

(a) 40A
(b) 60A
(c) 100A (i.e. 5 x I_n)
(d) 150A
(e) 200A
(f) 1000A
(g) 10,000A

(4) For a 63A (i.e. current rating, I_n = 63A), type C MCB used as protection device for a 63A motor circuit, determine the operating time of the MCB and state which tripping element operates for the following range of currents:

(a) 100A
(b) 200A
(c) 300A
(d) 630A (i.e. 10 x I_n)
(e) 700A
(f) 800A
(g) 900A
(h) 1000A
(i) 10,000A

(5) For a 100A (i.e. current rating, I_n = 100A), type C MCB used as protection device for a 100A tap-off unit, determine the operating time of the MCB and state which tripping element operates for the following range of currents:-

(a) 200A
(b) 300A
(c) 400A
(d) 1000A (i.e. 10 x I_n)
(e) 1500A
(f) 2000A
(g) 10,000A

(6) (a) A Type B MCB to BS EN 60898 and SS 359 rated 40A is used to protect a 230V single-phase distribution board. Calculate the maximum value of the earth fault loop impedance of the circuit to allow the MCB to operate within 0.4 seconds. (Draw a diagram to show the earth fault loop).

(b) If the actual measured Earth fault loop impedance is higher than your calculated value in (i), explain whether the 40A MCB is effective in protecting the circuit and what steps would you take to ensure effective protection.

(7) Determine the appropriate current rating of MCB for a 3-phase, 400V, 50Hz 4.5kW Motor with an efficiency 85% and power factor 0.8. Assuming that the motor is started by Direct On-Line starter (D.O.L.).

(8) 7.5 h.p. (5.5 kW) 3-phase motor has an efficiency of 87%. The motor is started by D.O.L. starter and started with mechanical load. Assuming that the initial starting current has its peak value at 15 x $I_{F.L.}$ for 0.04 sec and then decay to about 7.5 x $I_{F.L.}$ for 15 seconds. Determine

(a) the current rating of the MCB;

(b) whether Type B or Type C MCB is to be selected.

(9) Determine the MCB trip rating I_n of the following circuit for a Distribution Board (DB) in a residential unit.

(a) A lighting circuit with 5 nos. 40 watt fluorescent lamps (with efficiency 65% and power factor = 0.85) and 5 nos. 30 watt filament lamps (say maximum 10 points).

(b) A radial circuit for 6 nos. 13A switch socket outlet (SSO), assuming average load at each point is 400 watt in general area.

(c) A radial circuit for 3 nos. 13A switch socket outlet (SSO), assuming average load at each point is 1000 watt in kitchen area.

(d) A ring circuit for 10 nos. 13A switchboard socket outlet (SSO), assuming load at each point is 500 watt.

(e) An instantaneous water heater at 3.5 kW.

(f) A washing machine (with hot water heater) at 2.5 kW.

(10) A dwelling house in a high rise condominium apartment has been designed with the following loads:-

(a) Determine the total connected load.

(b) Determine the maximum demand of the distribution board (DB) based on the given diversity factor (DF) or each category of the loads in Table 3.2 and an overall diversity factor at 0.7 (or 70%).

(c) Determine the rated trip rating of the MCB for the main breaker.

	D.F.	M.D.
32 nos. Lighting points at 100 W per point	60%	______ watt
44 nos. 13A SSO at 400 W per point	50%	______ watt
5 nos. Water heater at 2000 W each	60%	______ watt
One cooker (rated at 4600 W)	50%	______ watt
One Washing machine with hot water heater at 2500 W.	100%	______ watt
Air-conditioning total load at 9775 W	60%	______ watt

Table 3.2

Note: For each final circuit, the MCB trip rating and circuit cable shall be designed to carry 100% connected load. However, for the main breaker of DB, the designer may design MCB trip rating and cable to carry maximum demand loads which is equal to DF x Connected Load.

CHAPTER 4
RESIDUAL CURRENT DEVICE

4.1 RESIDUAL CURRENT DEVICE (RCD)

(a) Residual current as defined in SS CP5: 1998 is the vector sum of the instantaneous values of current flowing through all live conductors (Live & Neutral in single phase system and R, Y, B & Neutral in 3-phase system).

Whereas residual current device is defined as mechanical switching device or association of devices intended to cause the operating for the contacts when the residual current attains a given value under specified conditions.

(b) Typical residual current devices include:-

(i) Residual Current Circuit Breaker (RCCB) or known as Earth Leakage Circuit Breaker (ELCB)
(ii) Earth Leakage Relay (ELR)
(iii) Earth Fault Relay (EFR)

(c) SS CP5: 1998 requires that metal work of electrical equipment be connected to earth and recommends that appropriate RCDs be provided for protection against the persistence of earth fault current in the installation.

4.2 RESIDUAL CURRENT CIRCUIT BREAKER (RCCB) OR EARTH LEAKAGE CIRCUIT BREAKER (ELCB)

Residual Current Circuit Breaker (RCCB) is identified by its sensitivity ($I_{\Delta n}$) to detect the residual current or earth leakage current when the vector sum of the instantaneous value of current flowing through all live conductors is not zero.

Therefore, in a healthy system where the vector sum of the instantaneous value of the current flowing through all live conductors is zero, RCCB (or ELCB) should not operate.

i.e. In a single phase system, $I_P - I_N = 0$. RCCB shall not operate. In a 3-phase system, $I_R + I_Y + I_B + I_N = 0$, RCCB shall not operate.

<u>Single Phase Double Pole (DP) RCCB</u>

(a) Purpose:
To monitor the leakage current and switch off the supply quickly if it rises to a preset level.

(b) Operating Principle:
RCCB will operate when phase (I_P) and neutral (I_N) current are not equal because of leakage to earth.

Therefore $I_P - I_N \neq 0$ and $I_P - I_N > I_{\Delta n}$
where $I_{\Delta n}$ is the sensitivity or operating current of RCCB

A magnetic flux results in the core of RCCD (or ELCB), this flux links with the search coil which will drive a current to the tripping system. This will cause the RCCD (ELCB) to trip.

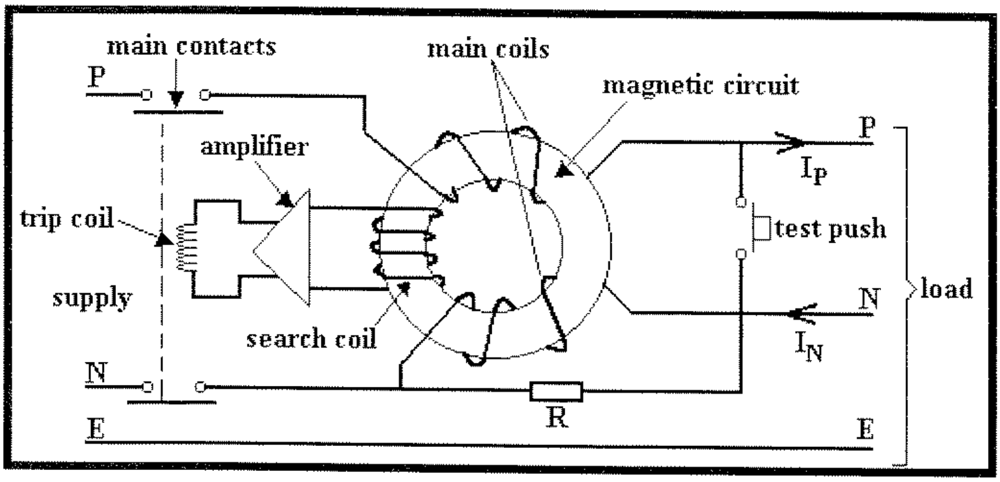


Figure 4. 1 Residual Current Circuit breaker (Single phase, Double pole)

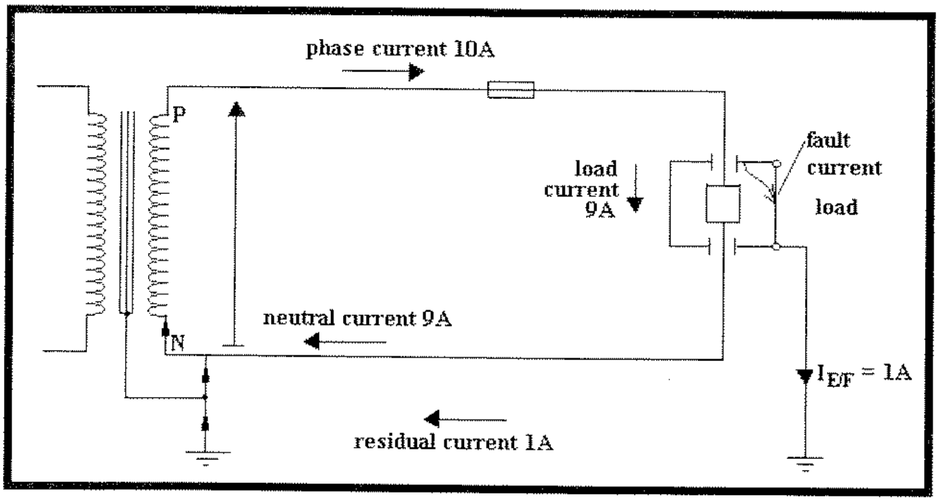


Figure 4. 2 The meaning of the term Residual Current

Three-phase Four-pole (4P) RCCB

RCCB works on core balance principle. For a 3-phase system, the currents in the 4 wires (R, Y, B & N) or conductors are to be checked on their vector sum;

If $I_R + I_Y + I_B + I_N \neq 0$
& $I_R + I_Y + I_B + I_N > I_{\Delta n}$
where $I_{\Delta n}$ is the sensitivity or operating current of RCCB

A magnetic flux results in the core of RCCB (ELCB), this flux links with the search coil which will drive a current to the tripping system. This will cause the RCCB (ELCB) to trip.

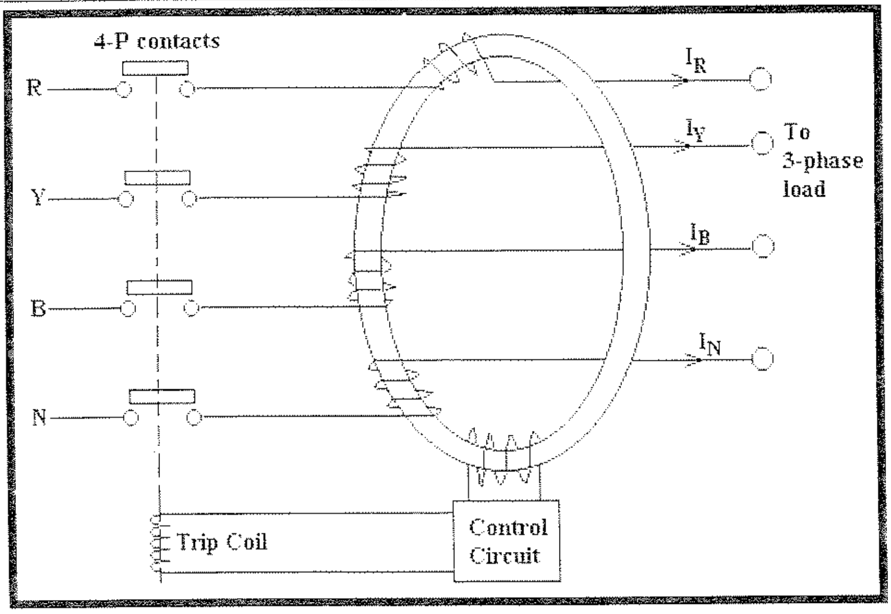


Figure 4. 3 Residual Current Circuit Breaker (3-phase, 4-pole)

4.3 SPECIFICATIONS OF RCCB (SS 97: PART 1: 1994)

Rated voltage

Single phase, phase to neutral system: 230V
Three phase, four-wire system: 400V

Rated current (I_n)

10A, 13A, 16A, 20A, 25A, 32A, 40A, 63A, 80A, 100A, 125A, of which 40A, 63A, 80A, 100A are commonly available in the market.

Rated residual operating current ($I_{\Delta n}$) or sensitivity

0.006A, 0.01A, 0.03A (30mA), 0.1A (100mA), 0.3A (300mA) of which 30mA, 100mA and 300mA sensitivity are more commonly used.

For domestic residential installation, RCCB with 30mA sensitivity must be used for the switch socket outlets and lighting circuits.

Operating Time

The Singapore Standard SS 97: part1: 1994 for residual current operated circuit breakers requires that RCCB operates as follows:-

- At the rated residual operating current $I_{\Delta n}$ (or sensitivity), RCCB must trip within 300 m-secs
- At 2 times the rated $I_{\Delta n}$, RCCB must trip within 150 m-sec
- At 5 times the rated $I_{\Delta n}$, RCCB must trip within 40 m-sec
- At ½ the rated $I_{\Delta n}$, RCCB must not trip

The main use of RCCBs is to provide for protection against electric shocks. Therefore, it is essential that the device maintain its sensitivity ($I_{\Delta n}$) and speed of operation (t sec) throughout the life of an installation.

To facilitate the maintenance of the RCCB sensing circuit, it must incorporate a test switch circuit for the user and it is important that this test switch is operated every 3 months.

Alternatively, a RCD tester can be used to test the tripping time of the RCCB.

4.4 APPLICATION OF RCCB & OVERCURRENT PROTECTION DEVICE

As RCCBs (ELCBs) are not overcurrent protection devices, which do not operate for overloading, phase to neutral short, phase-to-phase short or 3-phase short circuit, it must not be used as replacement to overcurrent protection devices such as MCB or MCCB. RCCBs (ELCBs) must be adequately protected by overcurrent protection devices against overloading and short circuit.

A typical design of meter board at Gate pillar and the distribution board (DB) of a residential unit is shown in Figure 4.4.

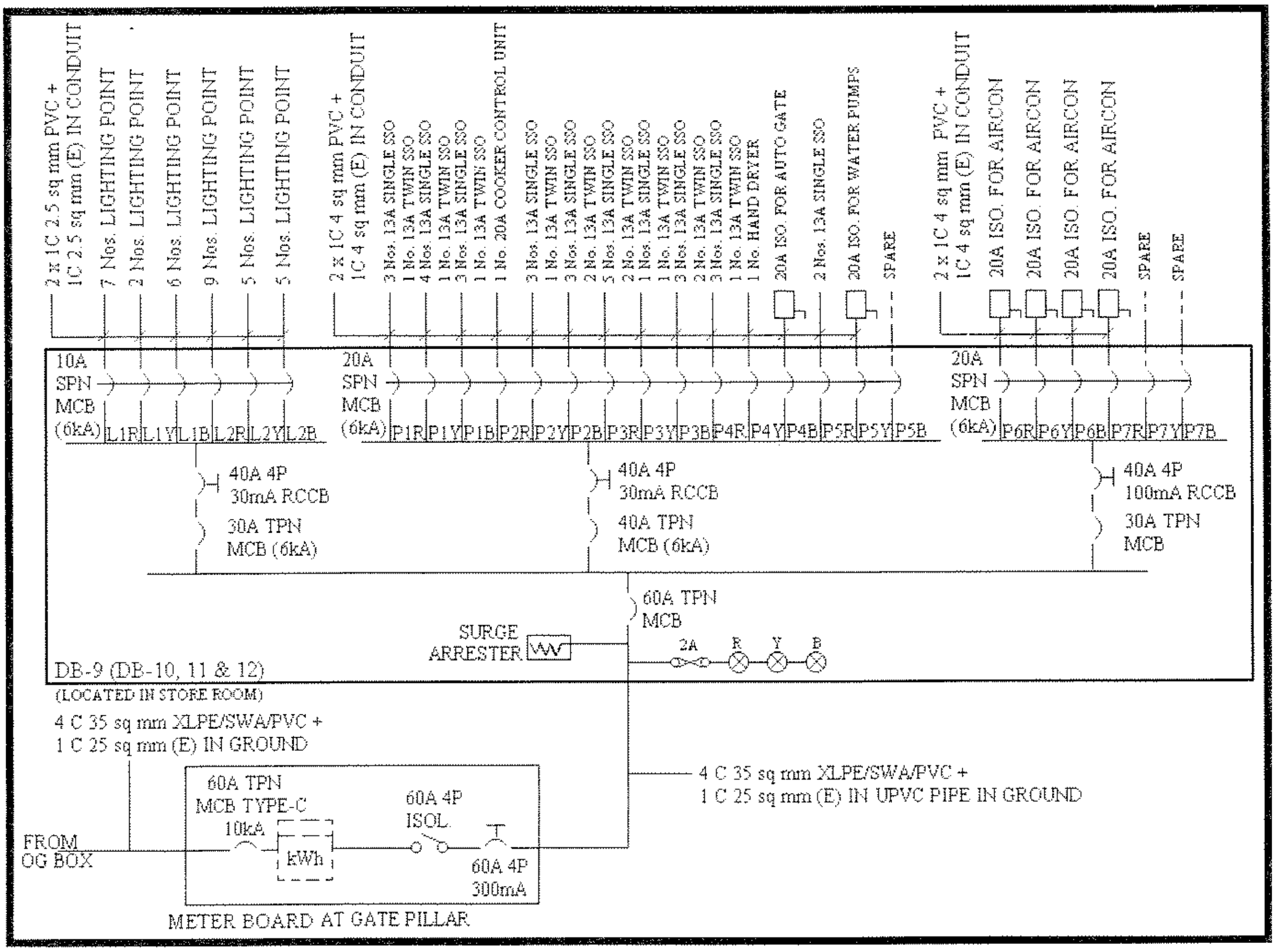


Figure 4. 4 RCCBs & MCBs for the DB of a residential unit

4.5 EARTH LEAKAGE RELAY (ELR)

For a larger distribution board (DB) or switchboard with rated current not more than 300A, earth leakage relay (ELR) with a zero phase current transformer (ZCT or zero sequence current transformers) are in combination to detect earth leakage current as shown in Figure 4.5

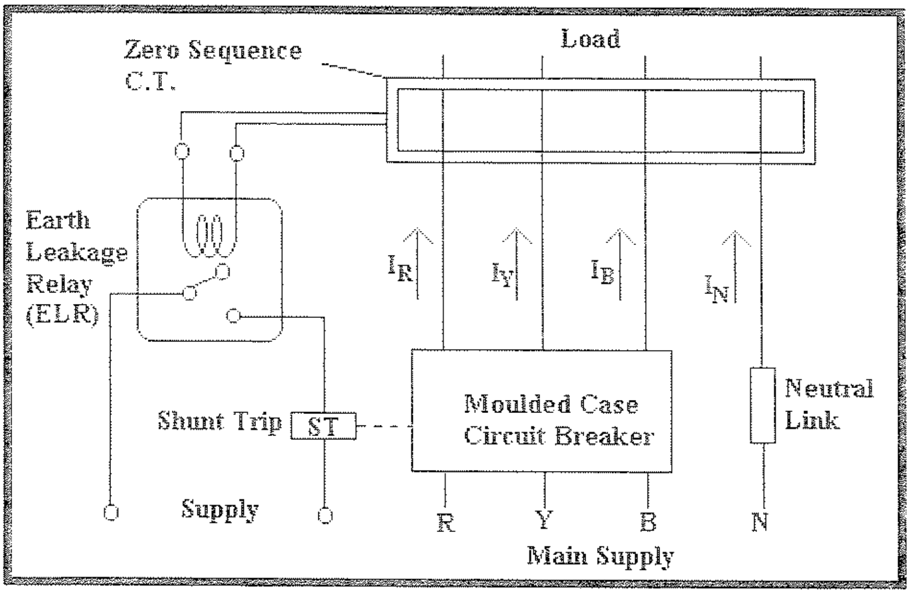


Figure 4. 5 Earth Leakage Relay (ELR)

ELR works on core balance principle. If the system is healthy without earth leakage from any of the live conductors (R, Y, B & N), $I_R + I_Y + I_B + I_N = 0$, no residual current is present and no magnetic flux is detected by the zero sequence current transformer (ZCT), ELR cannot operate.

However, if there is any leakage of current flowing from any phase conductors or neutral conductors to earth; $I_R + I_Y + I_B + I_N \neq 0$

ZCT detects a magnetic flux and will energize the ELR. ELR is wired to the shunt trip coil of the moulded case circuit breaker to cause it to trip.

ELR is normally used for consumer's incoming of 100A to 300A. It is also used for the sub-board intake point and high leakage equipment. The main usage of ELR is earth fault discrimination and equipment protection. Personnel protection is not provided. In general, consumer's earthing can achieve earth loop impedance of 20 ohm and below and 2A setting is commonly used.

4.6 EARTH FAULT RELAY (EFR)

For bigger systems with Main Switch Board (MSB) or sub-switchboard at rated amount 300A or more, one current transformer is too small to couple with the R, Y, B & N conductors. Four (4) nos. current transformers are employed to couple with respective phase and neutral conductors.

Residual current or vector sum of current in conductors and neutral conductors are being checked by the protection circuit.

For an unhealthy system with earth fault or earth leakage current,

$$I_R + I_Y + I_B + I_N \neq 0$$

and $I_R + I_Y + I_B + I_N = I_{E/F}$ in primary circuit

$i_r + i_y + i_b = i_n = i_{e/f}$ in C.T secondary circuit

The spill current $i_{e/f}$ will flow into EFR and cause it to operate.

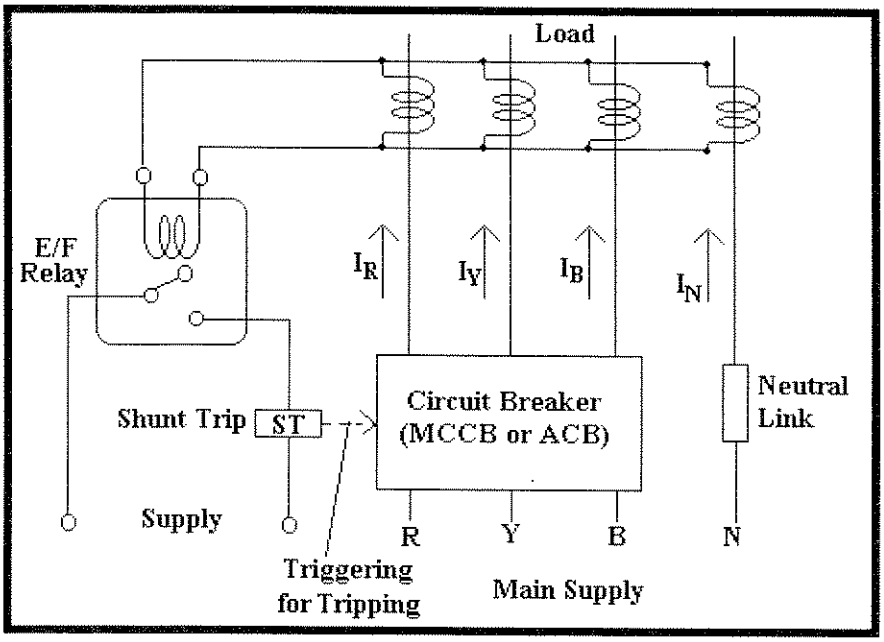


Figure 4. 6 Earth Fault Relay (EFR)

4.7 DANGER OF HIGH EARTH-FAULT-LOOP IMPEDANCE

Although residual current devices are current-operated, there are circumstances where the combination of operating current and high earth-fault loop impedance could result in the earthed metalwork rising to a dangerously high potential. SS CP5: 1998 & IEE regulations draw attention to the fact that if the product of operating current (A) and earth-fault loop impedance (Ω) exceeds 50, the potential of the earthed metalwork will be more than 50V above earth potential and hence dangerous. This situation must not be allowed to arise.

In this case, the voltage rise on the exposed conductive part (or metal enclosure) of the electrical equipment will be:

$$20\Omega \times 4A = 80V$$

which is more than the safe touch voltage limit 50V and hence is dangerous.

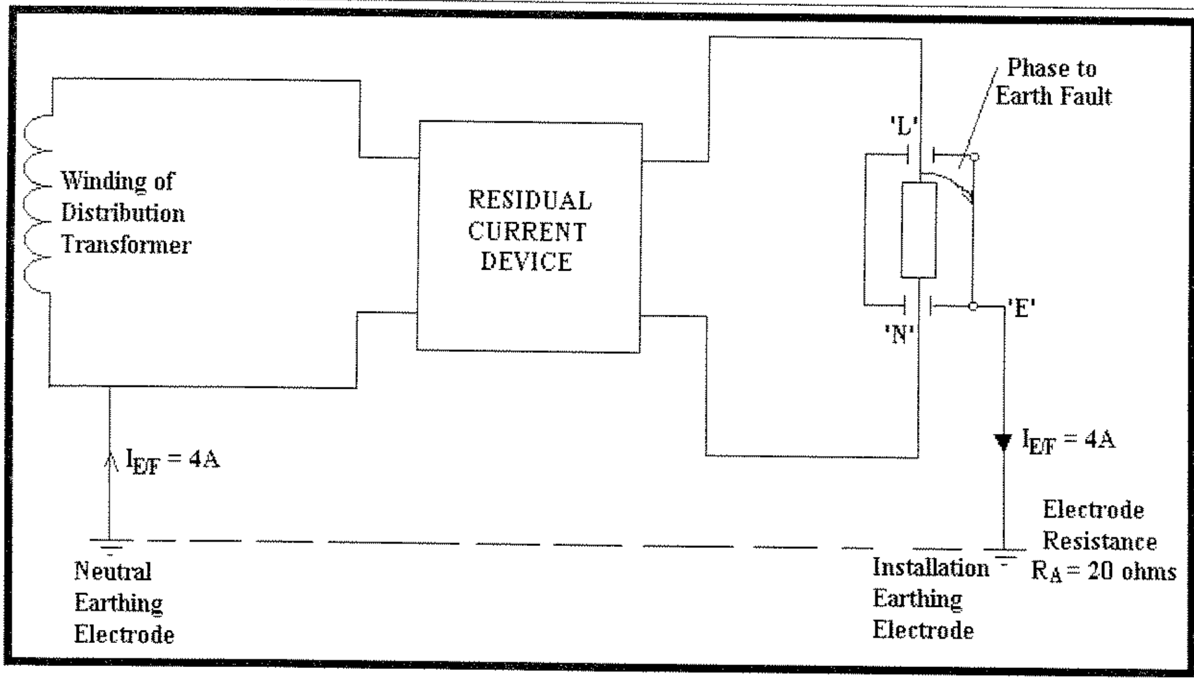


Figure 4. 7 Danger with high earth fault loop impedance

1. Explain briefly the meaning of the following terms:

    (a) Residual current & residual current devices

    (b) Earth fault loop & Earth fault loop impedance

2. Singapore Standard SS CP5:1998 requires that

    (a) For TN-S earthing system, if protection by residual current device is provided, the following condition shall be fulfilled:-

$$Z_s\, I_{\Delta n} \leq 50V$$

    where Z_s is the earth fault loop impedance in ohms
    and $I_{\Delta n}$ is the rated residual operating current of the protective device in amperes

    (b) For TT earthing system, if protection by residual current device is provided, the following condition shall be fulfilled:-

$$R_a\, I_{\Delta n} \leq 50V$$

    where R_a is the sum of the resistance of the earth electrode and the protective conductor (s)
    and $I_{\Delta n}$ is the current causing the automatic operation of the protective device

    Draw diagrams to show the phase to earth fault loop of TN-S & TT earthing systems and explain the rationale of the above requirements.

3. Briefly explain the specified operating time, range of sensitivity ($\triangle I_n$) and rated current (I_n) in the Singapore Standard SS97: Part 1:1994 for RCCB.

4. A 230V single-phase 20A final circuit is protected by a 20A Type B MCB and a residual current operated circuit breaker (RCCB) with a sensitivity of 30mA.

    With the aid of appropriate diagrams showing the path of fault current, explain briefly which protective device will operate under each of the following fault conditions and determine the tripping time of the protective device which will operate.

    (a) A 'Live' to 'Earth' fault current of 50A

    (b) A 'Live' to 'Neutral' fault current of 50A.

    (c) A 'Live' to 'Neutral' fault current of 1000A.

    (d) A constant 'Overload' current of 22A for 1 hour.

5. A 230 single-phase 63A distribution board (DB) has a 63A Type B MCB and a RCCB rated at 63A with a residual operating current $I_{\Delta n}$ =0.03A. Determine the operating time of the RCCB and MCB, if they do operate, under each of the following conditions:

   (a) A constant overload of 70A for 1 hour,

   (b) A sustained short-circuit current of 1000A from live-to-neutral,

   (c) A short circuit current of 120A from live to neutral,

   (d) A high impedance sustained short-circuit current of 50A from live-to-earth,

   (e) A short circuit current of 120A from live to earth,

   (f) A short circuit current of 80A from live to earth.

CHAPTER 5
MOULDED CASE CIRCUIT BREAKER - OVERCURRENT PROTECTION DEVICE

5.1 MOULDED CASE CIRCUIT BREAKERS

In industrial situations where high load current and high short circuit breaking capacity are required, moulded case circuit breakers (MCCBs) are frequently used.

A moulded case circuit breaker (MCCB) as shown in Figure 5.1 is a low voltage switching and automatic protective device assembled in a moulded plastic housing. The nature of the sealed enclosure makes it a non-maintainable device. Since inspection of contacts cannot be made, replacement is recommended after breaking high fault current.

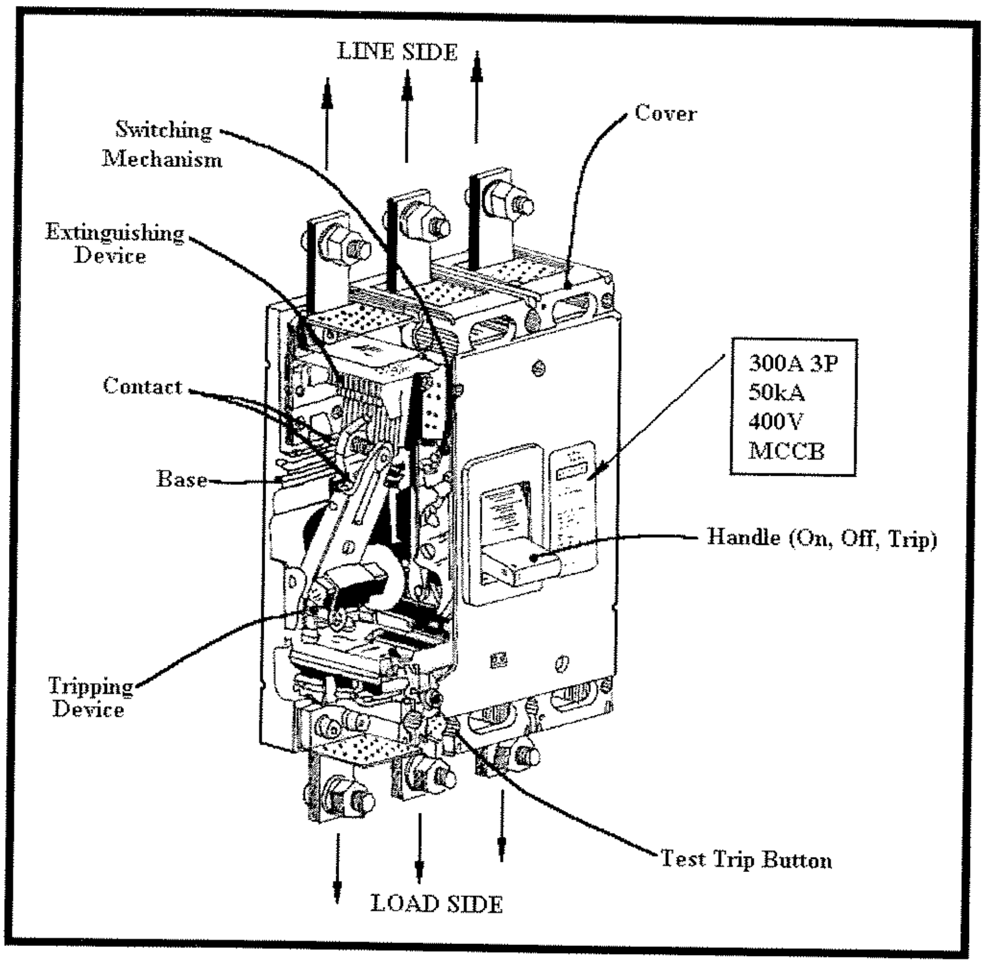


Figure 5. 1 Cutaway view of a MCCB

MCCBs are available in ratings from 10A to about 1200A or more. They are broadly classified by the type of trip units fitted:-

(a) At the lower end of the range, MCCBs usually have fixed (non-adjustable) thermal trip element and magnetic trip element.

(b) On breakers above 225A rating, thermal magnetic trip units are generally interchangeable within any given breaker frame size. In such case, the magnetic trip settings are adjustable.

MCCBs have short circuit breaking capacity from 10kA to 50kA.

Time current characteristic

As specified by British Standard BS EN 60947 or IEC 947-2, the time-current characteristic of the over-current element of the MCCB is specified at reference temperature of 30°C ± 2°C as follows:-

(a) At 1.05 times of the current rating for 2 hours, tripping shall not occur.
(b) At the end of the 2 hours, the value of current is immediately raised to 1.3 times the current setting, and tripping shall then occur in less than 2 hours. For breakers with trip rating less than 63A, the duration of 2 hours should be reduced to 1 hour.

5.2 THERMAL MAGNETIC TRIP UNITS

The standard moulded-case circuit breaker has thermal-magnetic trip unit with detection elements connected in series with each pole, as shown in Figure 5.2. the thermal action provides inverse time-delayed tripping on overloads, and the magnetic action provided instantaneous tripping on short circuits.

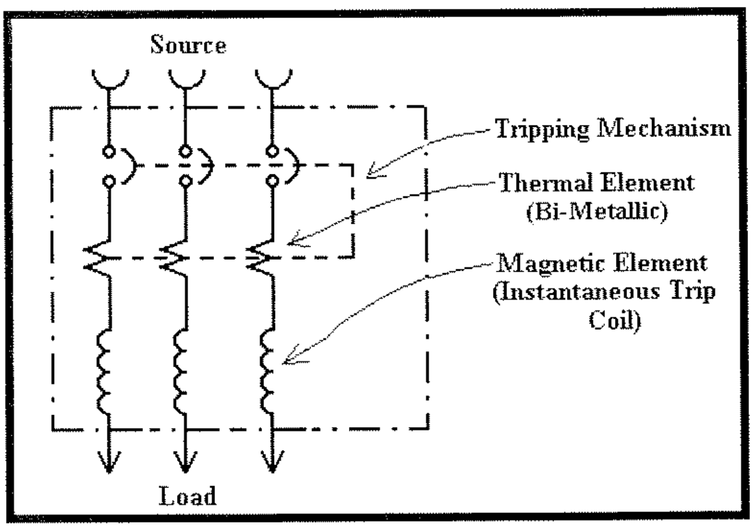


Figure 5. 2 Breaker with series trips. (Each series trip consists of a thermal element and a magnetic element.)

Thermal Tripping

The thermal tripping achieved through the use of a bimetal element that is heated directly by the passage of the circuit current. The bimetal element has two bonded strips of metal with different rates of thermal expansion. The heat from an overloaded current causes the element to bend, the rate being dependent on the amount of current. Ultimately, the element deflects far enough to physically push the trip bar and unlatch the breaker contacts.

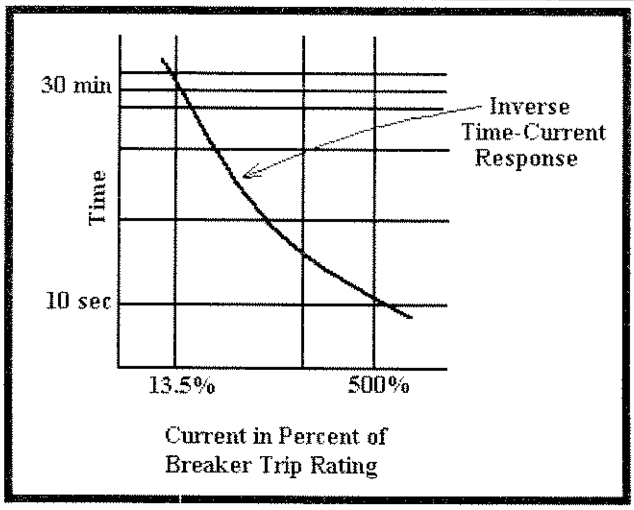


Figure 5. 3 Thermal Trip

Figure 5.3 shows a typical inverse time-current response curve indicating that, with an overload current of 135%, the tripping time is on the order of 30 minutes, whereas with a current of 500%, the time is down to 10 seconds. The thermal elements are calibrated in the factory and are not adjustable after the breaker has been assembled. A specific thermal element must be supplied for each trip rating.

Magnetic Instantaneous Trip

The magnetic instantaneous action is achieved through the use of an electromagnet in series with the load current. The passage of a short-circuit current through the coil of the electromagnet creates sufficient force to attract the armature, thus moving the trip bar and unlatching the breaker contacts. The only delaying factor is the fraction of time (1 cycle or less) that it takes for the unlatching action to take place. Thus the action is said to be instantaneous.

The smaller breakers have fixed magnetic trip elements, as shown in the time-current response curve in Figure 5.4. The breaker does not trip until the fault current reaches or exceeds its pickup value, usually 1000% of its rating.

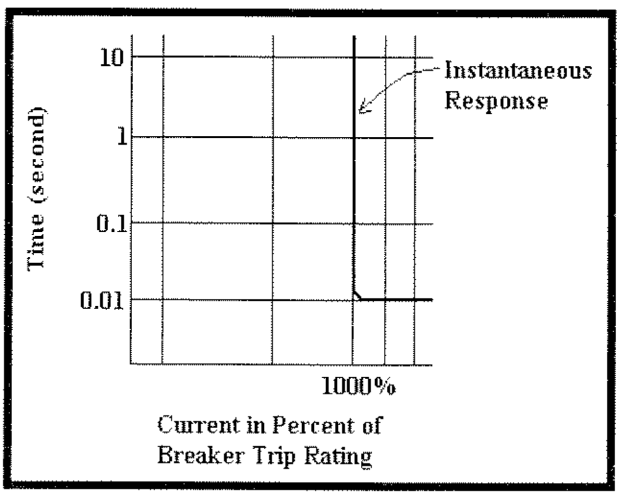


Figure 5. 4 Magnetic Trip

Combined Thermal-Magnetic Characteristic

The combined thermal-element action, together with the typical time-current response curve is shown in Figure 5.5. Thermal action with time-delayed tripping occurs up to a point where the current is large enough to activate the magnetic trip. Above this point, the magnetic action trips the breaker instantaneously.

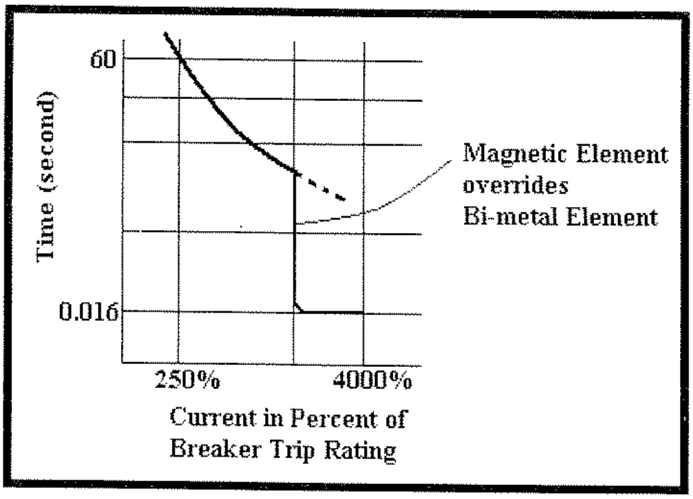


Figure 5. 5 Combined Thermal Magnetic Action

For example, a 250% overload current takes up to 60 seconds to deflect the bimetal element far enough to trip the breaker. On the other hand, a short-circuit current of 4000% (40 times the breaker tripping rating) attracts the magnetic armature and trips the breaker instantaneously (0.01 second).

5.3 ADJUSTABLE INSTANTANEOUS TRIP

The larger moulded-case breakers have adjustable instantaneously trip units. By adjusting the gap in the electromagnet, the actual value of the current required to activate the trip mechanism can be varied.

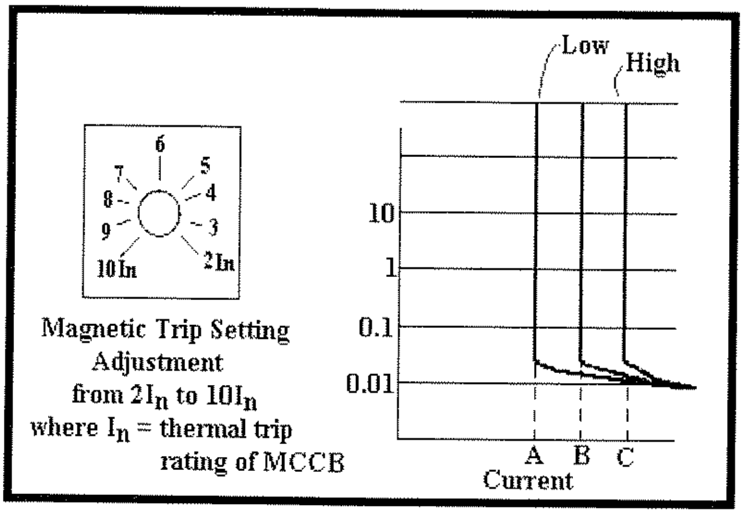


Figure 5. 6 Thermal-Magnetic Breaker with adjustable magnetic trip

Figure 5.6 shows a thermal-magnetic breaker with adjustable magnetic trips. The time-current curve shows the range of adjustments, from a low setting of 200% (2 times) of the current rating of the trip unit (line A) to a high setting of 1000% (10 times) (line C).

5.4 SHUNT TRIP FOR REMOTE TRIPPING

Shunt trip coil is sometimes provided as an optimal accessories of the MCCB for tripping by remote tripping button or tripping by external relays (such as earth leakage relay or earth fault relay).

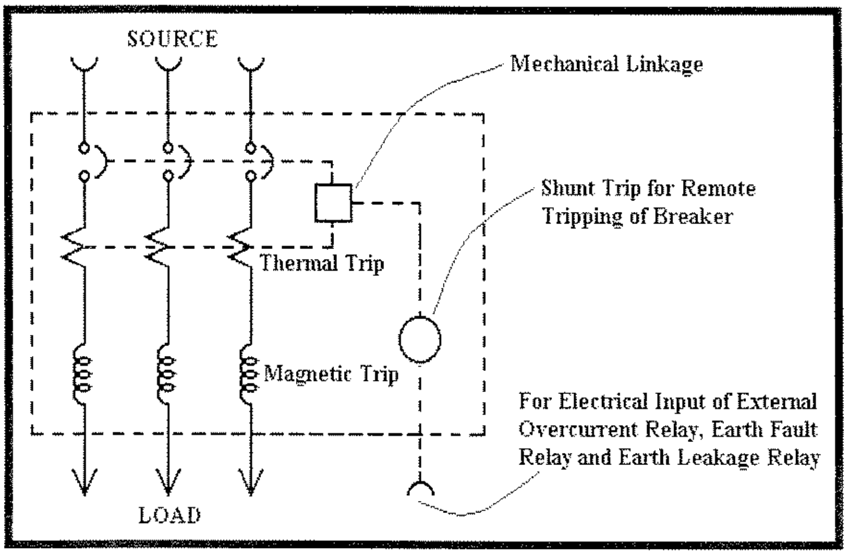


Figure 5. 7 MCCB with Shunt Trip

When the shunt trip coil is energised by external electrical signals, it will cause the mechanical linkage to open the MCCB's poles simultaneously.

5.5 FRAME SIZE DESIGNATIONS

In terms of applying rating to automatic circuit breakers (that is, tripped automatically on overcurrents), there are two separate components to consider:-

- The frame and,
- The trip unit.

Frame Size

The frame size of a breaker sets the following electrical characteristics:

- Maximum continuous voltage rating (insulation level)
- Maximum continuous current rating
- Maximum interrupting rating
- Maximum permissible rating of trip unit

Trip Rating

The trip rating then sets the value of the current above which the unit will response and initiate the tripping of the breaker.

To be able to provide close overcurrent protection for circuits, there are many more trip ratings available than there are frame sizes. For example, the smallest standard-duty moulded-case frame is 100 amperes. However, there are many trip units ranging from 15 to 100 amperes that can be installed within this frame size.

Frame Size and Trip Rating (AF & AT)

Many references to circuit breakers just indicate the one current rating, for example 70 amperes. However, this is incomplete because it presumably just refers to the trip rating. The frame size would normally be 100 amperes, but if a higher interrupting capacity is required, then the frame size may be 225 amperes. Therefore, both frame-size and trip rating should be specified.

Example: 100A Frame size and 70A trip rating will be abbreviated as 100 AF/70 AT and 225A Frame size and 70A trip rating will be abbreviated as 225 AF/70 AT MCCB.

5.6 RELATIONSHIP BETWEEN RATED BREAKING CURRENT AND RATED MAKING CURRENT

Power circuits can be seen as combination of resistance, inductance and capacitance. When a short circuit occurs, it will produce the typical transient current waveform, as shown in Figure 5.8.

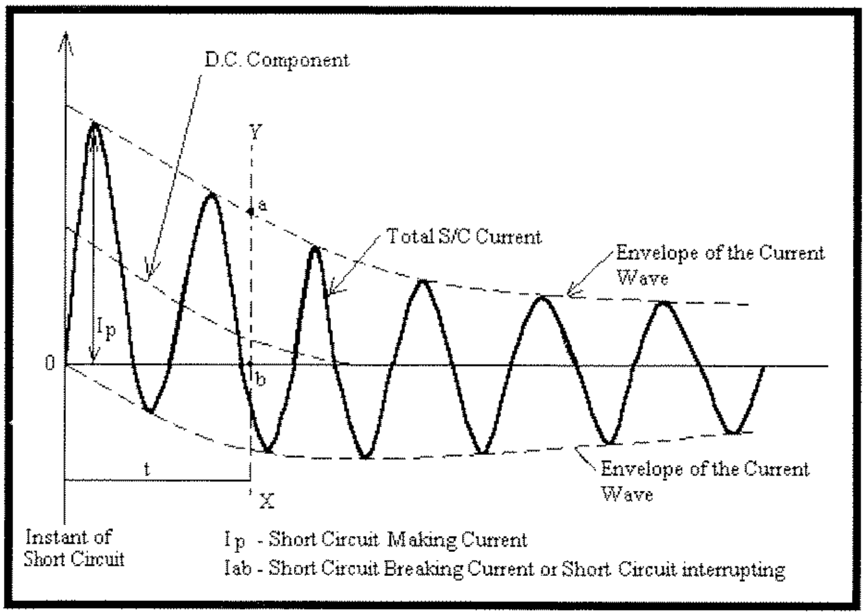


Figure 5. 8 Short Circuit Current Waveform

The current is displaced from the zero axis for the first few cycles due to the presence of circuit inductance and capacitance and gradually assumes a symmetrical waveform after the subsidence of the transient, that is, this waveform comprises a pure sinusoidal A.C. component superimposed into an exponentially decaying D.C. component.

Owing to the operating time of the series tripping element or external relays, the circuit breakers start to open its arcing contacts only sometime later, after the initiation of short circuit. Therefore, the actual current interrupted by the circuit breaker is less than the initial value of short circuit current.

The ratio of making and breaking current for L.V. circuit breakers are therefore defined with reference to standard power factors are tabulated as shown in Table 5.1.

Breaking capacity, I_{cn} kA (r.m.s.)	**Standard Power Factor**	**Minimum making capacity kA (peak)**
$I_{cn} \leq 1.5$	0.95	$\sqrt{2}\, I_{cn} = 1.41\, I_{cn}$
1.5 – 3.0	0.9	$1.42\, I_{cn}$
3.0 – 4.5	0.8	$1.47\, I_{cn}$
4.5 – 6.0	0.7	$1.53\, I_{cn}$
6.0 – 10	0.5	$1.70\, I_{cn}$
10 – 12	0.3	$2.0\, I_{cn}$
12 – 20	0.25	$2.1\, I_{cn}$
* 20 - 50	0.2	$1.55\sqrt{2}\, I_{cn} = 2.2 I_{cn}$

Table 5.1

For typical low voltage systems, the power factor of the system is about 0.15 to 0.2.

If power factor = 0.5, Ratio of $\frac{X}{R} = \frac{1}{0.15} = 6.6$

If power factor = 0.2, Ratio of $\frac{X}{R} = \frac{1}{0.2} =$ About 5

Therefore, the recommended rated making capacity of L.V. circuit breaker is about

Rated making capacity = 1.55 x ($\sqrt{2}$ x Rated Breaking Capacity)
= 2.2 x Rated Breaking Capacity

5.7 SPECIFICATIONS OF LOW VOLTAGE CIRCUIT BREAKER

British Standard BS EN 60947 and IEC Standard 947-2

British Standards BS 4752 Part 1:1997 and IEC define the ratings of Low Voltage (Below 1000 Volts) Circuit Breakers as follows:

(a) Rated Voltage

This is the r.m.s. phase-to-phase voltage for which the circuit breaker is designed for its breaking and making capacities.

(b) Rated Continuous Current

This is the maximum load current that the breaker can carry continuously without overheating any current carrying parts.

(c) Short-Circuit Breaking Capacity or (known as Interrupting Rating or Interrupting Capacity)

The r.m.s. value of the A.C. component of current at the initiation of arc which the circuit breaker can break safely under the specified conditions of voltage and power factor.

In accordance with IEC 947-2 standard for circuit breakers, the rated short circuit breaking capacities specifies are stated as:-

(i) Rated Ultimate Short Circuit Breaking Capacity (I_{cu}), based on operation sequence O-CO and
(ii) Rated Service Short Circuit Breaking Capacity (I_{cs}), based on operation sequence O-CO-CO.

In accordance with BS EN 60947 and IEC 947-2 Standard, there are two categories of short-circuit performance:

Category	Test Sequence	Condition after test
P1	O - t - CO	Required to perform reduced service
P2	O - t - CO - t - CO	Required to perform normal service

O : a breaking operation
CO : a making operation followed by a breaking operation
t : a specified time interval

The user should understand the differing aspects and should stipulate clearly in any specification which category of performance is required. Basically, a P1 circuit breaker is required to be inspected and possible replaced after a short circuit operation.

(d) Rated Short-Time Withstand Current

The r.m.s. value of current which the circuit breaker can carry for a specific short time (generally one second).

(e) Rated Short-Circuit Making Capacity

The prospective peak current the circuit breaker is capable of making at rated voltage, rated frequency and rated power factor. Rated short-circuit making current is related to the prospective asymmetrical peak short circuit current.

For more severe cases, the peak current can be $2\sqrt{2}$ rms value of the A.C. fault current if the fault occurs at voltage zero. The relatively high resistive element in a L.V. circuit, however causes the D.C. component to be attenuated quickly.

5.8 CURRENT LIMITING CIRCUIT BREAKER

Standard circuit breaker operated by the force from springs normally cannot separate fast enough to extinguish the arc before the fault current has passed through its first instantaneous peak value at half a cycle, this kind of breaker is therefore unable to provide current limitation when clearing a fault from the electrical installation and thus unable to limit the let through energy ($I^2_{sc}t$)

Manufacturers of circuit breakers have now been able to provide extremely fast contact separation required for current limitation. One method is to use the slot motor principle, where the slot motor is a U-shaped block of laminated steel plates as shown in Figure 5.9 (a) and (b).

The upper and lower arms of the contact are fixed within the slot motor. On overloading or small fault current, only the upper contact moves to open the circuit. When an extremely large fault current occurs, the large current through the two contract arms creates a tremendous repulsion force that cause the contacts to open apart extremely fast (normally less than 0.01 sec) and thus be able to limit the peak current flowing into the circuit being protected.

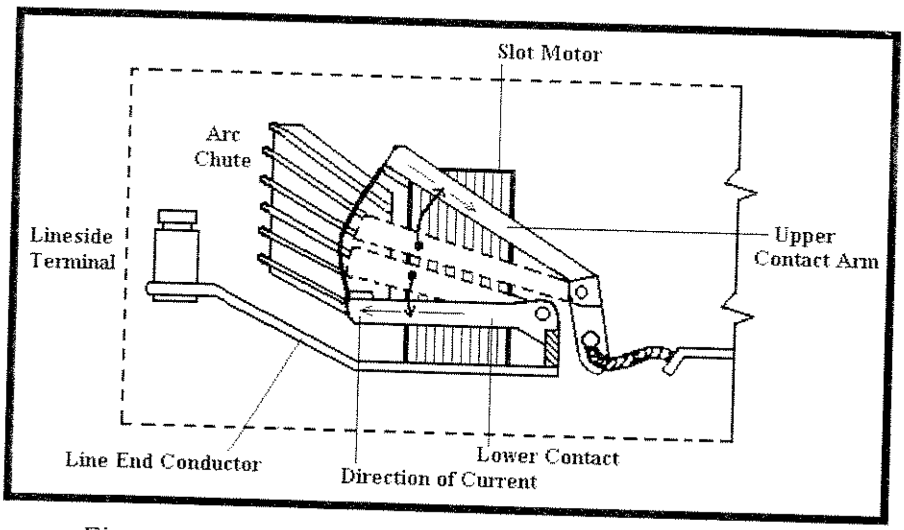


Figure 5. 9 (a) Slot Motor and Current Limit Breaker

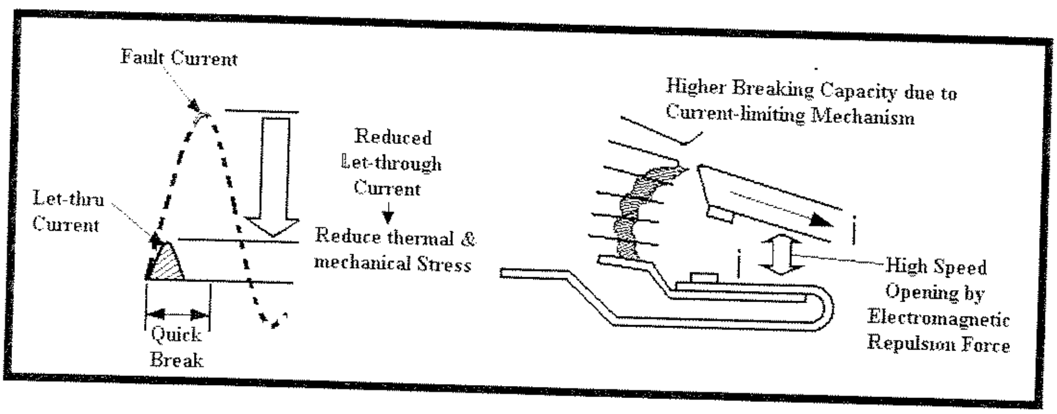


Figure 5.9 (b) Current Limiting Breaker and Breaker Capacity

5.9 CASCADING INTERRUPTION

Cascading is defined as the use of the current-limiting capacity of circuit breakers on the upstream to reduce the required breaking capacity of circuit breaker downstream on the load side. The upstream circuit breakers with current limiting features act as barrier against the high short circuit currents and it is therefore possible to use circuit breakers on the load side with breaking capacities significantly lower than the prospective short circuit current at the point considered.

Since the current is limited throughout the circuit controlled by the limiting current breaker, cascading applies to all switchgear on the load side of this circuit breaker. It is not restricted to two consecutive devices.

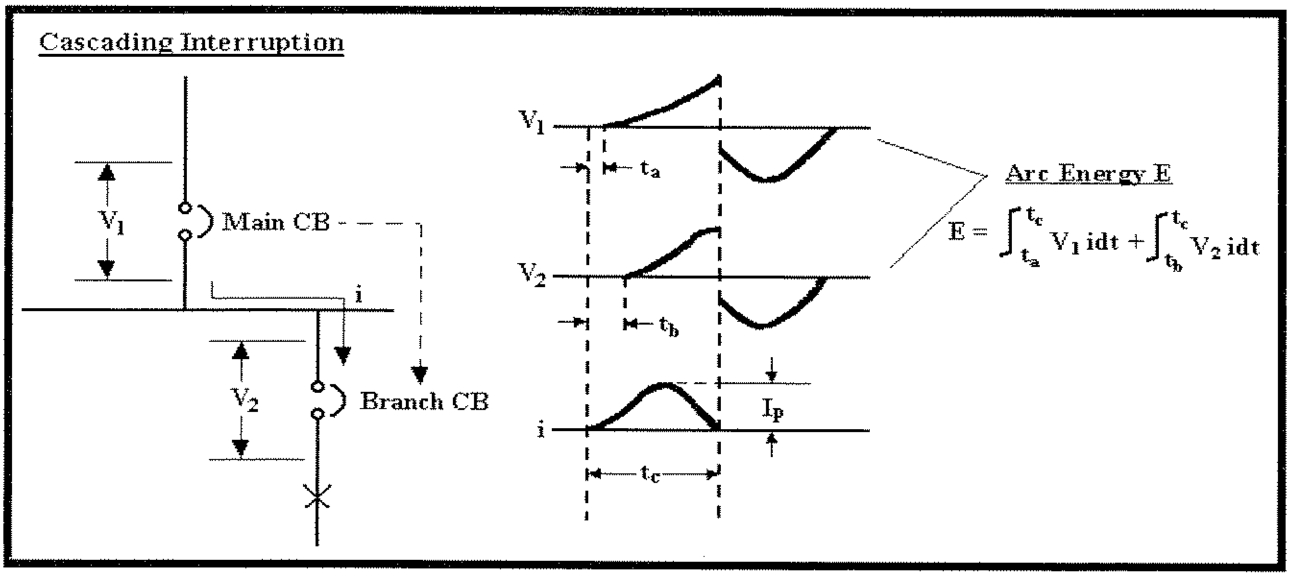
The advantages of cascading are:

(a) Reduction of the short circuit breaking capacity required for breaker on the load side, since these currents are severely limited by the current limiting circuit breaker on the source side.

(b) Simplification in the choice of equipment.

(c) Equipment savings up to 10%, since limitation of the short circuit currents allows the use of lower rated and thus lower cost equipment.

Cascading can only be checked by laboratory tests and the possible combinations can be specified only by the circuit breaker manufacturer. Through such tests, manufacturer is able to provide table for cascading combination of circuit breakers.



Essential Factors for Back-up Co-ordination:

(a) Branch CB has to have mechanical strength to withstand I_p.
(b) Branch CB has to withstand Let-through I^2t.
(c) Branch CB has to ensure its arcing energy ($\int_{tb}^{tc} V_2\, idt$).

5.10 SELECTION OF PROTECTIVE DEVICE

Generally, the trip rating of the circuit breaker should not be less than the design current of the circuit.

For motor circuit, the motor branch circuit protective device is allowed to be larger such that it will not operate during starting. The trip rating of the MCCB shall be selected as follows:

a) **Full Voltage Starting** (i.e. with Direct on Line Starter) circuit breaker trip rating shall be selected between **2 x Full Load Current and 2.5 x Full Load Current**.

b) **Reduce Voltage Starting** (i.e. with Star / Delta, Auto-Transformer Starter) circuit breaker trip rating shall be selected between **1.5 x Full Load Current and 2 x Full Load Current**.

The above rule of thumb serves only as a general guide, designers must use appropriate time-current characteristic of breaker and the motor starting current characteristic for detail analysis to finalise the selection of breaker's rated trip rating.

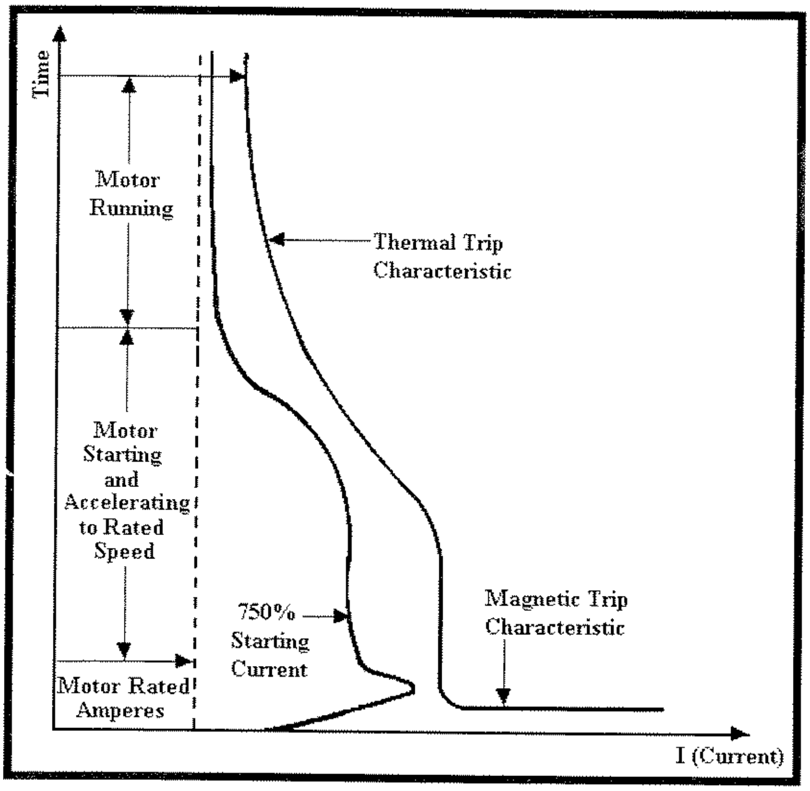
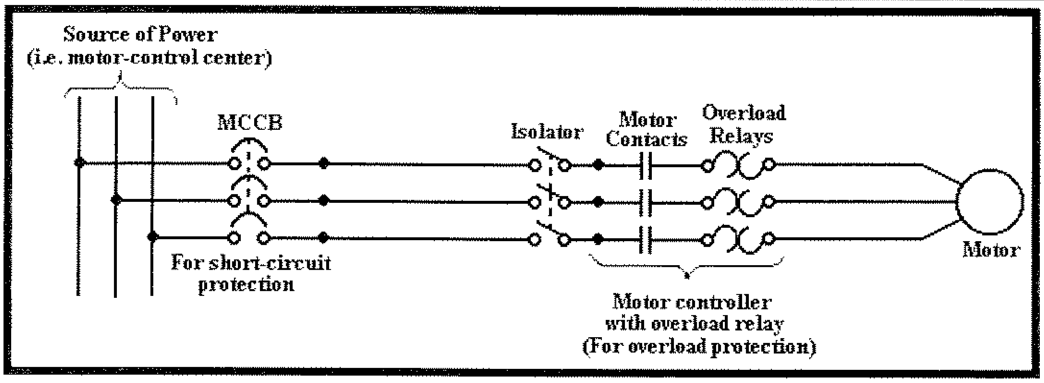


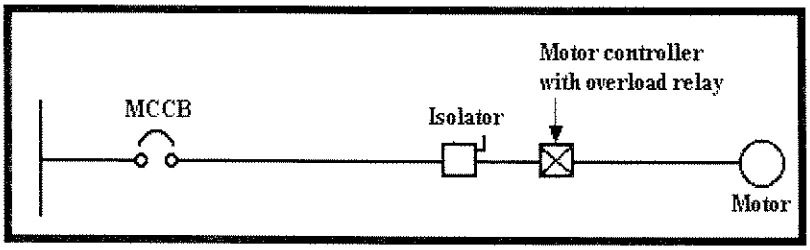
Figure 5. 10 Relationship of Motor Current and MCCB characteristic

As the circuit breaker for motor has been selected higher to avoid nuisance tripping by motor starting current, the circuit breaker is no longer effective in providing overload protection. The overload protection for the motor and motor feeder cable is provided by the overload relay mounted within the starting device to open the circuit if harmful overload occurs.

The overload device of the motor must be able to withstand the starting current before the motor accelerates up to its rated speed, but they do not require to respond to the short circuit current.



(a) Three-line Diagram



(b) Equivalent single-line Diagrams

Figure 5. 11 Protection of Motor Circuit

<u>**Protective device for feeder to a Group of Motors**</u>

When the largest motor is started at a time when all other motors in the group are running and draw their full load currents, the starting current can be very large. The protective device must be sized to handle such a transient condition and not to open the circuit.

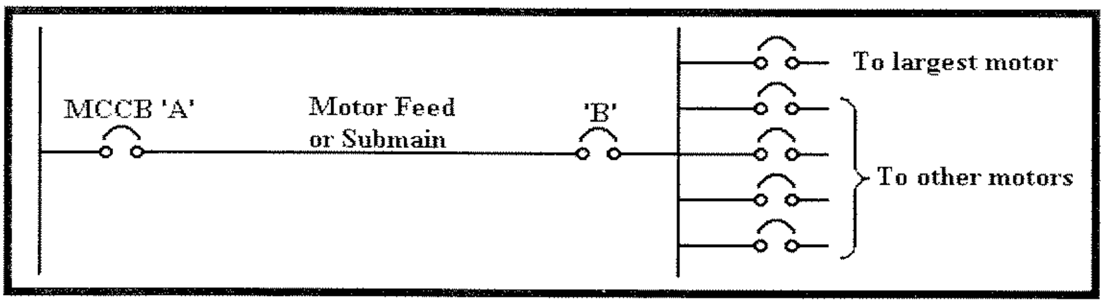


Figure 5. 12 Motor

However, if the motors are started one at a time, it assumes that the motors started from smallest one to the biggest one. The tripping of main breaker may be selected as follows:

The recommended trip rating of the feeder circuit breaker 'B':

I_n = Rating of the largest circuit breaker for motor + full load current of all other motors

For large industrial plants, the nature of work being performed may be such that all the motors are unlikely to be running fully loaded simultaneously. In this case, diversity may be applied to the sum of the motor's full load current.

5.11 MOTOR STARTERS & MOTOR CONTROL CIRCUITS

In accordance with the code of practice CP 5:1998, motor starter and control circuit is to be provided for protection and control of electric motors to meet the following requirements:-

(a) To provide overload protection with the provision of overload relays in motor control circuit.

(b) To prevent auto-restarting of motors upon resumption of electricity supply after a power failure.

(c) To reduce the motor starting current for large motor (Example: Star/Delta (⅄/D) starter and autotransformer starter (A/T) are considered as reduced voltage starter which help to reduce motor starting current, Direct on line starter (D.O.L) does not help to reduce motor starting current).

Direct On Line Starter (D.O.L)

The D.O.L starter switches the full voltage electricity supply directly on to the motor since the motor starting current can be seven to eight times greater than the running current, D.O.L starter is used only for small motors. The motor power circuit and motor control circuit are shown in Figure 5.13.

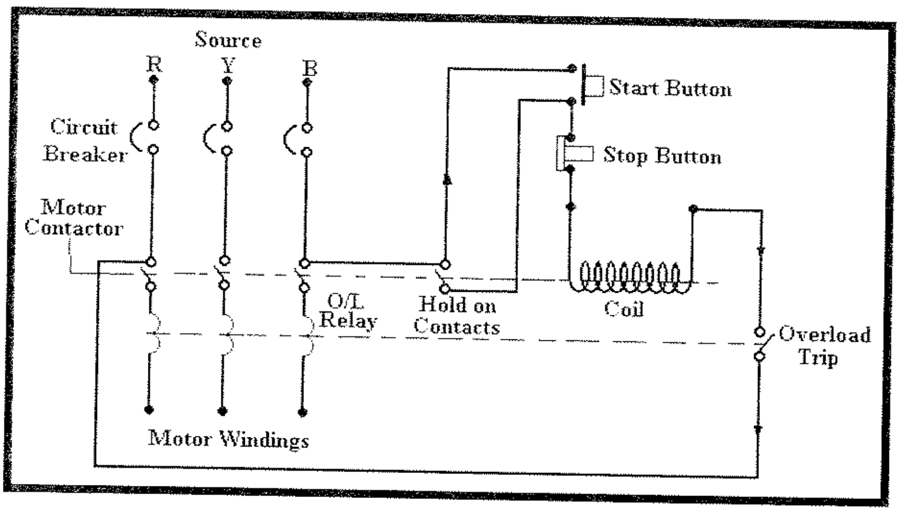


Figure 5. 13 Direct on Line Starter (or Full voltage starter) - Motor Power Circuit & Motor Control Circuit

When the start button is pressed, current will flow down from the red phase through the control circuit and the motor contactor coil to the blue phase which energise the coil and the motor contactors close, three phase electricity supply is connected to the motor. The release of the start button does not cause interruption of electricity supply to the motor because the electricity supply to the motor control circuit is maintained by the hold on contact (OR known as no-voltage release), which is connected in parallel with the start button.

If the stop button is pressed or the overload coil operates (i.e. the overload relays are often set to operate at 110% to 120% of the full load current), the control circuit is broken and the contactor drops out, electricity supply to the motor is cut off.

Once the electricity supply to motor is cut off, the motor can only be re-started by pressing the start button, because the holding contactors has already dropped out. This is to prevent the motor from re-starting after the supply is restored after a power failure.

Reduced voltage starting

When large industrial motors have to be started, a way of reducing the excessive starting currents must be found. The methods available are to connect the motor to

(a) Star-Delta starters
(b) Auto-transformer starters
(c) Electronic type soft starter

Star-Delta Starters

If direct switching is not allowed, a method of reduced voltage starting may be used in order to limit the motor starting current. The most popular method of reduced voltage starting is the star-delta due to its economy. The starting current is approximately one third the value of dol starting current (about twice full load current) and the starting torque is one third of that with dol starting current. A six-terminal motor must be used to enable the winding connections to be changed during the starting sequence.

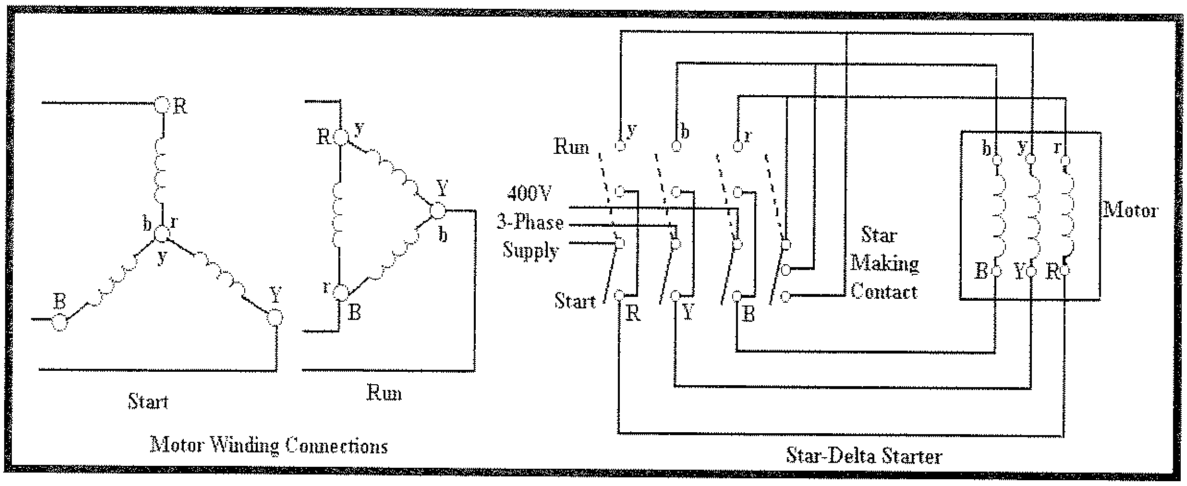


Figure 5. 14(a) Motor Winding Connections & Star-Delta Starter

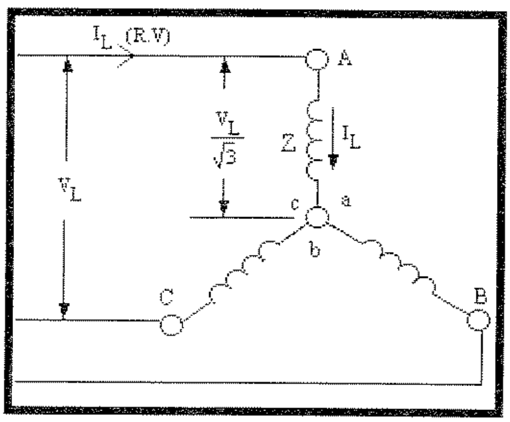


Figure 5.14 (b) Motor started in the star configuration (i.e. reduced voltage)

Starting voltage is $V_{start} = \left(\frac{1}{\sqrt{3}}\right) V_L$

$\therefore$ Line current at reduced starting voltage,

$$I_L\,(R.V) = \left(\frac{V_L/\sqrt{3}}{Z}\right)$$

$$= \left(\frac{1}{\sqrt{3}}\right)\left(\frac{V_L}{Z}\right) \quad \text{-----(1)}$$

where Z is the impedance of motor winding

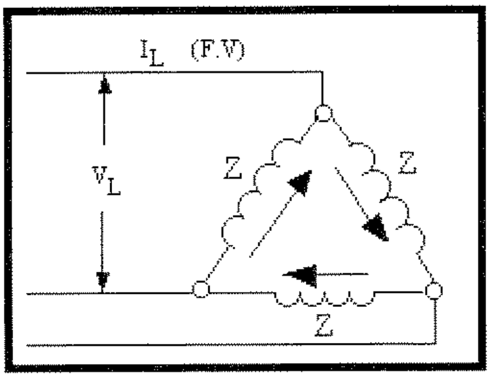


Figure 5.14(c) Motor started in the Delta Configuration (i.e. full voltage)

$V_{run} = V_L$

$I_{phase} = V_L/Z$

∴ Line current at full voltage starting

$I_L\,(F.V) = \sqrt{3} \times V_L/Z$ -----------(2)

$$\therefore \frac{I_L\,(R.V)}{I_L\,(F.V)} = \frac{1/\sqrt{3}}{\sqrt{3}}\left(\frac{V_L/Z}{V_L/Z}\right) = \frac{1}{3}$$

Therefore Motor starting current is reduced by $^1/_3$ and I_{start} (⅄/D) = $^1/_3$ x I_{start} (D.O.L starter).

Auto-transformer starter

Another reduced voltage motor starting method is that of using an auto-transformer, which has a significant benefits but is relatively expensive. It is particularly useful where progressive control of accelerating torque is required, for example with large fans or mixers, and is often used with submersible borehole pumps. The starting voltage at the motor terminals (and therefore the starting torque) can be selected to suit the load by means of tapping on the auto-transformer the usual values being 50%, 65% and 80%, where 65% is normally used.

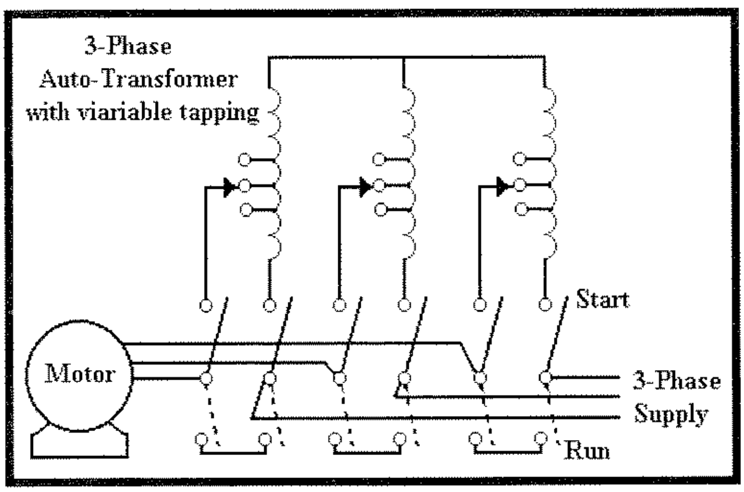


Figure 5. 15 (a) Auto-transformer starting

At $V_{start} = n \times V_L$

Where n is the tap ratio of the auto-transformer.

∴ Line current at reduced voltage starting,

$$I_L(R.V) = n \times I_n$$
$$= n \times \frac{(n \times V_L)}{Z} \text{ ------(1)}$$

Line current at full voltage starting,

$$I_L\,(F.V.) = \frac{V_L}{Z} \text{ ----------- (2)}$$

Therefore,

$$\frac{I_L\,(R.V)}{I_L\,(F.V)} = \frac{n^2 V_L/Z}{V_L/Z} = n^2$$

Therefore, Motor starting current is reduced by n^2 (normally n = 65% is used) and I start (A/T starter) = $n^2 \times I_{start}$ (D.O.L starter)

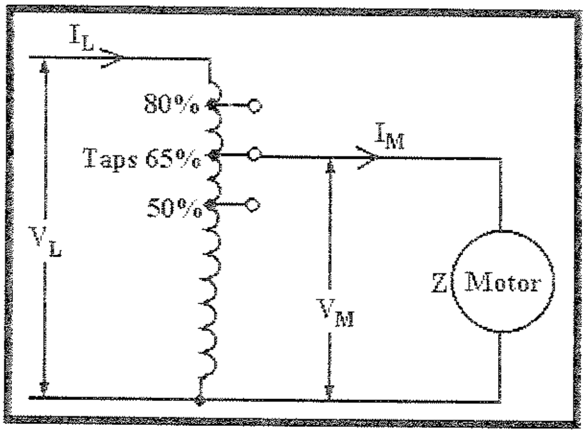


Figure 5.15 (b) Auto-transformer starter

Soft Starter - Solid State Reduced Voltage Starter

The basic solid-state power device used in this starter is a type of thyristor called the silicon controlled rectifier or SCR.

The SCR blocks the flow or current in one direction but allows current to flow in the other direction after it has received a "turn on" signal called a gate pulse. Six SCRs are arranged in what is called a full-wave rectifier configuration as shown in Figure 5.16.

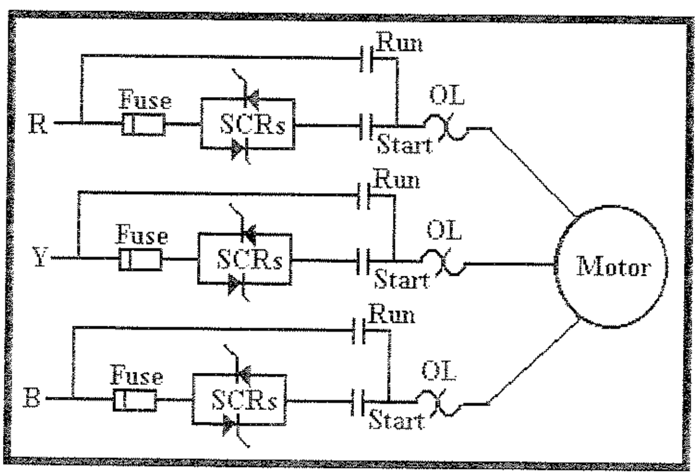


Figure 5. 16 Solid-State Starter Simplified Diagram

With the appropriate solid-state control circuitry control of motor current or acceleration time may be achieved by applying the gate pulses to the SCRs at different times within each half-cycle of the power-supply voltage. If the gate pulses are applied early in the half-cycle, the SCR output is high. If the gate pulse is applied late in the half-cycle, the output is low. Input voltage to the motor can thus be varied from zero to full value during the starting-period, causing the motor to accelerate smoothly from zero to full speed.

5.12 EXAMPLES IN SELECTION OF MCCBS

Example 5.1

A motor control centre (MCC) supplies the following motor loads:-

(a) 2 nos. of 25 h.p. three phase 400V motor with efficiency 88% and power factor during starting and normal operation are 0.5 and 0.9 respectively. The motor is started by a Direct-On-Line motor starter.

(b) 2 nos. of 75 h.p three-phase 400V with efficiency 88% and power factor during starting and normal operation are 0.5 and 0.9 respectively. The motor is started by a Star-Delta motor starter.

(c) 1 no. of 100 h.p three-phase 400V with efficiency 88% and power factor during starting and normal operation are 0.5 and 0.9 respectively. The motor is started by a Auto-transformer motor starter. (Assuming the tap ratio for starting is n=0.65)

(i) Calculate the full load current and starting current in each case and determine the trip rating of MCCB for each motor.

(ii) Determine the appropriate trip rating of the main breaker assuming the smallest motor started first and the largest motor started last.

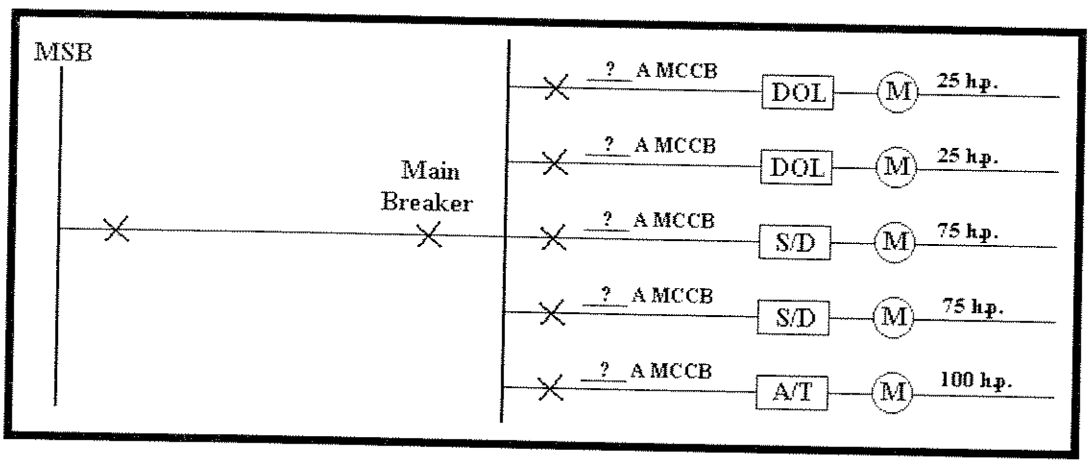


Figure 5. 17

Solution:

(i) (a) 25 h.p. motor with DOL starter
Full Load current of the 25 h.p. motor

$$I_{F.L.} = \frac{25 h.p. \times 746\ Watt/h.p.}{\sqrt{3} \times 400 \times 0.88 \times 0.85} = 36A$$

Motor starting current,

$I_{start} = 7.5 \times 36A = 270A$ which lasts for 5 to 20 sec

Maximum trip rating of MCCB is recommended at $2.5 \times I_{F.L.} = 2.5 \times 36A = 90A$
Therefore, a 80A Triple-Pole (TP) MCCB is selected.

(b) 75 h.p. motor with Star-Delta starter
Full Load current of the 75 h.p. motor

$$I_{F.L.} = \frac{75 h.p. \times 746\ Watt / h.p.}{\sqrt{3} \times 400 \times 0.88 \times 0.85} = 86.4A$$

Motor starting current

$I_{start} = {}^{1}/_{3} \times (7.5 \times 86.4) = 216A$, which lasts for 10 to 20 sec

Maximum trip rating of MCCB is recommended at $2 \times I_{F.L} = 2 \times 86.4 = 172.8A$

Therefore a 150A Triple-Pole (TP) MCCB is selected.

(c) 100 h.p. motor with Auto-transformer starter
Full load current of the 100 HP motor

$$I_{F.L.} = \frac{100 h.p. \times 746\ Watt/h.p.}{\sqrt{3} \times 400 \times 0.88 \times 0.85} = 223A$$

Motor starting current

$I_{start} = 0.65^2 \times (7.5 \times I_{F.L}),$ where tap ratio of auto-transformer, n=65%.
$= 0.65^2 \times (7.5 \times 223)$
$= 706A$

Maximum trip rating of MCCB is recommended at $2 \times 223A = 446A$

Therefore, a 400A Triple-Pole (TP) MCCB is selected.

(ii) Main Breaker

The MCCB main breaker trip rating
= Trip rating of the MCCB of largest motor in the group + full load current of all other motors
= 400A + (2 x 86.4A) + (2 x 36A)
= 644.8

Therefore, a 700A TP&N MCCB is selected for the main breaker.

(NOTE: Readers are advised to find appropriate trip rating of MCCB time-current characteristic of MCCB to further examine the selection of appropriate trip rating of MCCB for the above example).

Questions – Chapter 5

1. Explain briefly the operation of the following tripping elements of a moulded case circuit breaker:

   (a) Thermal trip
   (b) Magnetic trip
   (c) Shunt trip

2. Give the definitions for the following:-

   (a) The rated making capacity, and
   (b) The rated breaking capacity of circuit breakers.

3. Explain briefly the requirements of CP 5:1998 for the protection and control of electric motors and how these requirements can be met by the design of the motor control circuit.

4. Figure 5.18 shows a 3-phase, 400V, motor control centre (MCC) supplying the following loads:-

   A group of small 3-phase motors for which the total full load current is 100A per phase.

   A 80 h.p. 3-phase, 400V motor with an efficiency of 88%. The motor is provided with an auto-transformer starter.

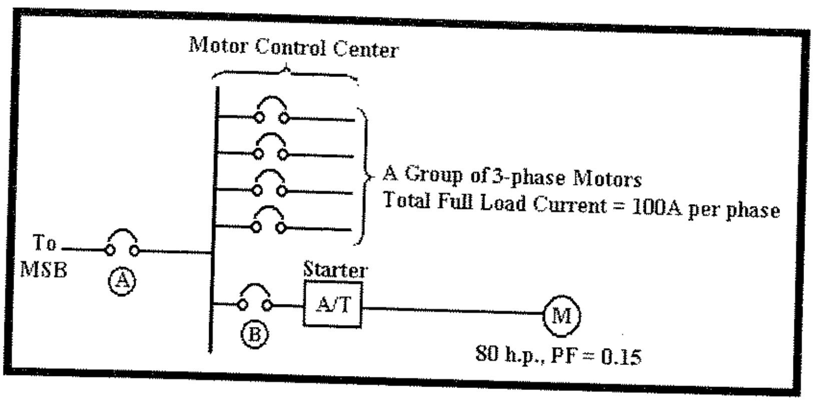


Figure 5. 18

   If the motor control centre (MCC) and the motor circuits are to be protected by moulded case circuit breakers (MCCBs) with built-in thermal and magnetic tripping devices, determine

   (a) The appropriate trip rating (AT) of circuit breakers 'A' and 'B'
   (b) The appropriate magnetic trip setting of MCCB 'A' and 'B'

5. The single line diagram in Figure 5.19 shows the motor control centre of an air-conditioning plant; determine:

   (a) The full load current & starting current of each motor.
   (b) The trip rating of each branch MCCB and the main MCCB.
   (c) The appropriate magnetic trip setting of each MCCB.

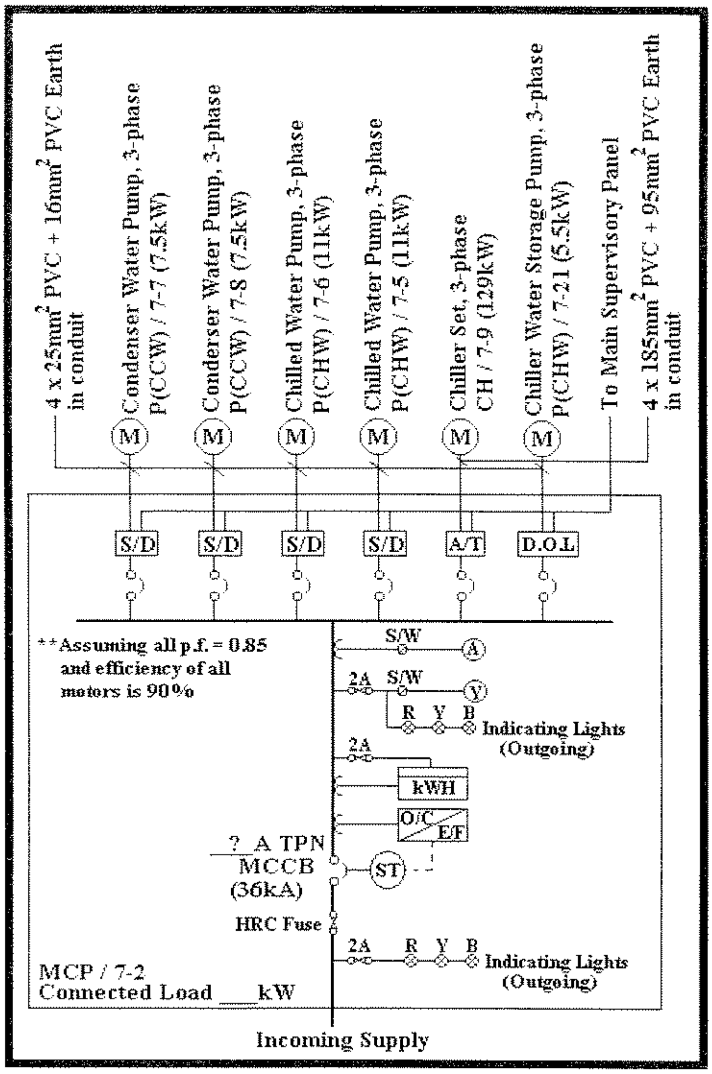


Figure 5.19 Motor Control Centre

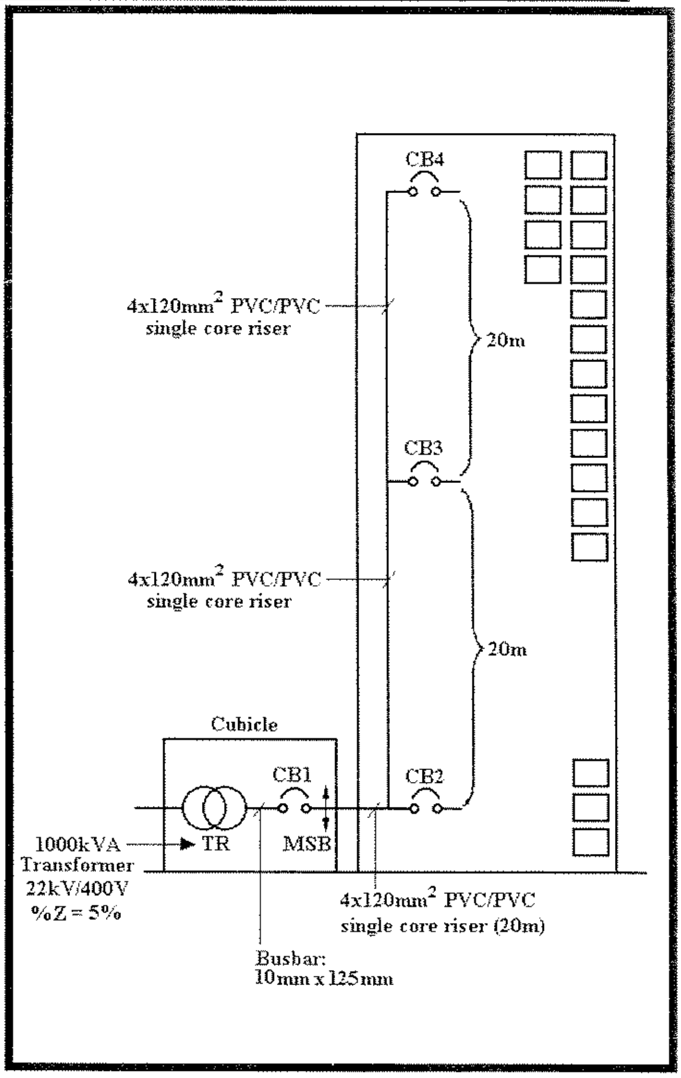


Figure 5.20

6. For the example as shown in Figure 5.20, with impedance of the power source, transformer and total motor impedances in the installation as follows:

Each impedance: (m-ohm)

Power Source Impedance,	$Z_S = 0.0069 + j0.172$
Transformer Impedance,	$Z_T = 1.894 + j8.045$
Motor Impedance,	$Z_M = 7.08 + j42.47$
Bus-duct impedance,	$Z_B = 0.326 + j0.206$
and Cable Impedance,	$Z_C = 2.88 + j1.52$ for 20 metre of 120mm²/SC PVC/PVC

Calculate the required short circuit breaking capacity of CB1, CB2, CB3 and CB4.

CHAPTER 6
AIR CIRCUIT BREAKER

6.1 INTRODUCTION

Air Circuit Breakers

This is the most common type of circuit breaker used in L.V. (400V, 3-phase) applications. It can be easily assembled into multi-tier withdrawable units switchboard. Modular construction together with moulded case circuit breakers (MCCBs) and motor starters is its added advantage.

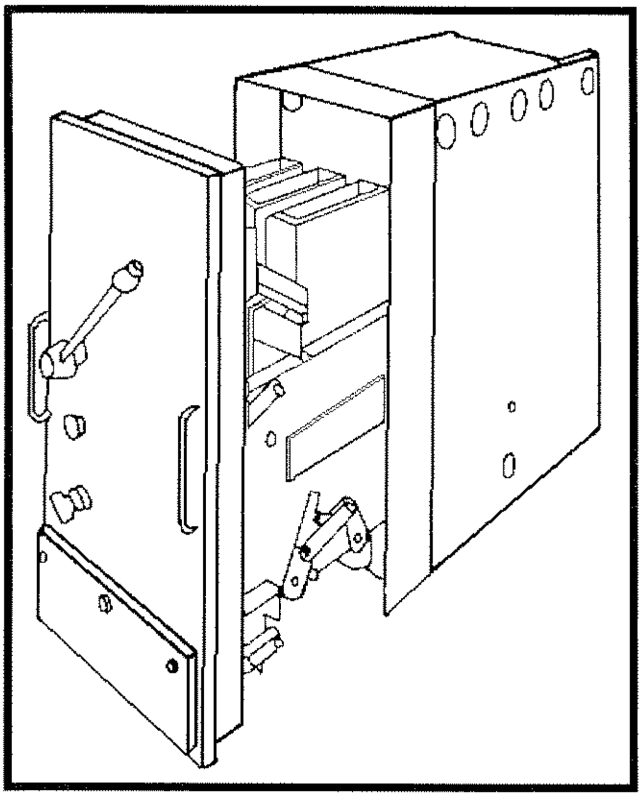


Figure 6. 1 3-phase 400V Air Circuit Breaker

6.2 CONSTRUCTION OF AIR CIRCUIT BREAKER (ACB)

An air circuit breaker consists of

(a) An operating mechanism:
which includes the spring charging mechanism, the opening and closing mechanism.

(b) Contacts:
which includes the fixed arc contact, the fixed main contact, the moving arc contact and the moving main contact.

(c) Arc interrupters (Arc chute)

(d) Built-in overcurrent tripping device connected in series with the load side breaker conductor.

The built-in overcurrent tripping devices are designed to give accurate tripping protection against overload current and short circuit current.

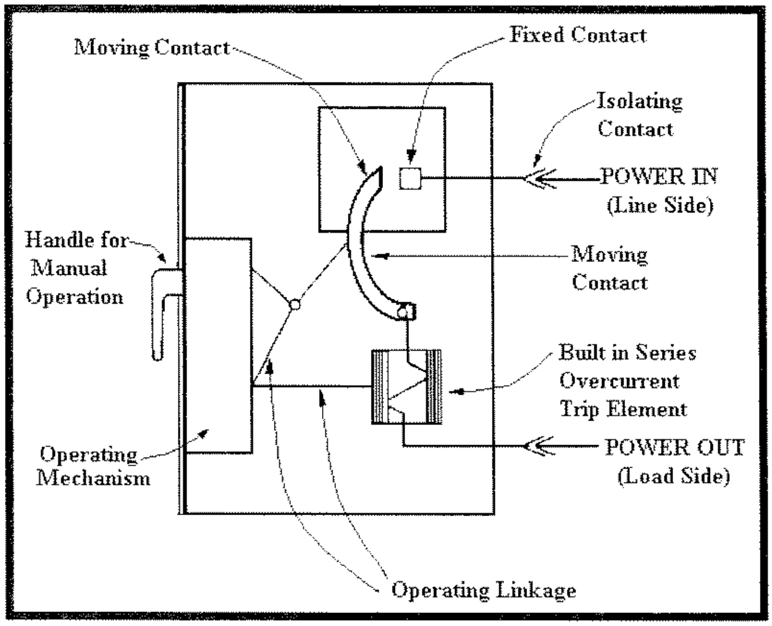


Figure 6. 2 Arrangement of build in series overcurrent trip element (or known as direct acting trip)

6.3 RANGE OF AIR CIRCUIT BREAKERS

Typical current ratings of air circuit breakers are as follows:

For Low Voltage (400V, 3-phase) system
Current Rating –Range from 600A to 3000A
Interrupting Capacity – 25kA, 36kA, 43kA, 50kA, 65kA, 70kA, 75kA, 100kA, etc.

6.4 OPERATING PRINCIPLES OF AIR CIRCUIT BREAKERS

Present day air circuit breakers are manufactured with contact system comprising main and arcing contacts. Steps involved in the arc extinction process are as follows:-

(a) On the occurrence of a fault, the fault current in the feeder will immediately initiate the tripping of the controlling air circuit breaker and on opening, an arc is struck between the fixed and moving contacts.

(b) The arc runners fitted to the arcing contacts assist the upward movement of the arc into the arc chute.

(c) The arc, established across the arcing contacts, is forced upwards by the electromagnetic forces and by thermal action, with the result that the arc travels rapidly along the arc runners until it is forced into the arc chute.

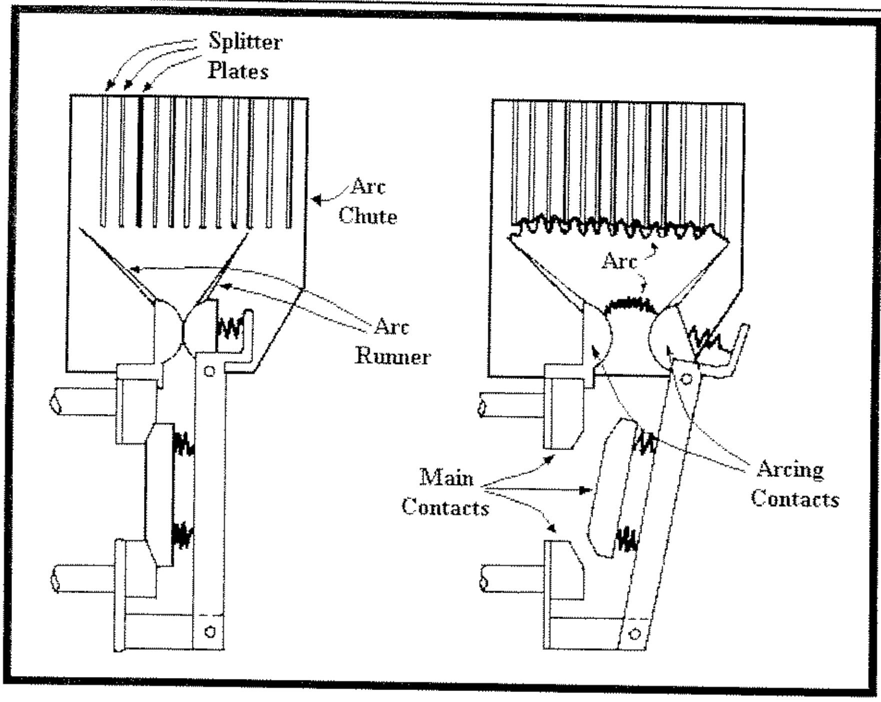


Figure 6. 3 Arrangement of Arcing Contacts & Main Contacts in ACB

(d) Here in the arc chute, the arc length is rapidly and considerably extended by the splitter plates of the chute which are made of metal.

(e) The arc length is now divided into a number of very short arcs formed between adjacent plates.

(f) The splitter plates cool the arc (thus assisting the de-ionisation process) and actually reduce the velocity of the arc products expelled above the chute.

(g) As the arc is cooled sufficiently, it is finally extinguished and the interruption process is complete.

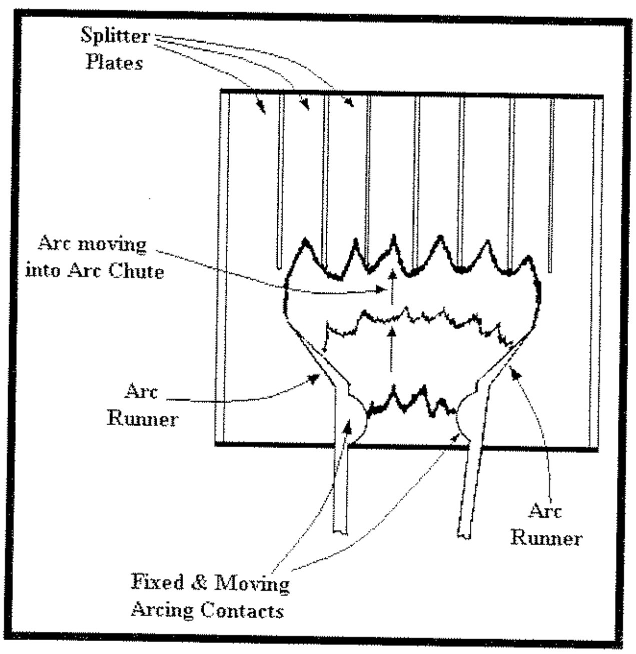


Figure 6. 4 Function of the Arc Runner and Arc Chute

6.5 FUNCTION OF THE ARC CHUTE

The function of the arc chute is to cool and split up the arc when it is drawn up into the chute by thermal and electromagnetic forces. The arc chute therefore acts as a chimney, the hot ionised gases rising rapidly through the chute and allowing cool air to be swept into the gap.

With modern air circuit breakers, arc control devices are so designed that fault current interruptions are extremely fast.

6.6 FIXED AND MOVING CONTACTS

The main fixed and moving contacts are constructed of high conductivity copper and high current carrying ability. The main contact faces are silver-plated.

The arcing contacts are made from arc-resisting metals and the arcing horns from high tensile brass to resist forces tending to deform them.

From the contact opening sequence mentioned above, it can be seen that arcing contacts will always open after, and close before the main contacts, in order to protect the main contacts from damage by electric arc.

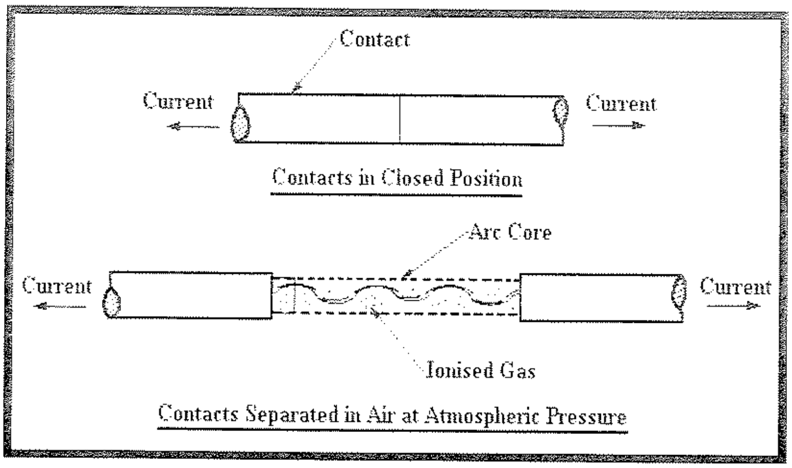


Figure 6. 5 Electric Arc

6.7 SHUNT TRIP COIL

The tripping mechanism of all circuit breakers are mechanical devices which can be activated by push buttons or handles on the front panel.

However, remote tripping or automatic tripping by protective relays must be carried out electrically.

A shunt trip coil is simply a coil wound around an iron core. When a current passes through the coil, it magnetises the core which then attracts a movable piece of iron. The movement of this piece of iron will then activate the tripping mechanism of the breaker.

Note that the shunt trip coil of the Low Voltage (400V) circuit breaker normally rely on 230V A.C. supply (between R-phase and Neutral) for its energisation.

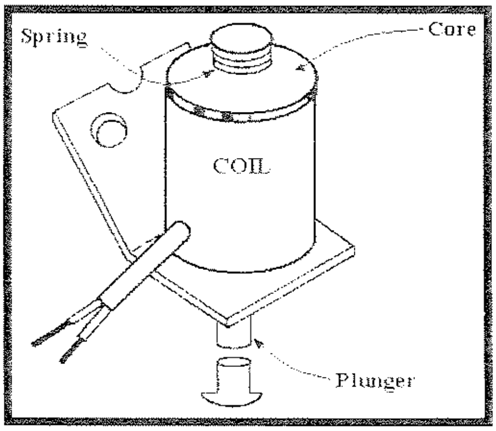


Figure 6. 6 Shunt Trip Coil

6.8 INSTRUMENTATION AND METERS

The following instrumentation and meters are also installed to monitor the on/off status of the air circuit breaker, the voltage and load current at the main circuit breaker:-

(a) Incoming Indicator lights with fuses – To monitor the ON/OFF status of the incoming supply to the air circuit breaker.

(b) Outgoing Indicator lights with fuses – To monitor the ON/OFF status of the outgoing supply from the air circuit breaker.

(c) Voltmeter with 7-position selector switch –To monitor the Line voltage and Phase voltage.

(d) Ammeter with 4-position selector switch – To monitor the current on the 3 phases. Current transformers are required if the supply capacity is 100A or above.

A typical wiring diagram of the protection system and instrumentation for the main circuit breaker is shown in Figure 6.8.

Note that the protection system (including the protection current transformers and protective relays) must always be installed immediately after the air circuit breaker and before all the volt-meter circuit and ammeter circuit. This is to ensure that any short circuit in these volt-meter and ammeter circuit is also protected

6.9 PROTECTIVE DEVICES FOR MAIN CIRCUIT BREAKER

Air Circuit Breakers are normally used as main circuit breakers for main switchboard (MSB) with capacity more than 800A per phase. The following type of protective devices shall be provided for protection:-

(a) Direct Acting Trip

Direct acting trip shall be provided to operate with no time delay under short-circuit condition. It is normally built in with the air circuit breaker as magnetic trip element. When fault current passes through this coil, it produces a magnetic force which actuates the circuit breaker trip mechanism to clear the fault current.

Range of Approved Load	**Maximum Allowable Direct Trip Setting**
200A & below	1200A
200A to 260A	2000A
260A to 400A	2400A
400A to 1500A	3200A
Above 1500A	4500A

Table 6.1

(b) External Overcurrent Relays and Earth Fault Relay

External overcurrent relays and earth fault relay are to be provided with tripping terminals wired to a shunt trip coil installed in the air circuit breaker (as shown in Figure 6.7).

When the overcurrent relay or earth fault relay detects a fault, it will cause the shunt trip coil to be energised and trigger the tripping of the circuit breaker.

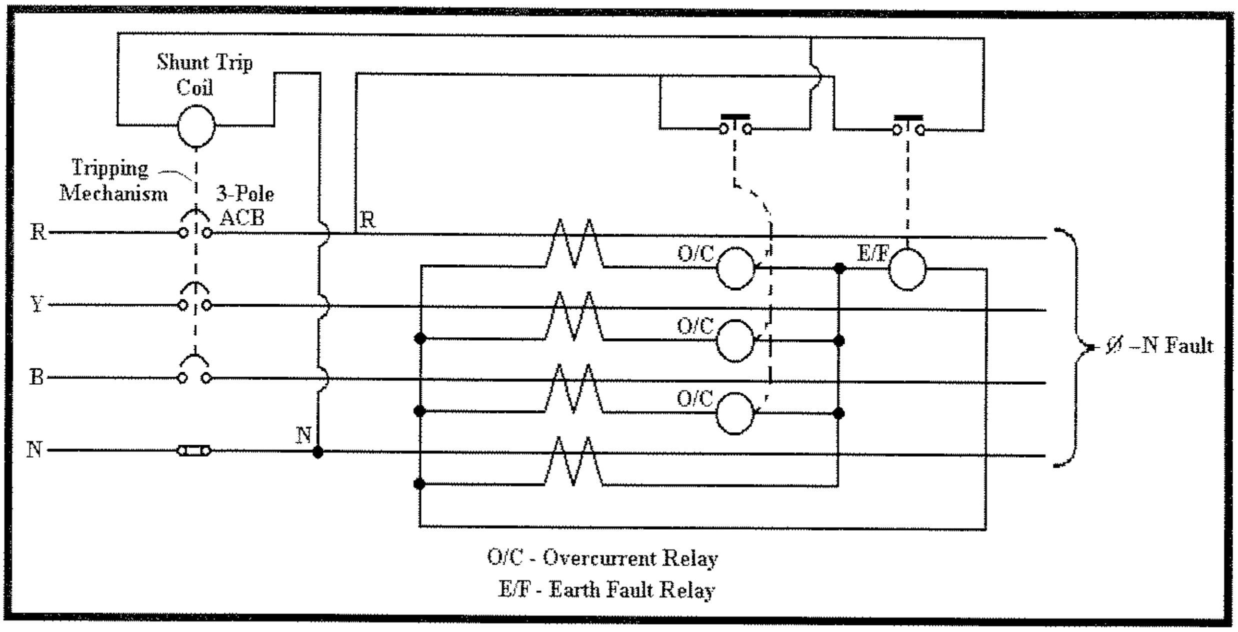


Figure 6. 7 Arrangement of External Protective Relays & Shunt Trip Coil

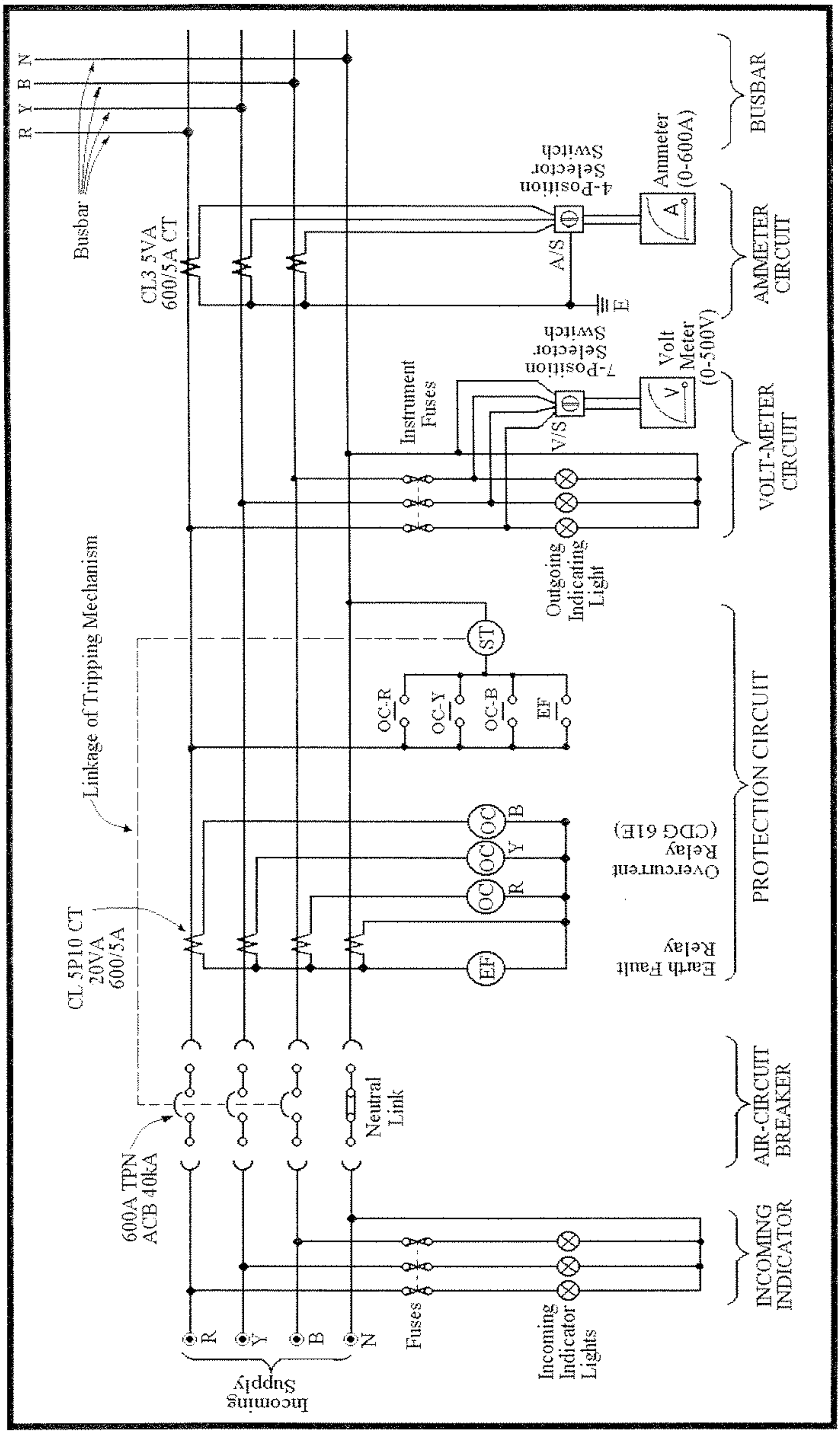


Figure 6. 8 Wiring Diagrams of the protective system & instrumentation for the incoming Air Circuit Breaker

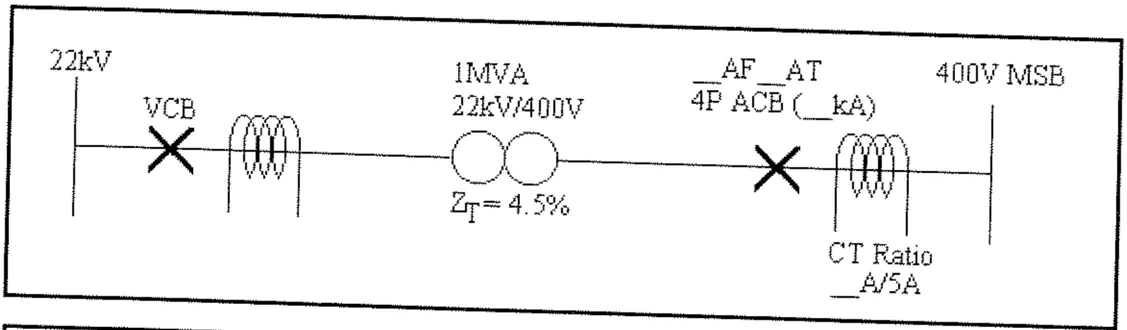
1. Define the following terms used in the context of Air Circuit Breakers (ACB):

   (a) Frame Size and trip rating
   (b) Rated Breaking Capacity

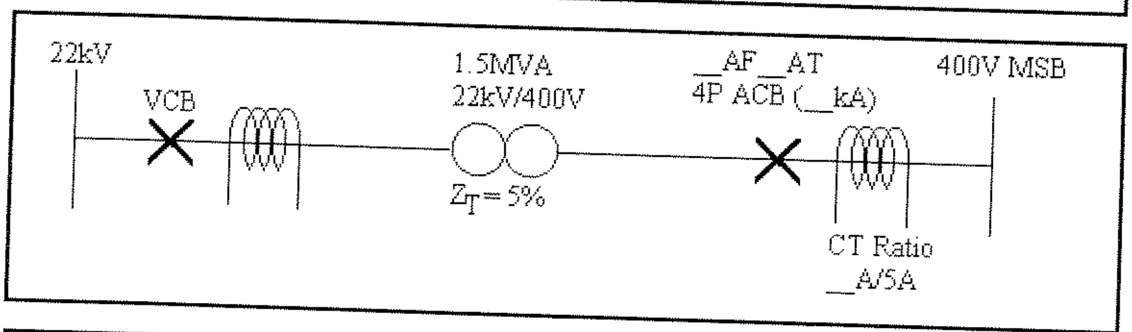
2. Explain briefly how "Electric Arc" is interrupted when the Air Circuit Breaker (ACB) opens.

3. For the main switchboard (MSB) shown in the following diagrams:-

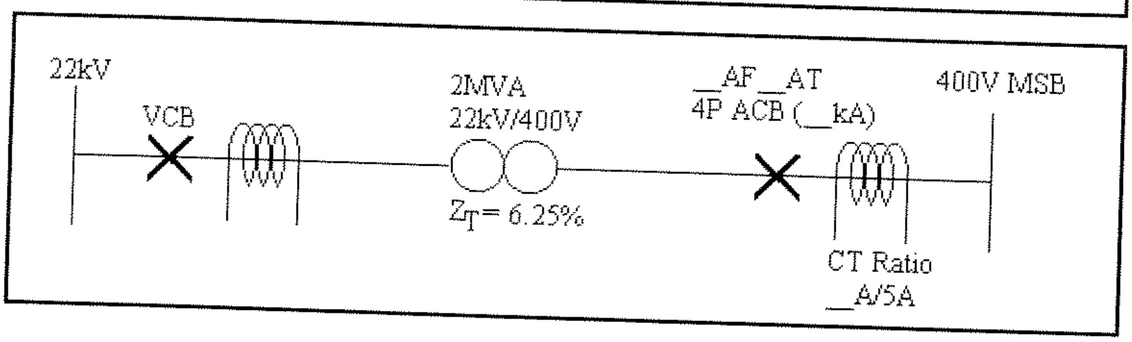
(a)



(b)



(c)



Determine the Frame size, trip rating, short circuit breakers capacity of the ACB and the appropriate CT ratio for protection circuit on 400V MSB.

CHAPTER 7
SIZING OF CABLE & LIVE CONDUCTORS

7.1 INTRODUCTION

An important stage in the design of electrical installation is the determination of cross-sectional area (S mm^2) of 'live' conductors and before this can be effectively determined, the following considerations must be decided:

(a) Type of Cable and Insulation

i.e. 70°C Polyvinyl Chloride (PVC) Cable
90°C Thermosetting or Cross-linked Polyethylene (XLPE) Cable
85°C Rubber Cable
Fire Resistant (FR) Cable
Low Smoke Zero Halogen (LSOH) Cable
Neoprene Cable

(b) Method of Installation

i.e. In conduit and trunking
In cable tray (flat spaced, flat touching or in trefoil)
In underground cable trench

7.2 PVC or XLPE INSULATION

PVC Insulated Cable

PVC insulation are often used up to only 600V/1000V and the continuous current rating of PVC cables are restricted by a maximum temperature of 70°C due to its thermoplastic nature and resultant softening at elevated temperature.

As PVC insulated cables are little affected by moisture, no metal sheath is required and this contributes greatly to ease of handling as well as simplifying jointing and terminating procedures.

XLPE Insulated Cables

XLPE insulated cable can be operated up to 90°C normally; with its superior overload characteristic, XLPE insulated cable has become increasingly popular. XLPE cables are used for low voltage (600V/1000V) to 32kV applications.

The internationally recognized limits for conductor temperatures with common types of insulation are shown in Table 7.1:

Conductor temperature limits		
Insulating Compound	**Temperature* (°C)**	
	Continuous	**Short-circuit**
Polyvinyl Chloride	70	160**
Polyethylene	70	130
Butyl Rubber	85	220
Ethylene Propylene Rubber	90	250
Cross-linked Polyethylene	90	250

* Temperature limits are based on intrinsic properties and do not take account of variations in cable and accessory design. Short-circuit ratings are affected by (a) reduction of thickness of PVC and PE by thermomechanical forces; (b) conductor and core screens; (c) design of accessories (e.g. soldered conductor joints are unsuitable).
** 140°C for conductors above 300 mm^2.

Table 7.1 Insulation and Conductor Temperature Limit

7.3 ARMOURED CABLE

A steel tape layer or steel wires are often used for the main mechanical protection and it may also be used as return path for earth currents.

Armoured PVC insulated cable or armoured XLPE insulated cable are often used for cable installed in trenches or buried underground. The following abbreviations denotes:

DSTA – Double Steel Tape Armoured
SWA – Steel Wire Armoured

7.4 CABLE SELECTION

To determine the minimum conductor cross-sectional area of the live conductors, a number of factors require attention, namely

(a) The application and type of loads

(b) The size of loads

(c) The circuit protection

(d) (i) The ambient temperature
(ii) The grouping and heating effect of adjacent cables and circuits
(iii) The installation method

(e) The permissible voltage drop

(f) The prospective fault current

7.5 CURRENT CARRYING CAPACITY CONSIDERATION

The tabulated current rating tables in Appendix 4: Current carrying capacity and voltage drop for cables and flexible cords in SS CP5:1998 are given upon certain assumptions as follows:

(a) Ambient temperature is 30°C

(b) Conductor operating temperature depends on type of insulation (i.e. 70°C for PVC and 90°C for XLPE as shown on top of each table).

(c) Grouping and heating effect of adjacent cables or circuits not considered.

Therefore, as these external influence and installation conditions varies, the designer must adjust the current carrying capacity of cables accordingly by proper use of

(a) Ambient Temperature Correction Factor, C_a
- whether the ambient temperature is higher than 30°C.

(b) Grouping Correction Factor, C_g
- whether the circuit runs singly or be bunched with other circuits.

(c) Thermal Insulation Correction Factor, C_i
- whether the circuit is totally surrounded by thermal insulation ($C_i = 0.5$) or one side by thermal insulation ($C_i = 0.75$)

<u>Circuit in which Overload Protection is provided by Circuit Breaker</u>

The size of the cable to be used is to be such that its tabulated current carrying capacity (I_t) is not less than the value of the nominal current rating of the protection device adjusted as below:

i.e. Effective Current Carrying Capacity of Cable:

$$I_Z = \frac{I_n}{C_a \times C_g \times C_i} \quad - (1)$$

This formula is applicable for a circuit in which overload protection must be provided by the protection device where I_n = Nominal current rating of protection device and therefore the cable size, S mm^2 must be selected from the respective tabulated table of current carrying capacity so that $I_t \geq I_Z$.

<u>Circuit in which Overload Protection is not provided by Circuit Breaker</u>

However for motor circuit where overload protection is already provided by overload thermal relays in motor starter and control circuit and protection circuit breaker (MCB or MCCB) has been oversized to avoid tripping by motor starting current, the following formula is to be used.

i.e. Effective Current Carrying Capacity of Cable:

$$I_Z = \frac{I_b}{C_a \times C_g \times C_i} \quad -(2)$$

where I_b = Designed Load Current for the circuit.

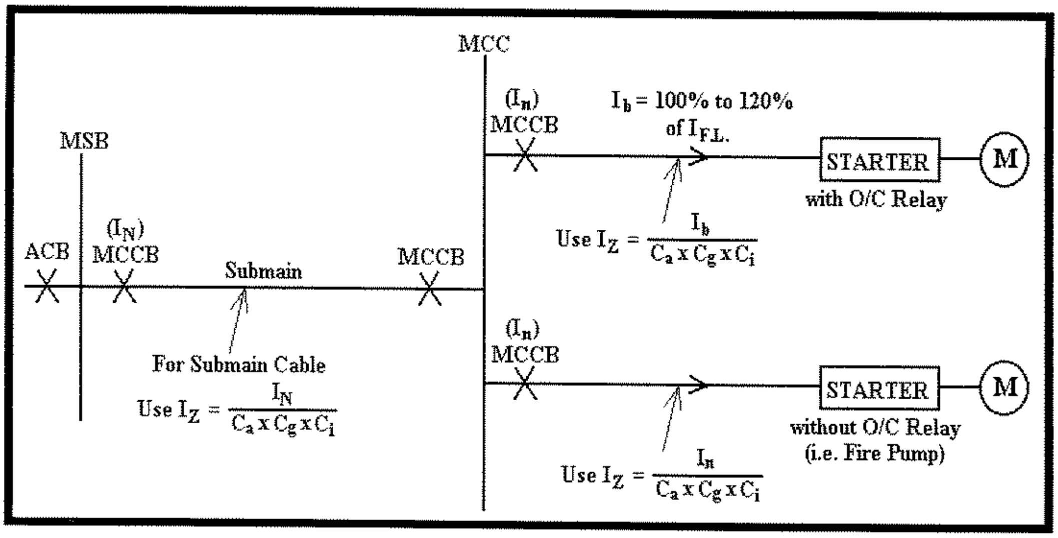


Figure 7. 1

I_b may be 100% or full load current or more (For example: some users may use 120% or more to enhance the current carrying capacity of the circuit cable and to minimize copper losses of the cable) and cable size S mm^2 is selected so that $I_t \geq I_Z$.

Grouping Factor Involving Lightly Loaded Circuits

If, due to known operating conditions, a cable is expected to carry out not more than 30% of its grouped rating, it may be ignored for the purpose of obtaining the rating factor for the rest of the group.

For example, a group of N loaded cables would normally require a group reduction factor of C_g applied to the tabulated I_t. However, if M cables in the group carry loads which are not greater than 0.3 C_gI_t amperes the other cables can be sized by using the group rating factor corresponding to (N-M) cables.

This special condition that allows the heating effects from adjacent lightly loaded cables to be ignored is given at the footnotes of Table 4B1 of SS CP5:1998.

7.6 VOLTAGE DROP CONSIDERATION

Voltage drop consideration is important and of great significance in the sizing of cables at 600V/1000V and below.

A typical requirement in the SS CP5:1998 and IEE regulation is that the voltage drop in a cable run should be such that the total drop in the circuit, of which the cable forms a part, does not exceed 4% of the nominal voltage.

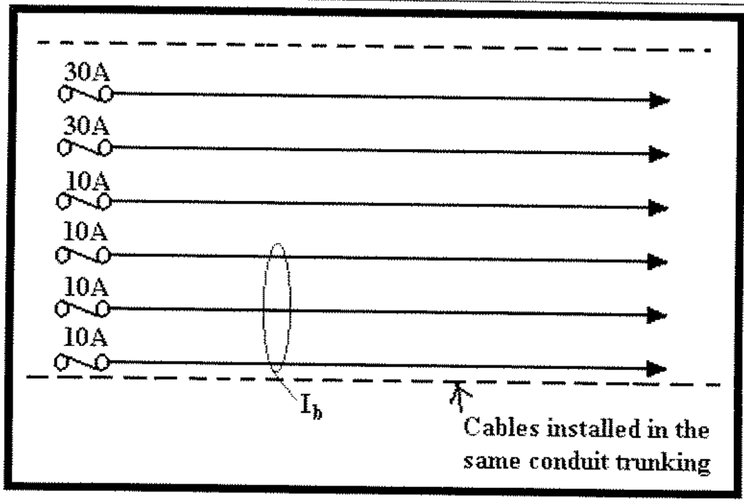


Figure 7. 2 Group Factor involving Lightly Loaded Circuits

The clauses quoted from SS CP5:1998 concerning voltage drop limits are as follows:

525 VOLTAGE DROP IN CONSUMERS' INSTALLATIONS

525-01 Voltage Drop in Consumers' Installations

525-01-01L Under normal service conditions the voltage at the terminals of any fixed current-using equipment shall be greater than the lower limit corresponding to the Singapore Standard relevant to the equipment.

Where the fixed current-using equipment concerned is not the subject of a Singapore Standard, the voltage at the terminals shall be such as not to impair the safe functioning of that equipment.

525-01-02L The requirements of Clause 525-01-01 are deemed to be satisfied for a supply if the voltage drop between the origin of the installation (usually the supply terminals) and a socket-outlet or the terminals of the fixed current-using equipment does not exceed 4% of the nominal voltage of the supply.

A greater voltage drop may be accepted for a motor during starting periods and for other equipment with high inrush currents provided that it is verified that the voltage variations are within the limits specified in the relevant Singapore Standards for the equipment or, in the absence of a Singapore Standard, in accordance with the manufacturer's recommendations.

For a motor circuit with motor starting current, designers often specify that the voltage drop under starting condition be limited to 8 to 10% of nominal voltage.

Example 7.1:

An instantaneous water heater rated at 230V, 3.5kW is to be installed using PVC single-core cables in conduit. The feed will be from an existing spare way in a consumer's unit containing Miniature Circuit Breaker to SS 359:1996 and will run for much of its 14m length in the room with ambient temperature 30°C, and, where leaving the consumer's unit, the cable will be bunched with two other circuits.

(a) Check Design Current

$$I_b = \frac{3600}{230} = 15.21A$$

Therefore $I_n = 20A$ is adequate.

(b) Grouping refer to Table 4B1
2 circuits in conduits
$C_g = 0.80$

(c) Ambient temperature refer to Table 4C1
Temperature 30°C
$C_a = 1$

(d) $$I_Z = \frac{I_n}{C_a \times C_g} = \frac{20}{1 \times 0.8} = 25A$$

Therefore, $I_t \geq I_Z$

By referring to Table 4D1A of SS CP5:1998 and check Reference Method 3. A 2.5mm cable with current rating of 25A with protective conductor $2.5mm^2$ would be required. (Therefore, 2 x $2.5mm^2$ PVC/SC + $2.5mm^2$ CPC)

(e) Voltage Drop

Maximum Voltage Drop allowed = 230 x 4%
= 9.2V

$$\text{Therefore, Maximum mV/A/m} = \frac{9.2 \times 1000\text{mV}}{\text{Designed Current} \times \text{Length}}$$

$$= \frac{9200}{15.21 \times 14} = 43.2 \text{ mV/A/m}$$

By referring to Table 4D1B of SS CP5:1998, $2.5mm^2$ PVC/SC will only give a voltage drop (between phase and neutral) at 18 mV/A/m which is less than the maximum value allowable (i.e. 43.2 mV/A/m).

Therefore, 2 x $2.5mm^2$ PVC/SC + $2.5mm^2$ CPC in conduit and trunking is finally specified.

Example 7.2:

A motor control centre (MCC) supplies the following motor loads:

- A group of small motor, the total full load current is three phase 100A.
- A 80 h.p. three phase motor located at 30m from the MCC. The efficiency of the motor is 88% and power factor during starting and normal operation are 0.5 and 0.9 respectively.

(a) If the maximum voltage drop allowance on the motor feeder during starting and normal operation are not to exceed 4% and 2% respectively, check whether 3 x 70 sqmm/1C PVC cables in trunking would be suitable.

(b) Determine the main circuit breaker size.

Solution:

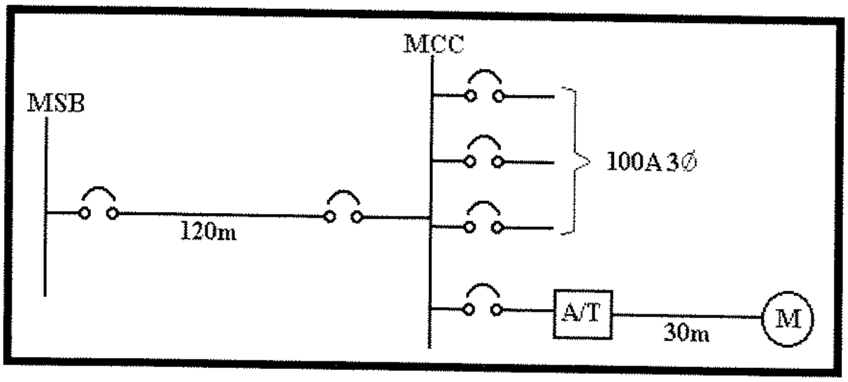


Figure 7. 3

Assume the 80 h.p. motor is having an auto-transformer starter, the full load current,

$$I_{F.L.} = \frac{80 \times 746}{\sqrt{3} \times 400 \times 0.88 \times 0.9}$$

$$= 109A$$

Assuming designed current I_b = 100% x $I_{F.L.}$ = 109A and require current capacity of cable

$$I_Z = \frac{I_b}{C_a \times C_g}$$

$$= \frac{I_b}{1 \times 1} = 109A$$

Therefore, 3 x 50mm^2 PVC/SC with I_t = 134A is selected. s

For motor with A/T starter, Maximum I_n = 109 x 2 = 218A, select 200A.
Assume starting current = n^2 (7.5 x $I_{F.L.}$)

i.e. Starting Current, $I_S = 0.65^2 \times 7.5 \times 109$
$= 345A$

From Table 4D1B, r = 0.56, χ = 0.25.
During normal operation, cosθ = 0.9, sinθ = 0.436

Voltage drop = $I_{F.L.}$ (r cosθ + χ sinθ) x L / 1000
= 109 (0.56 x 0.9 + 0.25 x 0.436) x 30/1000
= 2 V

This voltage drop is less than 2% of 400V, therefore is acceptable.

During starting, $\cos\theta = 0.5$, $\sin\theta = 0.866$

$$\begin{aligned}\text{Voltage drop} &= I_S\,(r\cos\theta + \chi\sin\theta) \times 30 / 1000 \\ &= 345\,(0.56 \times 0.5 + 0.25 \times 0.866) \times 30 / 1000 \\ &= 5.14\text{ V}\end{aligned}$$

This is less than 4% of 400V, therefore is acceptable.

For the main breaker, it is determined as follows:

Main CB size = Trip rating of the MCCB of the largest motor in the group + Full load current of all other motors
= 200A + 100A
= 300A

You may select a MCCB rated at 300A.

Reader may like to proceed with selection of cable size for submain cable with consideration of circuit current capacity and voltage drop, if the cable size of submain is likely to be 120mm^2 or more, it is advisable to install in cable tray.

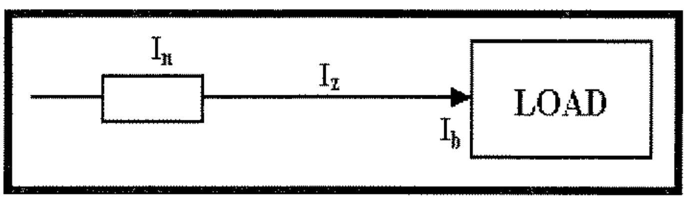
7.7 OVERLOAD CONSIDERATION

<u>Protection of Cable against Overload Current and Consideration with Protection Device</u>

For some types of cable, particularly wiring cables, the required current rating of the cable must be determined by the overload protective device rather than the circuit current. The rating of the device must not be less than the circuit designed current and, of course, such ratings are in discrete steps.

To provide an adequate protection against overloading, CP5:1998, Clause 433-02-01 requires that the following conditions to be satisfied.

(a) $I_b \le I_N \le I_Z$
(b) $I_2 \le 1.45\, I_Z$



Where
I_b = Design Current of Circuit
I_N = Trip Rating of Protective Device
I_Z = Effective Current Carrying Capacity of Conductor

Figure 7. 4

It means:

(a) The nominal current (I_n) of the protective device must be greater or equal to the design current (I_b) of the circuit so that the device will not trip under normal conditions.

(b) The current-carrying capacity of the conductor (I_Z) must be greater than or equal to I_n, so that the device will trip before damage to the cable.

(c) The current that will operate the protective device (I_2) must not exceed 1.45 times the lowest I_Z of the conductors.

Example 7.3:

A circuit with 4 x 16mm^2 PVC single core cable with designed load current, I_b = 52A is protected by a 60A (i.e. I_n = 60A) MCCB with minimum operating current 1.3 x I_n.

(a) Determine the current carrying capacity of the cable and whether the clause 433-02-01 of SS CP5:1998 on protection against overloading. Assuming ambient temperature is 30°C.

(b) Determine the minimum operating current of the MCCB as required by IEC 947-2 and whether the circuit is adequately protected against overloading.

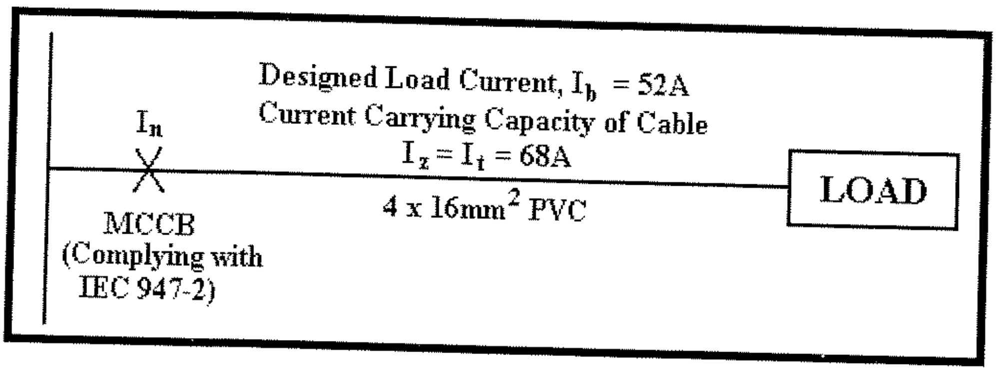


Figure 7. 5

Solution:

(a) From tabulated table 4D1A of SS CP5:1998 current carrying capacity of 16mm^2 PVC cable

I_t = 68A
$\therefore$ I_Z = 68A at 30°C.

Since I_n = Protection device nominal current
= Rating 60A.
I_b = Designed continuous load current
= 52A

$\therefore I_b \leq I_N \leq I_Z$, Clause 433-02-01 is complied.

(b) Since minimum operating current of protection device,

$I_2 = 1.3 \times I_n$

$= 1.3 \times 60 = 78A$

and $1.45\ I_Z = 1.45 \times 68 = 98.6A$

The requirement of $I_2 \leq 1.45\ I_Z$ is also satisfied, therefore this circuit is provided with adequate overload protection.

However, it is to be noted that the cable can effectively carry 68A and the MCCB can operate only at 78A, there is a small range of current from 68A to 78A for which the cable may be slightly overloaded and become warm. Selection of a bigger size cable (next bigger size) may avoid this problem and also minimize the losses on the cable.

7.8 SHORT CIRCUIT CONSIDERATION
- Protection of Cable against Fault Current

Often the conductor size necessary is related to short-circuit current rather than continuous current requirements. The short-circuit current, which may be 20 or more times normal, produces thermal and electromagnetic effects proportional to the square of the current. So far as the cable insulation itself is concerned, much higher conductor temperatures may be produced and the full temperature will not be sustained for significant time by the insulation.

Short-circuit ratings are not published for individual cables in any official documents, because of the large number of the cable types and sizes involved and the fact that they have to be related to the duration of short circuit which applies to the particular circuit.

IEE regulation and SS CP5:1998 specifies in Clause 434-03-03 that under fault condition, the clearance time of the protection device shall not result in the admissible limiting temperature of any live conductor being exceeded:

The formula used is $k^2S^2 \geq I_{SC}^2t$

The *t*, in which a given fault current will raise the live conductors from the highest permissible temperature in normal duty to the limiting temperature, can, as an approximation, be calculated from the formula:

$$t = \frac{k^2S^2}{I_{SC}^2}$$

where:

- t is the duration in seconds,
- S is the nominal cross sectional area of conductor in mm^2,
- I_{SC} is the value of fault current in amperes, expressed for A.C. as the r.m.s. value, due account being taken of the current limiting effect of the circuit impedances.
- k is a factor taking account of the resistivity, temperature coefficient and heat capacity of the conductor material, and the appropriate initial and final temperature. For the common materials indicated in Table 43A, the k factor shall be as shown in table 43A of SS CP5:1998.

Typical values of k are:

$k = 115$ for PVC Copper Cable

$k = 143$ for XLPE Copper Cable

Example 7.4:

For a 400V/230V, 3-phase main switchboard with prospective 3-phase short circuit current 36kA (r.m.s.), determine the minimum size of phase conductor of PVC insulated copper submain to be supplied with electricity from this MSB, assuming that the submain is protected by MCCB with magnetic trip or direct acting trip which can trip within 0.01 sec (10m-sec).

Solution:

Since $k = 115$ for PVC copper cable and MCCB tripping time, $t = 0.01\text{sec}$ and I_{SC} (maximum) = 36,000A.

Therefore,

$$k^2S^2 \geq I_{SC}^2 t$$

$$S \geq \frac{I_{SC}\sqrt{t}}{K} = \frac{36{,}000 \times \sqrt{0.01}}{115} = 31.1\text{mm}^2$$

Example 7.5:

For a 230V, single phase Distribution Board (DB) with prospective phase to neutral short circuit current 1.2 kA (r.m.s.), determine the minimum size of phase conductor of PVC insulated copper wire to be supplied with electricity from this DB, assuming that the MCB (Type B) used has magnetic trip which can trip within 0.01 sec (10 m-sec)

Solution:

Since $k = 115$ for PVC CU copper

$t = 0.01$ sec

$I_{SC} = 1200\text{A}$

Therefore, $$S \geq \frac{I_{SC}\sqrt{t}}{k} = \frac{1200\sqrt{0.01}}{115} = 1.04\text{ mm}^2$$

(1) Explain briefly what are the basic considerations in the sizing of 'live' conductors in low voltage electricity supply system.

(2) Explain briefly what are the additional considerations in the determination of circuit breaker trip rating and cable size for motor circuits.

(3) The following 230V, single phase final circuits run within a metal trunking. The cables are to be PVC/SC copper cable protected by MCB, ambient temperature 35°.

Circuit 1: 6 Nos. twin 40W fluorescent lamps and 4 Nos. 60W filament lamps

Circuit 2: 4.5 h.p. motor, 85% efficiency, 0.8 p.f.

Circuit 3: Water heater 6kW

(a) Determine the circuit breaker trip rating I_n, the designed current I_b and the effective current carrying capacity of the cable for each final circuit.

(b) Determine the final circuit live cable size and CPC cable size if voltage drop limit not exceeding 4% of nominal rated voltage.

(4) A final circuit of 4 x 25mm^2 PVC/SC copper cables (with I_t = tabulated current rating = 80A at 30°C ambient temperature from Table 4D1A SS CP5:1998) installed in trunking with designed continuous load current, I_b = 78A is protected by a MCCB with trip rating I_n = 80A. Determine whether the circuit cables are adequately protected against overloading.

(5) A motor circuit for a 2.5 h.p., 3 phase 400V motor (with efficiency 95%) is started by a D.O.L. starter (with overload relay set to 110%) has power factor at 0.4 and 0.85 during starting and running conditions respectively.

(a) Determine the appropriate trip rating of the MCCB.

(b) Determine the cable size (3 x _?_ mm^2 PVC) for the motor circuit if voltage drop during starting and full load running shall not exceed 5% and 2.5% respectively.

(6) The motor control centre (MCC) which takes electricity supply via a 3-phase motor submain from MSB has the following motor circuit:

a 7.5 kW Motor with D.O.L. starter
a 60 kW Motor with Star-Delta starter
a 105 kW Motor with Auto-transformer starter

Assuming all motors have efficiency, η = 95% and power factor 0.4 and 0.85 for starting current and full-load running respectively.

Determine

(a) The trip rating of MCCB for each motor circuit and the cable size for each motor circuit.

(b) The trip rating of main breaker of the submain and its cable size.

Assuming total voltage drop from MSB to motor shall not exceed 4% during full load running and 10% during starting.

CHAPTER 8
MAXIMUM DEMAND AND LOAD ESTIMATION

8.1 LOAD ESTIMATION

Introduction

Load Estimation is the computation of expected maximum electrical demand of a building for the purpose of determining the capacities of the switchgears required. This information is also used for the application of electricity supply to the local supply authority.

Estimation of the total load of the building should take into consideration the maximum electrical demand of all the facilities to be installed in the building and the possibility of future load extension, so that the capacities of the major equipment such as the transformers, standby generators, etc. are sufficiently allowed for.

Types of Load in a Commercial Building

The facilities provided in commercial buildings vary according to the operational requirement of the building, but may generally be classified into the following categories:

a) Lighting Load

Lighting load includes the loads of the interior and exterior lighting luminaries and their associated control gears.

b) Air-conditioning and Ventilation Loads

Air-conditioning load accounts for a major portion of the electrical requirement of a commercial building. Therefore, an efficient air-conditioning system not only lowers the operating cost, it will also lower the initial capital cost for the electrical installation.

c) General Purpose Power

The power that is required for general appliances such as computers, communication equipment, office automation equipment, etc.

d) Plumbing and Sanitary System

This includes domestic water pumps, electrical boilers, ejector pumps, etc.

e) Vertical Transportation System

This includes passenger and goods lift, escalators, dumb waiters, etc.

f) Kitchen Equipment

The electrical requirement for a kitchen can be quite substantial if the kitchen relies heavily on electrical cooking equipment.

g) Special Equipment

This may include air-compressors, hoisting equipment, etc.

h) Fire Fighting System

Fire fighting equipment such as fire pumps, wet riser pumps, etc. should be included in the load estimation even though they are operated only in the event of a fire, unless the operation of these equipment will automatically trip the power supply to other non essential equipment to compensate for the increased load.

Maximum Demand and Diversity Factor

In any electrical installation, it is unlikely that every piece of equipment will be used at the same time. This means that the maximum demand will be less than the sum of the load of all the connected equipment. The following definitions are used:

Connected load	-	The sum of all the loads connected to the electrical supply
Maximum Demand	-	The maximum power taken during a given period of time
Diversity Factor	-	The ratio of the maximum demand to the connected load

$$\text{Diversity Factor} = \frac{\text{Maximum Demand}}{\text{Connected Load}}$$

The maximum demand of the proposed installation has to be estimated with care. Too low a figure will result in operation of overload protective devices. The adoption of too high a figure without paying due regard to diversity will cause unnecessary expense in the employment of oversized cable and switchgear.

It follows therefore, that the designer needs an intimate knowledge not only of each equipment to be used but also the manner and frequency of its use in order to estimate the maximum demand of the installation. He must also make an informed estimate of likely future changes in the pattern of usage if costly alterations and extensions to the installations are to be avoided at a later stage.

Methods of Load Estimation

Two methods are normally required to be used for estimating the maximum demand of a building during the design stage:

Method 1: Load Density Method (W/m^2)

During the initial planning stage, the detail design of the lighting system, generally power and air-conditioning system are not known, therefore, the exact load requirement based on the actual design could not be made. A good preliminary estimate based on past experience of electrical load per unit area in similar type of development is therefore necessary. This estimated value could then be corrected and adjusted when more detailed information of the facilities are known. The following table may be used as a guide:

Type of Occupancy	Lighting (W/m^2)	Power (W/m^2)	Air-conditioning (W/m^2)
Auditorium:			
General	7 –20	0	120 – 200
Stage	200 – 400	5	
Art gallery	20 – 50	5	50 – 70
Bank	20 – 40	30	50 – 70
Cafeteria	25 – 45	5	60 – 70
Religious building	10 – 30	5	50 – 70
Computer area	15 – 25	15	120 – 200
Department Store:			
Basement	30 – 50	15	–
Main floor	25 – 45	10	50 – 70
Upper floor	20 – 40	5	–
Dwelling (not hotel):			
0 – 300m^2	30	5	–
300 – 12000m^2	20	2.5	–
Above 12000m^2	10	1.5	–
Garage (commercial)	5	1.5	–
Hospital	20 – 30	10	50 – 70
Hotel:			
Lobby	10 – 30	5	50 – 80
Rooms (no cooking)	10 – 25	5	30 – 50
Industrial building	10 – 20	10	–
Laboratories	30 – 40	50 – 200	60 – 100
Library	15 – 35	5	50 – 70
Office Building	15 – 35	15	40 – 70
Restaurant	15 – 25	2.5	60 – 100
Shops	20 – 50	5 – 10	40 – 90
School	15 – 35	15	35 – 50
Warehouse (storage)	2.5 – 10	2.5	–
General building:			
Halls, corridors	5	–	–
Storage spaces	2.5	–	–

Table 8.1

In this method, each individual category of the loads (lighting, general power and air-conditioning) are obtained by multiplying the floor area with the possible load density, and these figures are then added together, taking into account the diversity factor, to obtain the maximum demand load of the building.

Method 2: Actual Load Method

Other electrical loads such as vertical transportation equipment, kitchen equipment, special equipment etc. which are not proportional to the area usage should not be estimated using the Load Density Method. The actual load data must be gathered from the suppliers and then added to the total estimated load obtained using method 1.

8.2 DESIGN OF ELECTRICAL SYSTEM FOR LARGE INSTALLATION

The design of electrical installation for a large building begins with the estimation of the electrical load of the building. For a large, multi-function and multi-tenanted building, there will be wide range of electrical loads to be installed and the load usage patterns of the tenants will be very diversified. The design will depend very much on the knowledge and experience of the designer.

Design Procedure

Generally the design procedures are as follows:

a. Electrical load estimation based on areas involved
b. Decide the point of service entrance, voltage, substation requirements
c. Usage of all areas
d. Electrical loads for air-conditioning, plants, lifts, elevators, pumps, fans, etc.
e. Locations of switchroom, plants, transformer rooms, riser ducts, etc.
f. Detail design

Example 8.1
Load Estimation for Commercial Buildings

A 18 storey high-rise building is designed as an office building cum shopping centre and the usage of the floor areas are as follows:

Floor	Intended Usage	Rentable Area (m^2)	Circulation Area (m^2)
Roof	Roof garden / Plant room		2400
8 – 18th storey	Office	1680	720
4 – 7th storey	Car park		2400
3rd storey	Car park Restaurant	720	1680
2nd storey	Shopping centre	1680	720
Mezz. Floor	Exhibition hall	2400	
1st storey	Shops	1680	720

Table 8.2

Solution

The electrical demand is computed as follows:

Floors	Area (m^2)	Lighting (W/m_2)	Power (W/m^2)	A/C (W/m^2)	Demand (kW)
Roof	2400	5	3	-	19.2
18th storey					
Office	1680	18	10	45	122.6
Common area	720	10	5	45	43.5
8th storey to 17th storey (same as 20th storey)					165.8x10
7th storey (car park)	2400	5	-	-	12.0
6th storey **5th storey** **4th storey (same as 7th storey)**					12.0 12.0 12.0
3rd storey					
Car park	1680	5	-	-	8.4
Restaurant	720	15	10	65	64.8
2nd storey					
Shopping centre	1680	25	10	50	142.8
Common areas	720	10	5	50	46.8
Mezz. Floor	2400	30	20	65	276.0
1st storey (same as 2nd storey)					189.6
Sub-Total Demand					2619.4

Table 8.3

Other Services	QTY	Load (kW)	Diversity	Demand (kW)
Lifts	6	30	0.85	153.0
Escalators	4	20	0.85	68.0
Fire sprinkler pump	1	30	1.0	30.0
Domestic water pump	1	75	1.0	75.0
Wet riser pump	1	80	1.0	80.0
Sub-total Demand				406.0

Table 8.4

Therefore, Maximum Demand of the building = 3025 kW

Assuming an overall power factor of 0.85, the Maximum Demand = 3560 kVA

Example 8.2
Load Estimation and Preliminary Design for Residential Development

An 11-storey apartment building in a private condominium development has the following types of electrical loads:

(a) Residential units type A

30 apartments of type A with floor area 120mm^2 per unit, with 3 bedrooms, a living/dining hall, a kitchen and a private lobby.

Lighting points – 20 points (Assuming 100W per point)

13A SSO power points – 33 points (Assuming 300W per point)

Split Air-conditioning units – Three (3) compressor/condensing units with seven (7) fan coils units:

- Unit 1 for 2 FCUs in Living and Dining hall – 16.9A full load current
- Unit 2 for 1 FCU in master bedroom – 8.6A full load current
- Unit 3 for 4 FCUs in bedroom 2 and 3, kitchen and private lobby – 12.75A full load current

(b) Residential units type P2 (penthouse)

3 Apartments of type P2 with floor area 146mm^2 per unit, with 4 bedrooms, a living/dining hall, a kitchen and a private lobby.

Lighting points – 32 points (Assuming 100W per point)

13 A SSO power points – 44 points (Assuming 400W per point)

Split Air-conditioning units – Five (5) compressor/condensing units with eight (8) fan coils units:

- Unit 1 for 2 FCUs in Living and Dining hall – 16.9A full load current
- Unit 2 for 1 FCU in master bedroom – 8.6A full load current
- Unit 3 for 3 FCUs in bedroom 3, private lobby and kitchen - 7.5A full load current
- Unit 4 for FCU in bedroom 2 – 8.6 full load current
- Unit 5 for FCUs in bedroom 3 – 7.5A

(c) Other non essential loads for common facilities

Lifts: 2 passenger lifts not classified as firemen lift, 18kW for each lift at 400V/3ph

Swimming pool facilities:
Swimming pool pump (2 units) – 1.5kW each at 230V/1ph
Hydraulic chemical pump (2 units) – 1.5kW each at 230V/1ph
Soda ash pump (1 unit) – 1.5kW at 230V/1ph

Rain water pump: One unit of 7.5kW at 400V/3ph

Ejector pump: One unit of 2.5kW at 400V/3ph
Sump pump: Two unit of 4kW at 400V/3ph

(d) Essential loads for common facilities

Firemen lift	One unit of 18kW at 400V/3ph
Firemen lift MR fan	One unit of 1kW at 230V/1ph
Domestic water pump	Two units of 4kW each at 400V/3ph
Roof booster pump	Two units of 4kW each at 400V/3ph
Sprinkler pump	Three units of 6.5kW each at 400V/3ph
Sprinkler pump room fan	Two units of 1kW at 400V/3ph
Smoke lobby fan	One unit of 0.5kW fan at 230V/1ph
Car park fans	Four units of 7.5kW each at 400V/3ph
Car park drainage pump	1 No. of 5kW at 400V/3ph

(i) Estimate the connected load (C.L.) and Max Demand (M.D.) for each unit of type A and type P2 apartments.

(ii) Determine the trip rating of main breaker for the DB at each type of apartments.

(iii) Estimate the maximum demand of each riser for residential unit and hence design the risers the tap-off arrangement and the metering arrangement for the residential building.

(iv) Estimate the maximum demand of total non essential loads and essential loads to determine the total load requirements for the building (in Ampere and kW).

(v) Determine the size of standby generator required for the essential load.

(vi) Show your complete design of the electrical installation in a main single line diagram and DB diagrams for typical units for preliminary submission.

Solution:

(i) Maximum Demand of Apartment – Type A

Load Description	Connected Load	DF	MD
Lighting points	20 x 100W = 2000W	66%	6600W
Water Heater	3 x 2000W = 6000W	2/3 or 66%	4000W
Cooker	4600W	50%	2300W
Washing Machine	3450W	100%	3450W
Air Conditioning	40A x 230V x 0.85 = 7800W	60%	4680W
Total			22082W

Table 8.5

Therefore, $I_{F.L.} = \dfrac{22082W}{230V \times 0.85} = 113A$

Use overall D.F. = 80%

Therefore M.D. = 113A x 0.8 = 90A single-phase

(i) Maximum Demand of Apartment – Type P2

Load Description	Connected Load	DF	MD
Lighting points	32 x 100W = 3200W	66%	2112W
13A Single Socket Outlet	44 x 400W = 17600W	50%	8800W
Water Heater	5 x 2000W = 10000W	3/5 or 60%	6000W
Cooker	4600W	50%	2300W
Washing Machine	3450W	100%	3450W
Air Conditioning	50A x 230V x 0.85 = 9775W	60%	5865W
Total			28527W

Table 8.6

Therefore, $I_{F.L.} = \dfrac{28527W}{230V \times 0.85} = 150A$

Use overall D.F. = 80%

Therefore M.D. = 150A x 0.8 = 120A single-phase or 40A 3-phase

Readers may like to proceed to solve part (iii) – (vi)

1. You are assigned to carry out a preliminary design for a 10 storey office building where the usable floor area is given as 1200 m^2 per floor.

   (a) Explain briefly the design procedures.

   (b) Determine the lighting load, small power and air-conditioning load by load density method.

   (c) Determine actual specific loads such as lift and escalator, water pumps, fire protection equipment, etc.

   (d) Sketch the main single line diagram for the distribution system.

2. A residential block consists of 12 storeys with 3 apartments per floor. Each apartment has a floor area of 100 m^2 and is provided with the following:

   - Total 2kW for lighting load
   - Total 6kW for general power (i.e. by 13A switch socket outlets)
   - Total 4.5kW for air-conditioning load
   - A 3kW washing machine (i.e. by a 15A switch socket outlet)
   - 3 Nos. of 3kW instantaneous water heaters

   (a) Determine the maximum demand for each apartment.

   (b) Assuming a group diversity factor D.F. = 0.8, determine the maximum demand of the residential block.

3. An office building with 7 storeys of office area, and its floor area is 500m^2 per floor with the following type of electrical loads:

   Lighting
   Office equipment and general power
   Air-conditioning
   Lifts (2 Lifts, 25kW each)
   Fire pumps (50kW)
   Other power (pump, ventilation, fan etc)

   Estimate the maximum demand of this building.

4. The rental space and service areas for a multi-storey office building is as follows:

   Major electrical equipments to be installed are:

   - 6 number of lifts : 15 hp each
   - 2 number of escalator : 8 h.p. each
   - Air-conditioning load : 1000kW
   - Ventilation, pressurisation fans and pumps: 180kW

Description	Area
Rentable areas:	
(i) 1st storey	500m^2
(ii) 2nd – 12th storey	1800m^2 per storey
Service areas:	
(i) corridor, staircase	2500m^2
(ii) lobby	2500m^2
(iii) car park	6000m^2
(iv) others	500m^2

Table 8.7

(a) Estimate the maximum demand of the building. You should indicate clearly all assumptions made.

(b) Sketch the main single-line diagram for the distribution system, assuming that there are two 22kV incomers from power supply company.

CHAPTER 9
CURRENT TRANSFORMERS

9.1 CURRENT TRANSFORMERS

The current transformer is a device that transforms a high primary current to a low secondary current.

The functions are:

(a) To reduce the power system primary current to a secondary value, in proportion to the primary value so that the current can be carried by small cross-sectional area wires associated with panel wiring and relays.
(b) To insulate the protective relays, instrumentations and meters and their associated secondary circuits from the voltage of the primary circuits of the power system.

9.2 METERING CURRENT TRANSFORMER

Metering current transformer is designed for measuring purpose and operates over a range of current up to a specific rated value, which usually corresponds to the circuit normal rating and has specified errors at that value.

9.3 PROTECTION CURRENT TRANSFORMER

Protection current transformer is required to operate over a range of current many times the circuit rating and is frequently subjected to conditions greatly exceeding those which would be subjected to as a measuring current transformer.

Under such conditions, the flux density corresponds to advanced saturation and the response during the transient period of short-circuit current is important.

The methods of specification of current transformer for measurement purposes and those for protection are therefore different.

9.4 COMPARISON OF METERING C.T. AND PROTECTION C.T.

Measuring C.T.s has to be accurate from about 10% to 120% of their rated current. On the other hand, protection C.T.s have to be accurate for currents well in excess of their rated current – i.e. at least 10 times their rated current.

A protective C.T. is therefore always larger than a measuring C.T. with the same ratio and burden.

To provide the accuracy required, the C.T.s have to operate in the linear portion of the magnetising curve. Figure 9.1 shows a typical magnetising curve.

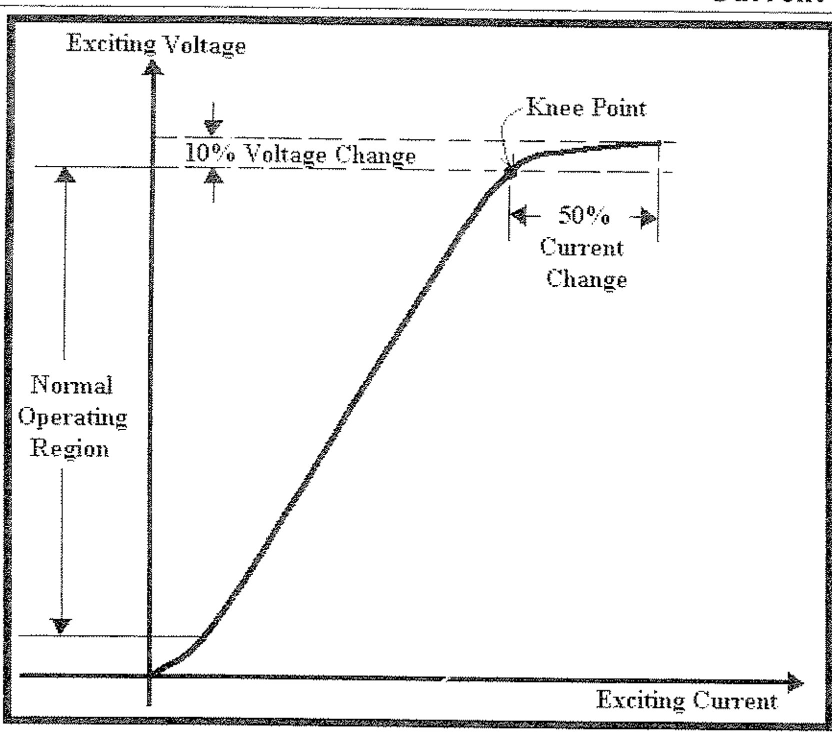


Figure 9. 1 Typical Magnetising Curve

To protect the C.T. and meters, the measuring C.T. must saturate for currents exceeding 120%. Saturation occurs at the knee point of the magnetising curve – the knee point is defined as the point at which the secondary voltage increases by only 10% for a 50% increase in the exciting current. Therefore, in the event of a short circuit, the secondary current of the measuring C.T. will be restricted to a very small increase.

9.5 CONSTRUCTION

Current transformers are usually designed so that the primary winding is actually the line conductor which is passed through an iron ring that carries a secondary winding.

They are mostly of this type and are known as ring-wound current transformers, as shown in Figure 9.2.

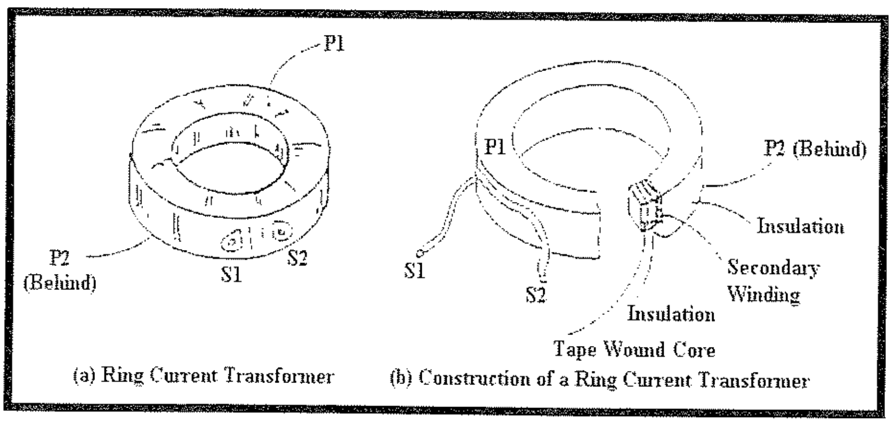


Figure 9. 2 Ring-wound Current Transformer

9.6 POLARITY OF CURRENT TRANSFORMER AND CONNECTION

(a) Terminals

The primary 'terminals' of a current transformer are marked with P1 and P2 and the terminals of the secondary winding are marked with S1 and S2.

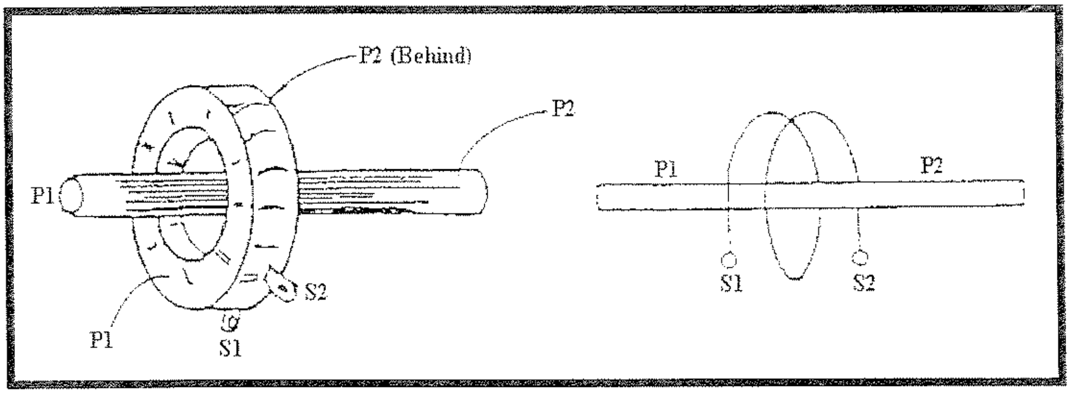


Figure 9. 3(a) Polarity of Current Transformer

(b) Polarity

Polarity gives the relative instantaneous directions of current in the primary and secondary leads. According to British Standards (BS 3938), the polarity is marked as in Figure 9.3(b).

If instantaneous primary current flows from P1 to P2 as marked by the arrow, the instantaneous current in the secondary winding will flow from S1 to S2 through ammeter as shown by arrow for I_S.

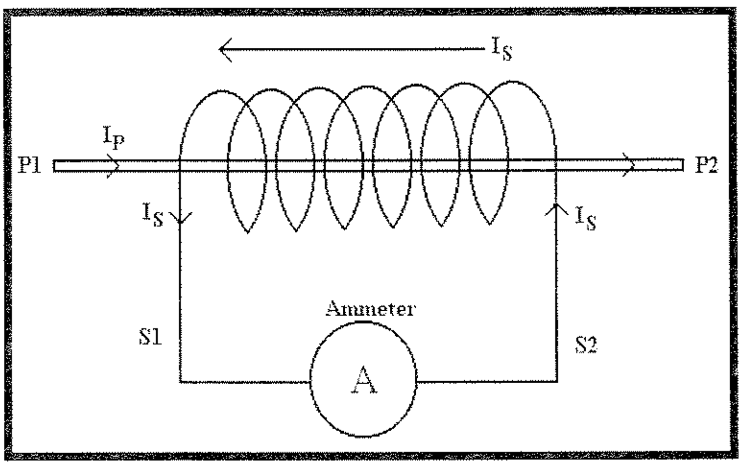


Figure 9.3(b)

(c) Polarity of current transformers for overcurrent (O/C) and earth fault (EF) protection

The polarity and connection of the current transformers for overcurrent relays and earth fault relays are therefore as shown in Figure 9.3(c).

P1 and P2 : Primary Terminals
S1 and S2 : Secondary Terminals

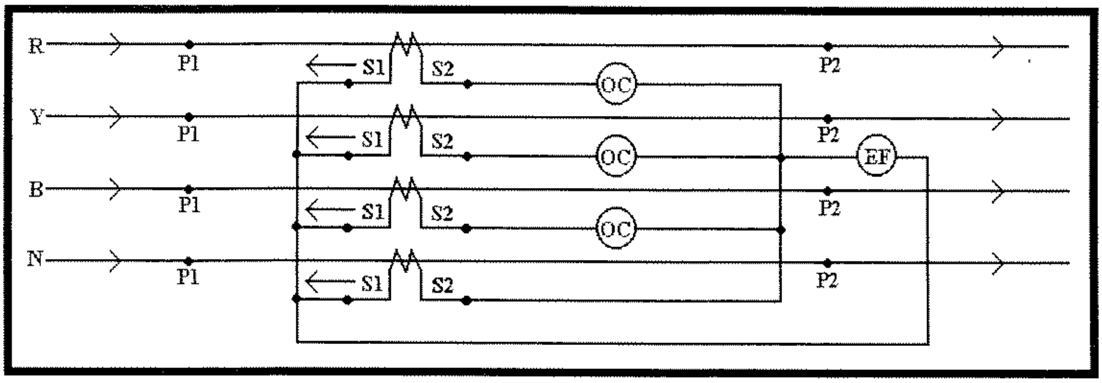


Figure 9.3(c) Polarity of Current Transformers

9.7 BURDEN

(a) The load connected to the secondary of a current transformer is called the burden. The lead and the relay in the protection circuit are all considered to be the burden.

(b) Burden is expressed preferably in terms of impedance (Ω) of the circuit connected to the secondary. However, the British method is to specify the burden on the current transformer in VA at rated secondary current.

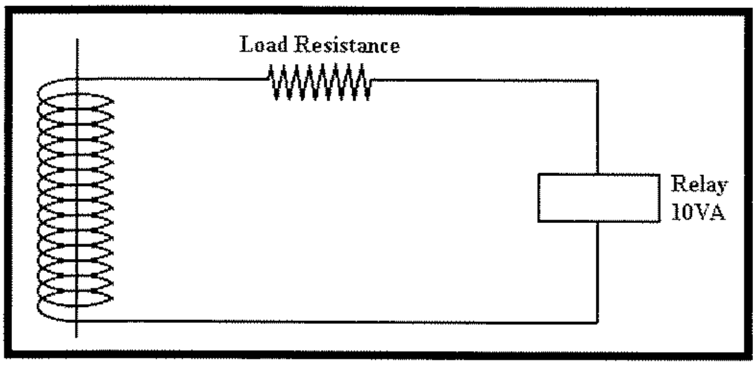


Figure 9. 4(a) The Lead and Relay are considered as Burden

The Burden in VA can therefore be calculated by the formula

$$P = I_s^2 Z_b$$

if the impedance of the load is known.

Example 9.1:

For a 0.5Ω Burden, the equivalent VA at rated secondary current 5A is given by

$P = I_s^2 Z_b = (5)^2 \times (0.5) = 12.5$ VA

Example 9.2:

Calculate the VA output required for a C.T. of 5A rated secondary current when burden consists of relay requiring 10VA at 5A plus load lead resistance of 0.1 ohm. Suggest the choice of current transformer.

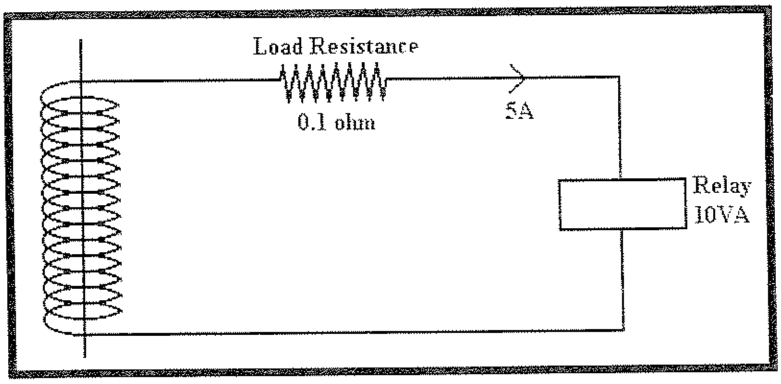


Figure 9.4(b)

Solution:

VA required to compensate load lead resistance = $I^2R = 5^2 \times 0.1 = 2.5VA$
Relay requires 10VA

Hence total VA output required = 10 + 2.5 = 12.5VA
Hence, a C.T. of capacity 15VA and rated secondary current 5A may be used.

Burden Requirements

The Burden imposed on a Current Transformer consist mainly of the following:

(a) The impedance of pilot wire between C.T. and Relay/instruments.
(b) The impedance of the relays or instruments.
(c) The sum of (a) and (b) constitute the external burden required.

Guide Table for Pilot Lead Burden

The following chart, as shown in Figure 9.5, shows the approximate burden imposed on the C.T. for various size of wires at varying distances.

9.8 SPECIFICATION OF PROTECTION CURRENT TRANSFORMERS

Protection of current transformers are specified in terms of:

(a) Rated Primary Current

The value of primary current on which the performance of the current transformer is specified by the manufacturer.

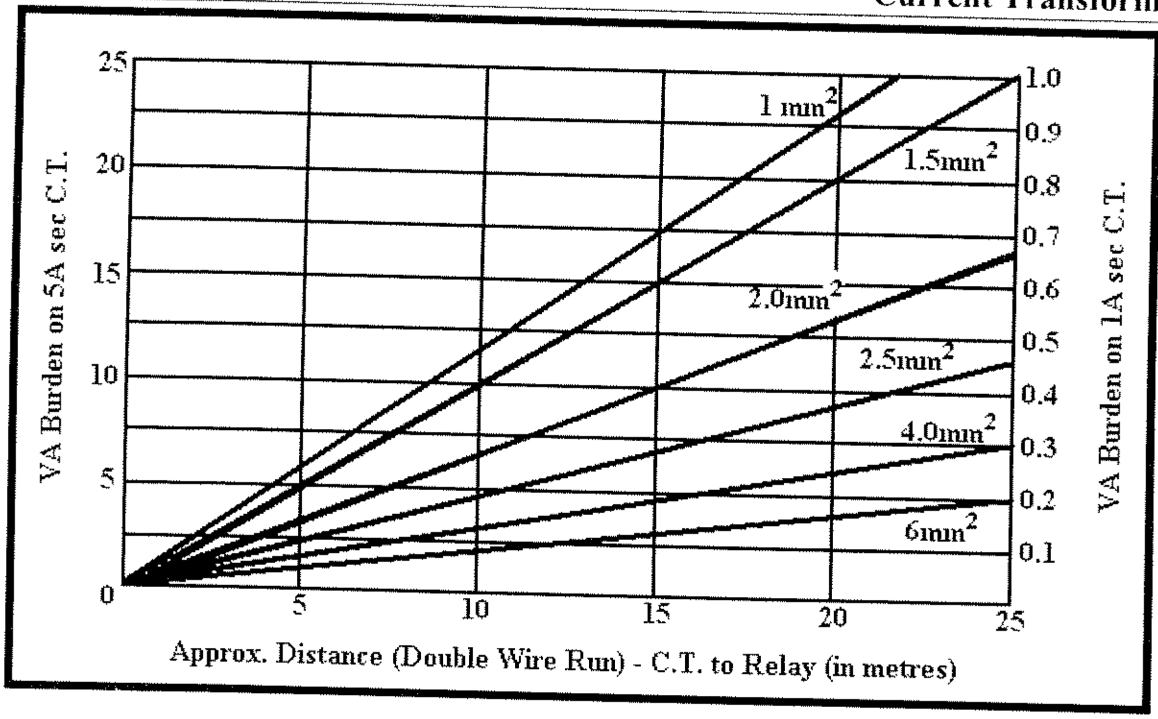


Figure 9. 5

(b) Rated Secondary Current

The value of secondary current on which the performance of the current transformer is specified by the manufacturer.

Current Transformers (C.T.s) are usually designed to have rated current of 1A or 5A.

(c) Rated Transformer Ratio

The ratio of the rated primary current and rated secondary current:

$$\text{Transformation Ratio} = \frac{\text{Rated Primary Current}}{\text{Rated Secondary Current}}$$

For example, transformation ratio can be 2000/5A, 1600/5A, 400/5A, 300/5A.

(d) Rated Burden

Rated Burden is the value of load (in VA capacity) that can be connected across the secondary of current transformer at rated secondary current. Standard values of rated burden are 5, 7.5, 10, 15, 20 and 30VA.

(e) Accuracy Class

The class assigned to the current transformer with the specified limit of composite error (combination of ratio error and phase angle error).Two accuracy classes are quoted, namely Class 5P and Class 10P which give a composite error of 5% and 10% respectively.

Class 5P – composite error 5%, Class 10P – composite error 10%

Class	Current error at rated primary current (per cent)	Phase displacement at rated current (minutes)	Composite error at rated accuracy limit primary current (per cent)
5P	±1	±60	5
10P	±3		10

Standard accuracy limit factors are 5,10,15,20 and 30

Table 9.1 Limit of error for accuracy class 5P & 10P

(f) Accuracy Limit Factor

Accuracy limit current is the largest current value at which the protection current transformer is still able to maintain a reasonable accuracy.

Accuracy limit factor is the ratio of the accuracy limit current to the rated current of the current transformer.

Therefore,

$$\text{Accuracy Limit Factor} = \left(\frac{\text{Accuracy limit current in Primary}}{\text{Rated Primary Current}}\right)$$

$$= \left(\frac{\text{Accuracy limit current in Secondary}}{\text{Rated Secondary Current}}\right)$$

Example 9.3:

For a 2000/5A, Class 5P10, 20VA transformer, list the values of

(a) Rated primary current
(b) Rated secondary current
(c) Rated transformation ratio
(d) Accuracy class and the specified composite error of the current transformer
(e) Accuracy limit factor and accuracy limit, current in the primary
(f) Rated Burden

Solution:

From the specifications, it is known that this is a protection current transformer.

(a) Rated primary current = 2000A
(b) Rated secondary current = 5A
(c) Rated transformation ratio = 2000/5
(d) Accuracy class is 5P, which means the composite error is within ±5%
(e) 5P10, the 10 means that accuracy limit factor is given as 10.

Therefore, the primary accuracy limit current = 10 times of primary rated current
= 10 x 2000A = 20kA

which means that the current transformer will only have a composite error of ±5% up to a maximum primary current of 20,000A.

9.9 MEASURING CURRENT TRANSFORMERS

The accuracy class of measuring current transformers is shown in Table 9.2.

For Classes 0.1 to 1, the current error and phase displacement at rated frequency shall not exceed the values given in the above table when the secondary burden is any value from 25% to 100% of the rated burden.

Class	± Percentage current (ratio) error at percentage of rated current shown below			Phase displacement at percentage of rated current shown in minutes		
	10 up to but not incl. 20	20 up to but not incl. 100	100 up to 120	10 up to but not incl. 20	20 up to but not incl. 100	100 up to 120
0.1	0.25	0.2	0.1	10	8	5
0.2	0.5	0.35	0.2	20	15	10
0.5	1	0.75	0.5	60	25	30
1	2	1.5	1	120	90	60

Table 9.2 Limits of error for accuracy classes 0.1 to 1

Class	± Percentage current (ratio) error at percentage of rated current shown below	
	50	120
3	3	3
5	5	5

Note: Limits of phase displacement are not specified for class 3 and class 5

Table 9.3 Limits of error for accuracy class 3 and class 5

For Classes 3 and 5, the current error at rated frequency shall not exceed the values given in the above table when the secondary burden is any value from 50% to 100% of the rated burden.

Ratings of measurement C.T. are expressed in terms of rated burden and class.
For example: 15VA Class 0.5

9.10 VOLTAGE TRANSFORMERS

It is not practical to manufacture meters and indicating lamps for direct operation on 3.3kV, 6.6kV, 22kV or higher voltages. Voltage transformers that step down the high voltages to working voltages of 110V, 230V or 400V are used.

1. Explain briefly the meaning of the following abbreviated descriptions:

   (a) 2000A/5A CL5P10 20VA C.T.
   (b) 600A/5A CL0.1 5VA C.T.
   (c) 1000A/5A CL3 5VA C.T.
   (d) 5000A/5A CL5P20 20VA C.T.

2. A 15MVA 33kV/11kV distribution transformer with an impedance of 10% is connected to a 11kV switchboard. If the transformer is allowed to be overloaded by 15% for a short duration, Determine the appropriate current transformer ratio for the protection circuits of 33kV and 11kV circuit breakers.

3. A 2.5 MVA 22kV/400V distribution transformer with an impedance of 6.25% is connected to a 400V main switchboard. Determine the appropriate current transformer ratio for the 22kV and 400V circuit breakers.

4. A 1400A air-conditioning switchboard with D.T.L Earth Fault Relay (EFR) connected to 4 nos. of Class 5P5 current transformers, the earth fault relay often trip on starting of the air-conditioning plant.

   (a) Explain briefly the reason of the tripping and how this problem could be resolve.

   (b) Draw wiring diagram of the protection circuit to explain the cause of the problem and the solution.

CHAPTER 10
ELECTRICAL SWITCHBOARD

10.1 INTRODUCTION
- Switchgear and Switchboard

In accordance with IEC 439-1 and Singapore Standard SS482:Part1:2000 for electrical switchboard: -

Switchgear may be defined as 'apparatus for controlling the distribution of electric energy or for controlling or protecting apparatus connected to a supply of electricity'.

And a switchboard as an assembly of such switchgear. It may include devices such as circuit breakers, switches, protective relays, instrumentation, metering, and the equipment for the control of these devices and of any electrical machines and prime movers in the installation.

A typical arrangement of a 400V main switchboard is shown in Figure 10.1.

10.2 LOW VOLTAGE MAIN SWITCHBOARD

The L.V. Main Switchboard is the meeting point of incoming and outgoing feeders. It is an assembly of circuit breakers, busbars, protective relays and instrumentation meters.

(a) Incoming Circuit Breaker

(i) Air Circuit Breaker (ACB) is used normally at switchboard where total load capacity exceeds 800A per phase and at switchboard where high prospective fault current is expected.

For switchboard of lower current capacity, MCCBs (Moulded Case Circuit Breaker) with back-up HRC fuse may be used as main breakers.

(ii) Except in the cases of single-phase intake or the maximum demand is low, it is always advisable to have two incoming cables to improve on both the security and reliability of the supply, as shown in Figure 10.2

The two incoming circuit breakers and the bus-coupler are interlocked so that only two of them can be closed at any one time. Normally the bus coupler is open in order to avoid the flow of circulating current in case the two sources are from parallel network transformers connected directly or indirectly at the primary side.

(iii) Protection Devices

For incoming supply exceeding 300A per phase. External overcurrent relays and earth fault relay are required to be installed with tripping terminals wired to the shunt trip coil of the main circuit breakers.

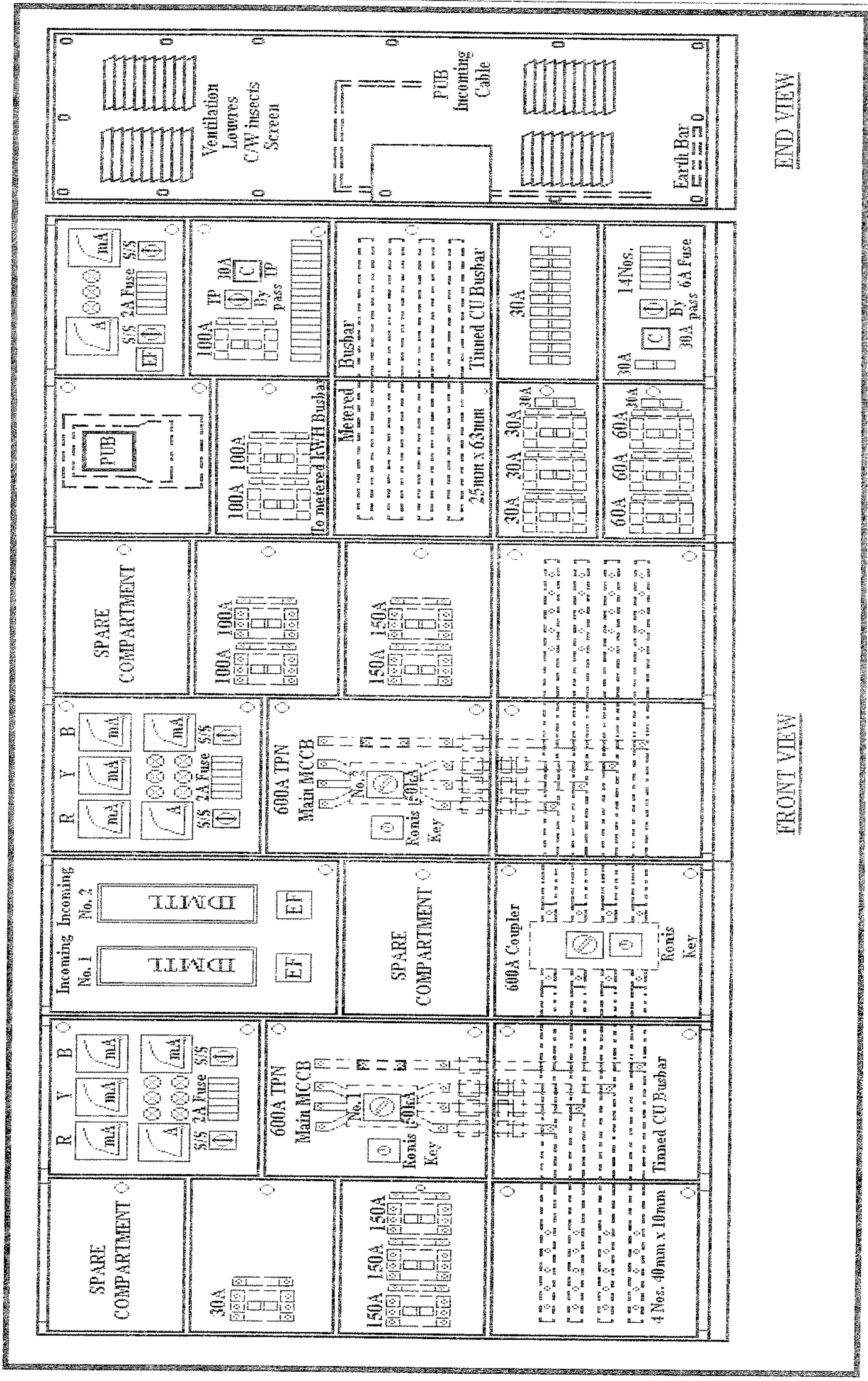


Figure 10. 1   A Typical Arrangement of 400V Main Switchboard

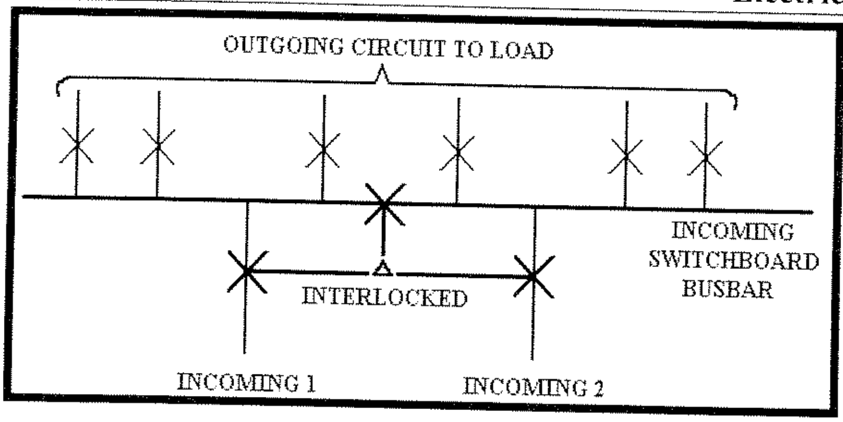


Figure 10. 2 400V Main Switchboard

(b) Incoming Feeders

The electricity supply to the L.V. main switchboard can be taken directly from the supply authority or from the consumer's transformers.

(c) Submains (Outgoing Feeders)

(i) Submains are installed to provide electricity to sub-boards and equipment. They include PVC cables, PVC/PVC cables, MICC cables, Fire-resistant cables, busducts, etc.

(ii) Electricity is also tapped-off at regular intervals to supply distribution boards (DB) for small power and lightings at various floors.

(d) Busbars

(i) A busbar is the conductor constructed in the switchboard for distributing electricity from a supply source to outgoing circuits. It is usually made of copper.

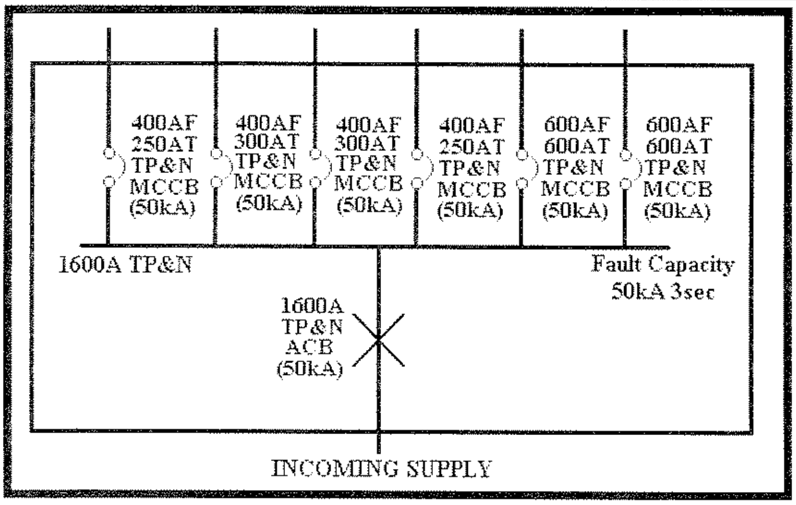
In general, busbars consist of three-phase, four-wire arrangement, i.e. three phases plus neutral, and run throughout the length of the switchboard. For identification, busbar should be marked red, yellow, blue and black for R, Y, B phases and neutral.

(ii) Busbars must be designed to carry rated continuous current. The current capacity of the copper busbar can be estimated by its approximate current density which is approximately 1550A per 1000mm^2.

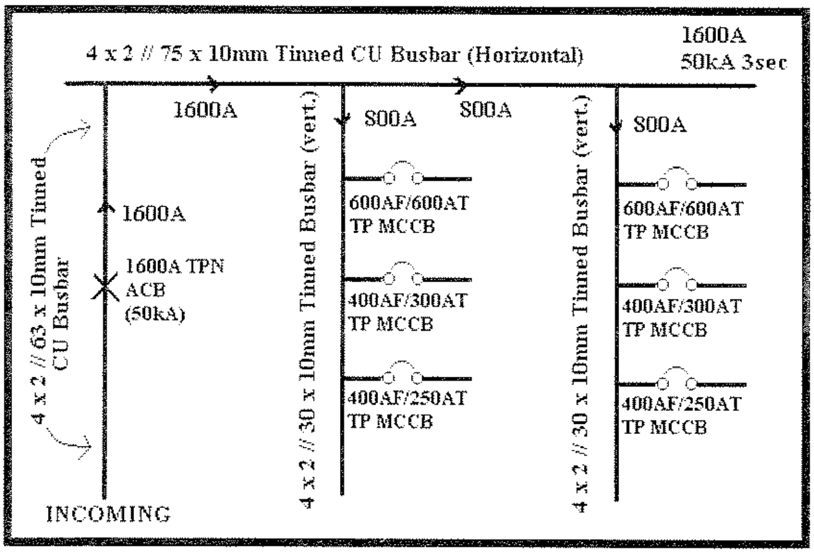
Main busbars and branch busbar of a 3-phase 400V, 1600A switchboard may be designed as shown in Figure 10.3.

10.3 EMERGENCY SWITCHBOARD (ESB)

Essential loads which cannot tolerate interruption of electricity supply shall be connected to "Emergency Switchboards". Such loads include risers / submains for emergency lightings, lifts, sprinkler pumps, etc.



(a) Single line Diagram of a Proposed 1600A L.V. Switchgear Assembly with Incoming ACB and Outgoing MCCB



(b) Physical Arrangement and Design of Main Busbars and Branch Busbars designed for Electrical Installation as shown in Figure (a)

Figure 10. 3 Arrangement of Busbars & Circuit Breakers in a 400A Main Switchboard

The emergency switchboard has two sources of electricity supply:

(a) Normally it receives electricity supply from the main switchboard which takes its supply directly from the power supply company or from the consumer's own transformers.

(b) In the event of power failure, the sensing contacts installed in the normal supply section will initiate the starting of the standby generator. As soon as the generator supply voltage stabilized (i.e. approximately 8 to 10 seconds after the power failure), the motorised circuitries will start and automatically switch the ATS (Automatic Transfer Switch) to the generator supply incoming, the change over time is less than 15 seconds.

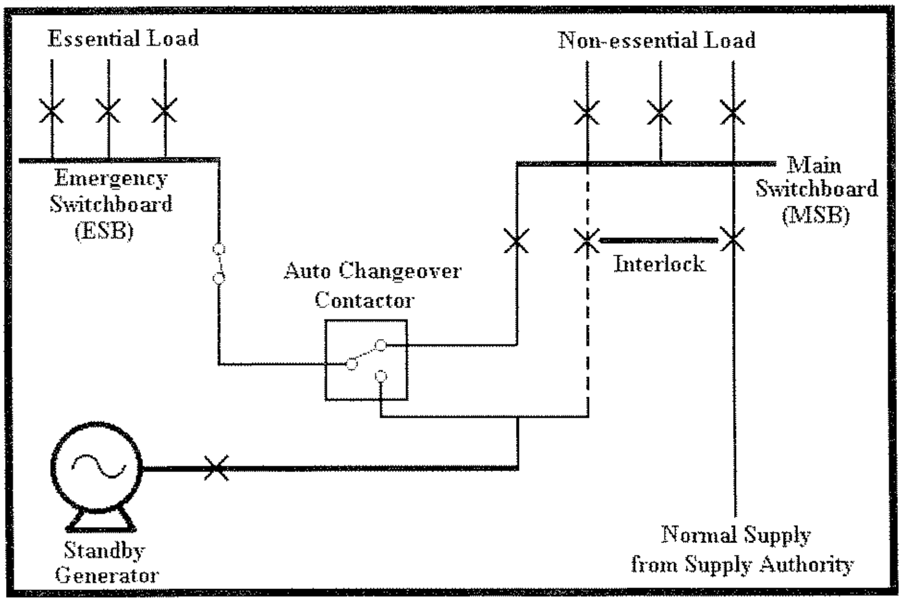


Figure 10. 4 Arrangement of Auto Change-Over from MSB & ESB

10.4 CURRENT TRANSFORMER SELECTION

It is often difficult and expensive to detect or measure very large values of current by placing the coil in series with the circuit. Current transformers (C.T.s) are used instead to isolate the circuit and transform the high primary current to a lower secondary current.

The commonly used C.T. is the ring (or toroidal) type. A round iron core is the electromagnetic material around which the secondary windings are wound. The C.T. is placed around the cable (single core) or busbar, which acts as the primary winding.

Current transformers are selected based on the following parameters:

(a) Rated primary / secondary current: the primary rating is based on the maximum demand expected, while the secondary is usually 1A or 5A maximum output. So a 2000/5A C.T. ratio says that a 2000A current through the busbar or cable will yield an output current of 5A at the secondary.

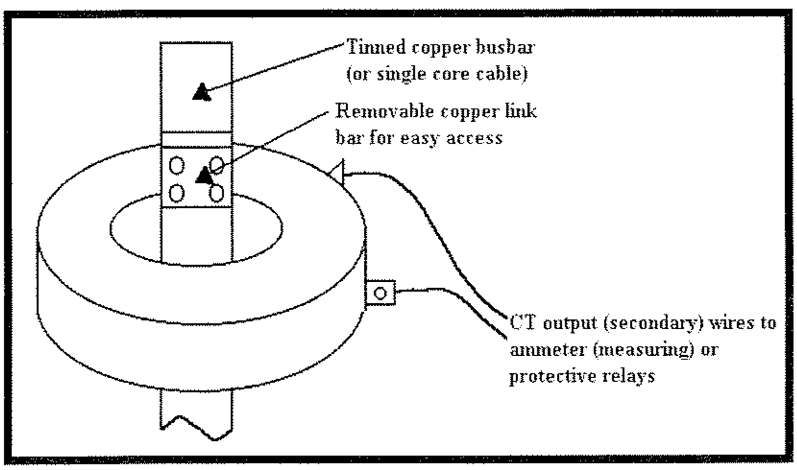


Figure 10. 5

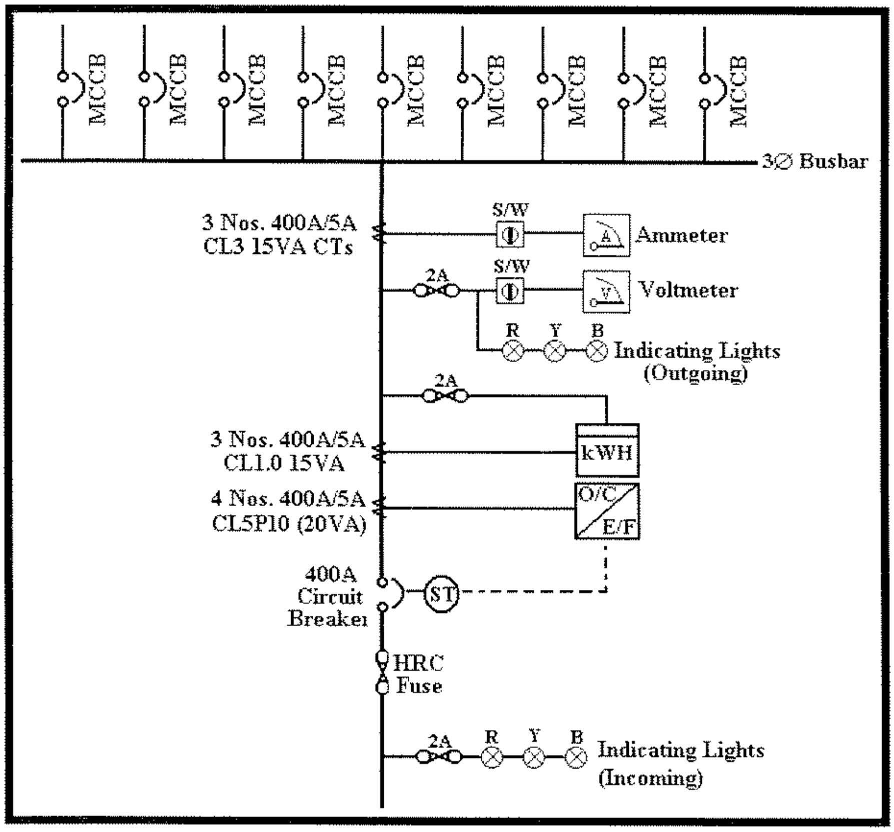


Figure 10. 6 Specifications of measurement & protection current transformers

(b) Burden (in VA): the usual practice is burden of 15VA to 20VA.
(c) Accuracy Class: this differs depending on whether the C.T. is used for measuring (connected to ammeters or Watt-hour meters) or protection (circuit breakers or alarms).

For measuring C.T.s, Class 0.5 or 1.0 is common. It means that the C.T. has a % current ratio error (due to manufacturing tolerances) for currents between 100% to 120% of the rated current.

Protection C.T.s have to be accurate well in excess of the rated current (to account for short circuits). The term 5P10 or 5P20 is common. It says that the C.T. has a composite error of 5% (due to magnetising and winding losses) for currents up to 10 (or 20) times the rated current.

10.5 BUSBARS

The material used for busbars is copper, because of its greater strength, high-conductivity hard-drawn copper is universally preferred to the cold rolled types.

<u>Busbar selection</u>
- Current Carrying Capacity (A.C.)

The current carrying capacity of busbars and connections was based on a rough and ready rule of $1000A/in^2$ or $1.55A/mm^2$ for copper. Tables of current ratings published by the Copper Development Association of its handbook Copper for Busbars, and calculated from formulae derived in tests carried out at the National Physical Laboratory, indicated that approximations of the kind noted were, for small conductors, very pessimistic, i.e. densities well over 1000A/in^2 could be sustained with acceptable rises in temperature, while for larger conductors optimistic ratings were likely.

Conductor Size (mm)	Sectional Area (mm^2)
2.5 x 12.5	31.25
16.0	40.0
20.0	50.0
25.0	62.5
31.5	78.75
40.0	100.0
50.0	125.0
63.0	157.5
4 x 16.0	64
20.0	80
25.0	100
31.5	125
40.0	160
50.0	200
63.0	252
80.0	320
100.0	400
6.3 x 25.0	157.5
31.5	198.45
40.0	252.0
50.0	315.0
63.0	396.9
80.0	504.0
100.0	630.0
125.0	787.5
160.0	1008.0
10 x 50.0	500
63.0	630
80.0	800
100.0	1000
125.0	1250
160.0	1600
200.0	2000
250.0	2500
16 x 100.0	1600
125.0	2000
160.0	2560
200.0	3200
250.0	4000
315.0	5040

Table 10.1. Standard Cross Sectional Area of Single Rectangular Copper Busbar

It was recognised that the factor which controls the current rating is that of a safe temperature, and BS 159 specifies that the temperature rise when carrying rated-normal current at rated frequency shall not exceed 50°C and that this be based on an ambient temperature having a peak value not exceeding 40°C and an average value not exceeding 35°C measured over a 24hr period.

Standard sectional area (mm^2) of rectangular copper busbars are as shown in Table 10.1

The current carrying capacity of busbars is determined by the material's conductivity and the operating temperature. In the air insulated busbar arrangements, heat is dissipated from the bars in varying degrees by:

- Convection;
- Radiation; and
- Conduction.

Because bars are supported on insulating materials, the amount of heat conducted away is small indeed. It is even smaller where bars are 'sleeved' in thick insulation.

Convection and radiation account for dissipation of most of the heat generated. Efficiency of heat transfer to the surrounding air depends very much upon the shape and size of conductors, and the temperature difference between them and the surrounding air. Optimum convection cooling of a rectangular bar is achieved when it is mounted edgewise (i.e. with its major cross-sectional axis vertical). As much as 18% more heat can be dissipated by a bar mounted in this way than when it is mounted horizontally. This equates to a 9% increase in current-carrying capacity.

Conductors comprising multiple laminations will not carry a current equal to that of the rating of the single laminations multiplied by the number of laminations. Thus, for copper, the single bar ratings need to be multiplied by one of the factors given in Table 10.2 to obtain the current rating of a multiple bar arrangement.

Total area of cross-section (mm^2)	**Multiplying factors**		
	2 bars	**3 bars**	**4 bars**
500	1.78	2.45	3.13
1 000	1.72	2.36	3.00
1 500	1.65	2.24	2.84
2 000	1.60	2.16	2.70
2 500	1.55	2.10	2.60
3 000	1.52	2.02	2.52
3 500	1.48	1.98	2.48
4 000	1.44	1.96	2.45

Table 10.2. Multiplying Factors for A.C. Copper Bars

The influence of the skin and proximity effects on A.C. ratings may be illustrated by the fact that the A.C. capacity of a copper four-bar lamination of $2500mm^2$ total cross-sectional area is about 70% of its D.C. rating. Because of the skin effect, the current-carrying capacity of laminated bars is severely limited.

Busbar Joints

The most widely used method of making a joint between unit lengths of busbars or between a conductor and a busbar is that of bolting or clamping two rectangular sections, a method which is simple and flexible and in which the joint can easily be dismantled if required. Other methods include riveting or welding, but with these, the joint has to be regarded as permanent. When rod or tubular bars are used, special fitments will be required.

Whatever method is used, the efficiency of the joint depends on a few essential precautions which are:

(a) The contact pressure must be ample and maintained.

(b) The surfaces of the conductors must be clean.

(c) With flat conductors, the overlap should be equal to or greater than the width of the bars or ten times the bar thickness, whichever is greater.

(d) Joints between aluminum conductors must be treated to exclude moisture.

Busbar Clearances

The recognised minimum clearances to earth and between phases for a variety of conditions are given in Table 10.3. They assume an altitude not exceeding 1000m (3300ft) and should be increased by 3% for each 300m (1000ft) higher than this. Atmospheric pollution by smoke, chemical fumes, salt-laden spray, etc. may require that larger clearances be provided.

Rated voltage up to and including (kV)	**Minimum clearance to earth in air**				**Minimum clearance between phases in air**			
	Open		**Enclosed**		**Open**		**Enclosed**	
	in	mm	In	mm	in	mm	in	mm
0.415	¾	19	⅝	16	1	26	¾	19
0.6	1	26	¾	19	1¼	32	¾	19
3.3	2	51	2	51	2	51	2	51
6.6	2½	64	2½	64	3½	89	3½	89
11.0	3	77	3	77	5	127	5	127
15.0	4	102	4	102	6½	165	6½	165
22.0	5½	140	5½	140	9½	242	9½	242
33.0	8¾	223	8¾	223	14	356	14	356

Notes: (1) Based on Table 3 of BS 159: 1957

(2) Millimetre dimensions rounded up to whole figures

(3) The clearances are for electrically non-exposed installations. For electrically exposed installations, special consideration is required – see Appendix C in BS 158: 1957. When, for special or more onerous conditions of service, Class B clearances are employed on associated circuit – breakers (see BS 116: 1952) then the clearances of bare busbars and connections should be correspondingly increased.

Table 10.3. Clearances for Open and Enclosed Indoor Air-Insulated Busbars and Connections

The busbars with solid insulation shall be capable of withstanding the appropriate power-frequency test voltage as shown in Table 10.4.

Power Frequency Test Voltages at Works	
Rated Voltage (kV)	Test kV RMS
0.6	2
3.3	9.5
6.6	17
11	27
15	36
22	52
33	76
44	100
66	150

Notes: (1) Based on Table 8 of BS 159: 1957
(2) The test voltages are applied between phases and each phase to earth, in turn,with other phases earthed.

Table 10.4. Power Frequency Test Voltages at Works

Creepage distances of Busbar

The minimum creepage distance over insulation which should be provided in indoor types of switchgear cannot be laid down too specifically, because so much depends on the design and the conditions under which it may have to operate. One of the problems to be contended with is that of dust and damp, so that the essential creepage distance will depend on the degree of protection the switchgear provides against this hazard, which is clearly greater in open types and less in enclosed types. The configuration of the insulating parts can have a considerable bearing on the problem, noting also that dust is less likely to collect on vertical surfaces than on those which lie flat. If the dust or dirt is free from carbon or metal and in a dry state, creepage distances can be much less than when moisture is present.

Surface tracking is another problem, and here the degree of resistance to such tracking of the insulating material is important, some having considerably greater anti-tracking properties than others. Surface tracking is also influenced by contamination, and resistance to it in laminated materials is influenced by the direction of the voltage stress.

BS 159 notes these problems and includes guidelines as shown in Table 10.5 purely as a guide to apply only when the insulation is of porcelain or synthetic resin, which is resistant to tracking and adequately protected from dust and damp. Where busbars and other parts can be encapsulated in epoxy resin, some part of the creepage problem is at once resolved.

Short Circuit Effects

The busbars must have the ability to withstand the thermal and mechanical stresses imposed on them by prospective fault currents in the power system. Their momentary and short-time current ratings should correspond to the equivalent ratings of the switching devices connected to them.

Of the several types of fault considered (balanced 3-phase, and unbalanced line-to-line and line-to-earth), we concluded that the 3-phase fault condition generally gives the maximum short-circuit current values, and is therefore the one on which power system fault calculations should be based.

Rated Voltage up to and including (kV)	Minimum creepage distance in air, phase to earth	
	in	mm
0.415	¾	19
0.6	1	26
3.3	2	51
6.6	3½	89
11	5	127
15	6	153
22	8	204
33	12	304

Notes: (1) Based on Table 11 of BS 159: 1957
(2) Millimetre dimensions rounded up to whole figures
(3) Increase by at least 50% when applied to insulation between phases

Table 10.5. Creepage Distances to Earth in air for Open and Enclosed Busbars for Indoor-Type Switchgear

Reverting to the stress-inducing effects that momentary and short-duration fault currents have on busbars, we shall now consider each in turn.

Thermal Stress

This is directly related to the square of the r.m.s. value of the fault current and to its duration (i.e. I_{SC}^2 t). In practical case studies, it is usual to ignore asymmetry in fault currents. The period for which the current flows is determined by the break time of the circuit protective device (breaker or fuse). It is so brief that one must neglect all possibilities of heat dissipation by convection or radiation. The heat generated is, therefore, entirely absorbed by the conductors, and their temperature rise is governed only by their specific heat and weight.

The following formula enables the temperature rise per second to be determined. An intelligent estimate may have to be made of the conductor's temperature at the instant of fault.

$$T = k(I/A)^2[1+\alpha\theta] \times 10^{-2}$$

where T = temperature rise per second (°C)
I = current, r.m.s. symmetrical (amperes)
A = cross-sectional area of conductor (mm^2)
α = temperature coefficient of resistivity at 20°C/°C = 0.00393 for copper
= 0.00386 for aluminium
= 0.0036 for aluminium alloy
θ = temperature of the conductor at the instant at which the temperature rise is being obtained (°C)
k = a constant : 0.52 for copper, 1.166 for aluminium

Final-temperature limits (initial temperature + temperature rise over the duration of the fault current) are a matter of judgement, but the general consensus is 200°C for bare copper and 180°C for bare aluminium.

Conductors will expand or contract with variations in temperature. For example, the expansion of a 6m length of copper conductor on a temperature rise of 100°C under fault conditions, is about 8mm.

The thermal problem is therefore to determine the sectional area of the conductors to carry the calculated fault current for a defined time with a temperature rise which is safe, not only for the conductors themselves, but also for any insulation which may be in contact with or near to the conductors and for sweated joints such as at cable sockets. What a safe temperature limit is must be decided taking into account all factors in a particular design of switchgear and while some designers suggest that a temperature rise of 175/200°C is permissible, others suggest a safer limit is 100°C. This latter figure has merit when it is remembered that the conductor may, prior to the fault, be running at 80-90°C so that the final temperature would be 180-190°C. It may be noted in passing, that solder as used at cable sockets, will tend to soften at 180°C and will run out at higher temperatures.

Electromagnetic stresses

Current-carrying conductors in a magnetic field are subjected to forces which tend to deform the circuit in such a way as to increase the number of magnetic lines of force enclosed. When the currents flowing in two adjacent conductors are in the same direction the force between them is one of attraction (the pinch effect), but when the currents are in opposition, it is repulsive (the loop effect).

This mechanical force depends upon the magnitude of the current and the geometrical configuration of the conductors, i.e. their shape and their relative spacing. In the case of parallel busbars, it is uniformly distributed along their length. At the extreme ends of the bars, the force actually tails off due to the so-called 'end effect'. When the ratio of the length of the bars to their spacing is larger than about 20, this end effect may be ignored. The maximum forces near the middle of the bars are used in design calculations.

It can be shown that, in three-phase busbars, the maximum force is that produced by a two-phase short-circuit (line-to-line); and busbar designs should, therefore, be based on the stresses set up in this condition. In practice, two-phase shorts are more likely to occur than those involving all three phases.

The maximum force on the bars, and their associated structures and insulators, will coincide with the instantaneous maximum peak value of the short-circuit current. It is prudent to cater for worst-case conditions, and assume that the short-circuit current waveform will be completely asymmetrical; so that, with the 'doubling effect' the peak current could be as much as twice the r.m.s. symmetrical value. Due allowance is made for this in the numerical terms of the force equation given below:

$$F_m = \frac{16 \times I^2 \times K \times 10^{-4}}{S} \text{ N/m}$$

where F_m = maximum force under conditions of asymmetry
I = r.m.s. current (amperes)
K = a shape factor for rectangular bars (K=1 for circular conductors)
S = spacing between conductor centres (mm)

The formula shows that increasing the spacing between phases gives reduced electromagnetic forces which, while desirable, can only be obtained at the cost of larger busbar enclosures.

10.6 ENCLOSURES

Indoor L.V. and H.V. switchgear are mounted in metal enclosures. The form of construction falls within one of two classifications: the cubical type, and the metal clad type.

Cubicle Type

In cubical type of switchboard, circuit breakers and auxiliaries are mounted in sheet steel cubicles, which are extendable on either side and are bolted together to form composite switchboards. The jig-built, rigid framework of each cubicle usually consists of standardized bolted members. Removable side cladding panels allow for future extensions. Front and rear access is provided by combinations of interlocked doors and removable panels. The circuit breakers may be of the fixed or drawout type. Main busbars are run in chambers above the vertical risers and adjacent sections are connected by links for extensions. Sealed inter-cubicle barriers may be fitted to contain any arcing products to individual cubicles.

Metal Clad Type

Metal clad switchboards are built in self-contained cubicle form. Several cubicles may then be placed side by side to build up large installations. By definition, this type of equipment must incorporate circuit breakers of the horizontal or vertical withdrawable pattern. They must be compartmented so that each is completely separated from other apparatus. Safety shutters that close automatically when the breaker is withdrawn must be provided. All live parts should be enclosed in earthed, metal-encased compartments. These would include busbars, current and voltage transformers, control power transformers and cable terminations. Circuit instruments, protective relays and control switches may either be mounted on hinged front panels/doors or in separate chambers.

Protection Degree of Enclosure

- Index of Protection

Enclosures should be designed to give protection against contact with the live and moving parts housed within them, and to protect internal devices against specified external conditions. The degree of protection provided is classified by BS 5420 (IEC 144). Enclosures are designated by a symbol consisting of the code letters IP, followed by two reference numbers which define the degree of protection. Additional letters may be used, after the code letters or after the reference numbers, to qualify methods of test, etc. The first numeral of the code (0 to 6) defines the protection against accidental contact and the protection of internal equipment against the ingress of solid foreign bodies. The second numeral defines the protection against the harmful ingress of moisture.

Most indoor equipment will be designed to comply with IP 31, where protection is provided against:

- The ingress of solid foreign bodies having a diameter in excess of 2.5mm
- Contact by the fingers with live or moving internal components (numeral 3)
- Water droplets falling vertically (numeral 1)

In the indoor context, the highest classification that is likely to be required is that corresponding with IP 55. This gives complete protection against:

- Live or moving internal parts
- Harmful deposits of dust (ingress of dust is not totally prevented, but such quantities that do penetrate will not interfere with the satisfactory operation of the enclosed equipment)
- Water projected by jets from any direction under stated conditions

Figure 10.7 (a) and (b) show the charts for IP Code explaining the meaning of IP Index number:

10.7 SEGREGATION AND COMPARTMENTATION

Electrical fault in one section of the switchboard produces a high degree of ionized gas during arcing and it encourages the striking of arcs in other regions. Segregation by barrier between compartments or between one circuit and the next is essential if the fault on one circuit is to be restrained from developing on other healthy circuits.

Power supply company requires that all consumers' main switchboard be compartmentalised so that the main circuit breakers, outgoing circuit breakers, cable/wirings/meters of instrumentations and metering panels are segregated for protection.

Singapore Standard SS 482:Part 1:2000, IEC Standard 439-1 and British Standard BS EN 60 439-1:1990 addresses the specification for L.V. switchgear and controlgear assemblies. Its requirements include constructional considerations and allow for four distinct forms of physical separation of circuits.

The degree of segregation of functional equipment (from one another and from the busbars) may be pre-planned to satisfy one of the following requirements:

(a) No separation between circuits
(b) Functional units separated from the busbars
(c) Functional units separated from busbars and from one another (outgoing terminals and busbars may be in a common chamber)
(d) Functional units, including outgoing terminals, separated from the busbars and from one another (when combined with segregating barriers between the main horizontal busbars and vertical risers increased busbar security is obtained).

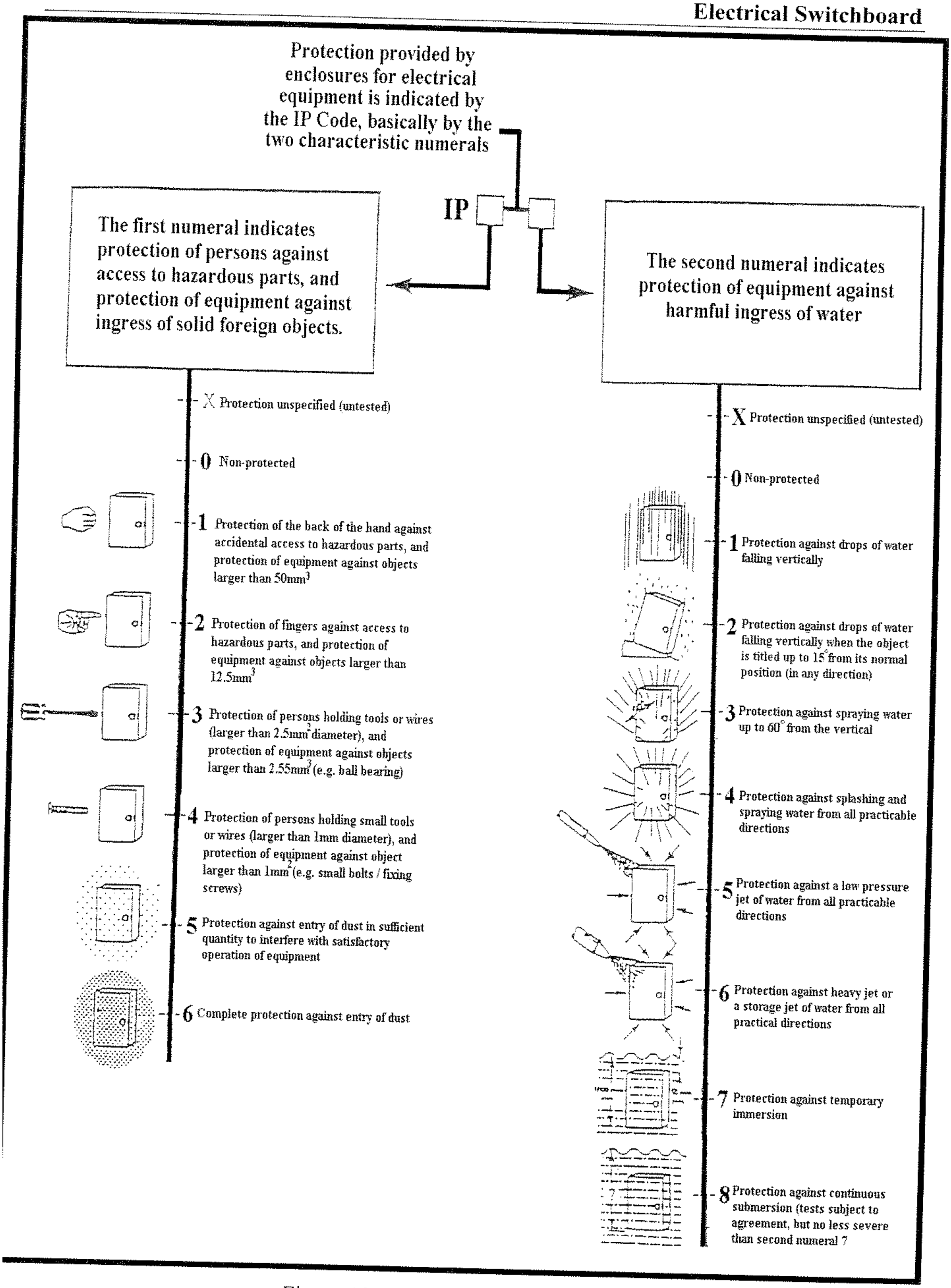


Figure 10. 7 (a) IP Code Chart

Protection Degrees of Enclosures

IP □ □ □

	Protection against solid objects
0	no protection
1	protected against solid objects up to 50mm e.g. accidental touch by hands
2	protected against solid objects up to 12mm e.g. fingers
3	protected against solid objects over 2.5mm (tools + wires)
4	protected against solid objects over 1mm (tools + wires + small wires)
5	protected against dust (no harmful deposing)
6	total protected against dust

	Protection against liquid
0	no protection
1	protected against vertically falling drops of water (e.g. condesation)
2	protection against direct sprays of water up to 15° from the vertical
3	protected against sprays up to 60 from the vertical
4	protected against water sprayed from all directions
5	protected against low pressure jets of water from all directions
6	protected against strong jets of water (e.g. for use on shipdecks)
7	protected against the effects of immersion between 15cm and 1m
8	protected against long periods og immersion under pressure

0	no protection
1	impact 0.225 joules
2	impact 0.375 joules
3	impact 0.500 joules
5	impact 2 joules
7	impact 6 joules
9	impact 20 joules

Figure 10.7 (b) IP Code Chart

Depending on the circumstances all 4 forms of assembly may be employed. Very careful consideration is essential to establish the methods of operation and of maintenance of the equipment with particular regard to personnel who will be required to do such work. Form 4 offers the highest level of safety and will usually be used where it is necessary for access to be gained without the need to isolate the whole assembly.

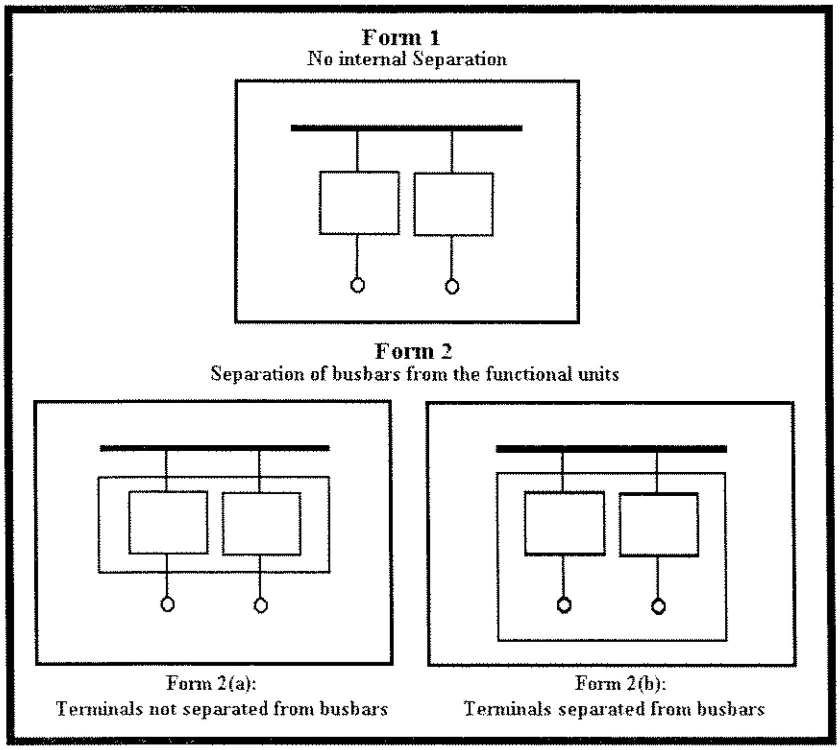


Figure 10. 8 Forms 1 and 2 of Compartmentation as specified in SS482:Part1:2000

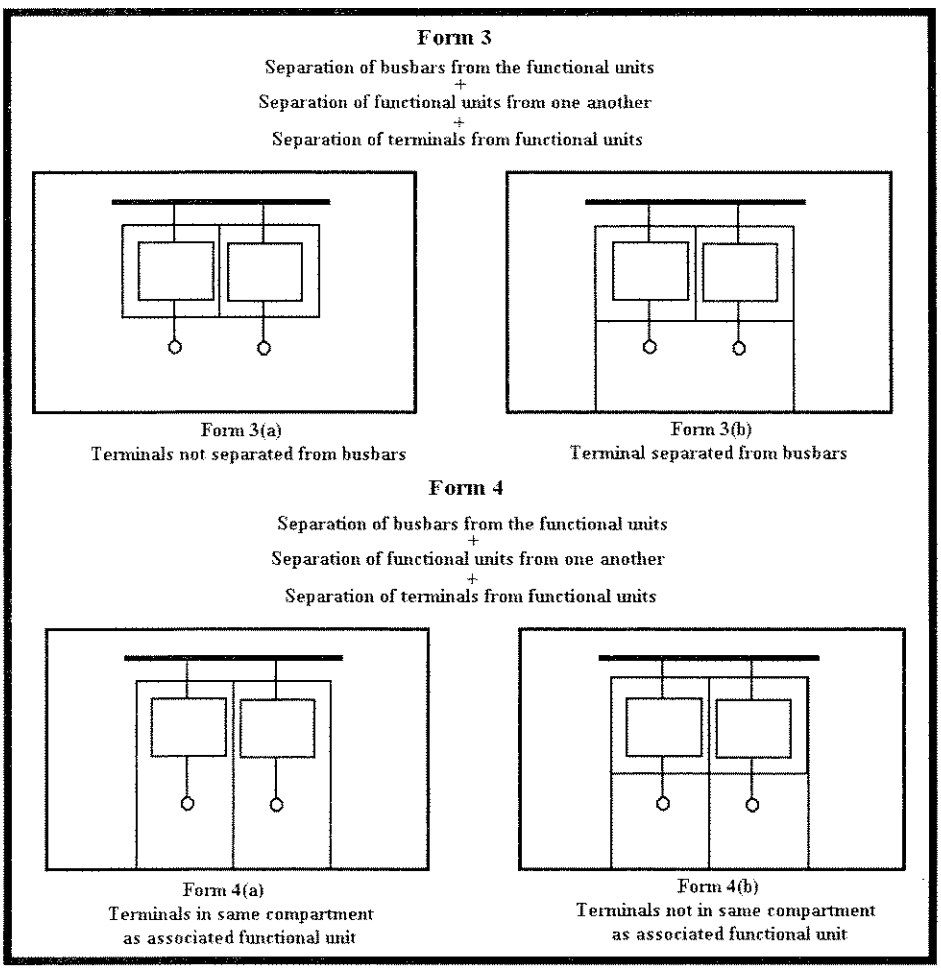


Figure 10. 9 Forms 3 and 4 of Compartmentation as specified in SS482:Part 1:2000

10.8 CERTIFICATION OF SWITCHGEAR AND EQUIPMENT

User specifications may contain a clause such as:

All switchboards are to be designed to meet BS EN 60439-1: 1990 and equipment shall be of a type that has been tested at these ratings and classification, and covered by a certificate issued by a member of ASTA, KEMA or similar.

ASTA is the Association of Short-circuit Testing Authorities (Inc.). Formed in 1938, it has among its objectives:

- The co-ordination of the type testing of electrical power transmission and distribution equipment, and
- The issuing of certificates based on the satisfactory performance of type tests under the direction of independent ASTA observers.

Type-Tested Switchgears:

(a) Switchgears and switchboards are usually not accepted by the end users until its prototype has passed a series of "type tests" designed to simulate the different kinds of severe stresses normally encountered in a power system.

(b) There are a few testing laboratories which perform these stringent tests as a third party to the manufacturer and buyer. For example,
   - KEMA - Holland
   - ASTA - UK
   - PHELA - Germany
   - CSEI - Italy
   - ESEF - France

(c) A test certificate is issued for switchgears which successfully meet the conditions of the complete range of type tests stipulated under a national or international standard/recommendation (e.g. BSI/IEC).

(d) A list of verifications and tests to be performed in type test is specified in Table 7 of Singapore Standard SS482:Part 1:2000 for electrical switchboards.

10.9 MAIN EARTH BAR

The cross-sectional area of the Main Earth Bar of the switchboard is calculated from the formula:

$$k^2S > I^2t \qquad \text{OR} \qquad S > I\sqrt{t} / k$$

where S = C.S.A. in mm^2
I = r.m.s. value of A.C. fault current
t = operating time of the disconnecting device, in seconds
k = Thermal constant for material of conductor

The method for calculation and appropriate k values can be obtained from Annex B of Singapore Standard SS 482:Part 1:2000 for switchboard.

Example 10.2:

With a short time withstand current of 50kA for 3 seconds and k=176 for bare copper conductor the calculated size is 492 mm^2. A copper bare of 50mm x 10mm is selected and installed at the bottom part of the cubicle for bonding to every sections of the cubicles, connection of incoming and outgoing protective conductors.

$$S > \frac{50 \times 10^3 \times \sqrt{3}}{176} = 492 \text{ mm}^2$$

Therefore, 50mm x 10mm bare copper bar is selected.

1. Explain briefly the requirements of Singapore Standard SS 482:Part 1:2000 on the following items: -

   (a) Segregation and Compartmentation
   (b) Enclosure protection (IP No.)

2. Explain briefly the function of the following items which can be found on the main electrical switchboard: -

   (a) Incoming indicator lights (R, Y & B)
   (b) Outgoing indicator lights (R, Y & B)
   (c) Main busbars for phase and neutral conductor
   (d) Main Earth Bar
   (e) Maximum Demand Ammeter
   (f) Voltage Meter and Ammeter
   (g) Overcurrent Relays and Earth Fault Relays
   (h) Shunt Trip Circuit
   (i) Current Transformers for metering and protection

   Draw a Single Line Diagram and Wiring Diagram to show all the necessary components of a 1000A MSB.

3. For a main switchboard connected to incoming cable 8 x 500mm^2 XLPE/SC from a 1000kVA (or 1MVA) DY11 22kV/400V distribution transformer with percentage impedance Z_T = 4.5%. Determine: -

   (a) The designed capacity of the MSB and the main breaker (ACB)
   (b) The fault level and prospective 3-phase short circuit current at the 400V MSB. (Ignore upstream H.V. source) impedance and the short circuit breaking capacity of the ACB.
   (c) The appropriate C.T. Ratio for protection and metering
   (d) The appropriate cross-sectional area of main busbar for phase and neutral conductor
   (e) The appropriate cross-sectional area of main earth bar of the MSB

4. For a main switchboard connected to incoming cable 12 x 630mm2 XLPE/SC from a 2000kVA (or 2MVA) DY11 22kV/400V distribution transformer with percentage impedance Z_T = 6.25%. Determine: -

   (a) The designed capacity of the MSB and the main breaker (ACB)
   (b) The fault level and prospective 3-phase short circuit current at the 400V MSB. (Ignore upstream H.V. source) impedance and the short circuit breaking capacity of the ACB.
   (c) The appropriate C.T. Ratio for protection and metering
   (d) The appropriate cross-sectional area of main busbar for phase and neutral conductor
   (e) The appropriate cross-sectional area of main earth bar of the MSB

CHAPTER 11
EARTHING

11.1 EARTHING FOR ELECTRICAL SYSTEM

Earthing for electrical system is essentially required by Singapore Standards CP5: 1998 and CP16: 1991 to ensure electrical safety against the risk of electric shock by "direct contact" and "indirect contact". Clause 130-04-01 of CP5: 1998 specifically required the metal work of electrical equipment, other than the current carrying conductors, to be connected with earth in a manner as will cause discharge of electrical energy without danger, and protection against the persistence of an earth fault current by residual current devices (such as residual current circuit breaker, earth leakage relay and earth fault relay).

Installation Earthing

The earthing for electrical installations and electrical equipment are to meet the following objectives:

(a) To maintain, as close as possible, the voltage on the exposed-conductive parts (or metal enclosures) of electrical equipment and electrical appliances at 'Earth potential' so as to provide protection against electric shock.

(b) To enable the phase to earth fault current to flow and return safely to its source via a properly designed low impedance path, so that the protection devices can operate expeditiously for automatic disconnection to cut-off the electricity supply.

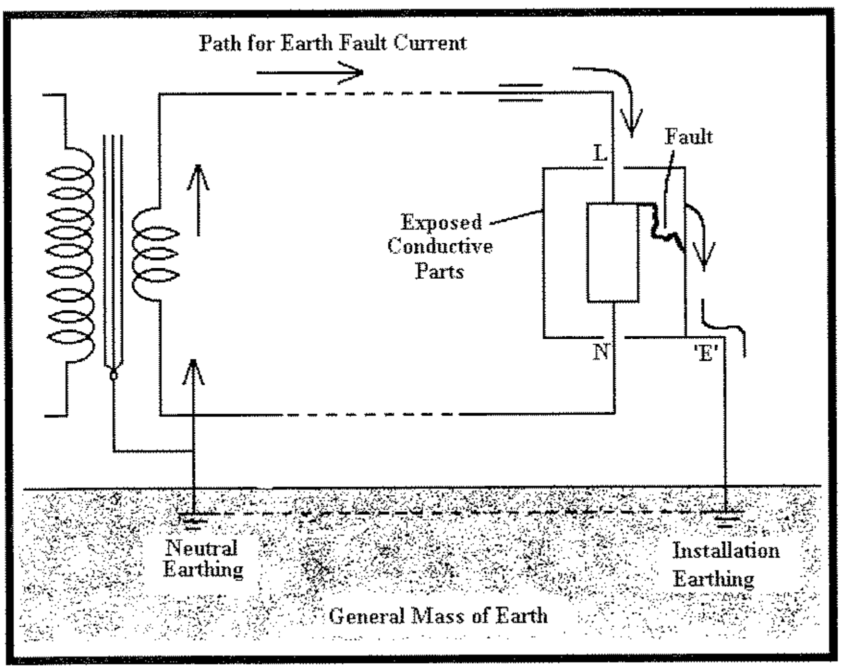


Figure 11.1

Neutral Earthing

The earthing for the star point (or Neutral point) of the star windings of a H.V./L.V. distribution transformer (DY11) are to meet the following objectives:

(a) To maintain, as close as possible, the voltage on the neutral point and neutral conductors of the electrical installation at 'Earth potential'

(b) To enable the safe return of phase to earth fault current to the star point (or Neutral point) of the star windings of the distribution transformer.

11.2 TT EARTHING SYSTEM & TN-S EARTHING SYSTEM

In Singapore and Malaysia, two types of electrical earthing systems are permitted; these are the TT earthing system and TN-S earthing system.

TT EARTHING SYSTEM

(a) TT earthing system is used when consumers receive electricity supply at 400V/230V.

(b) As the distribution transformer is installed on the power supply company side, Neutral earthing electrode system is installed at the power supply company's substation.

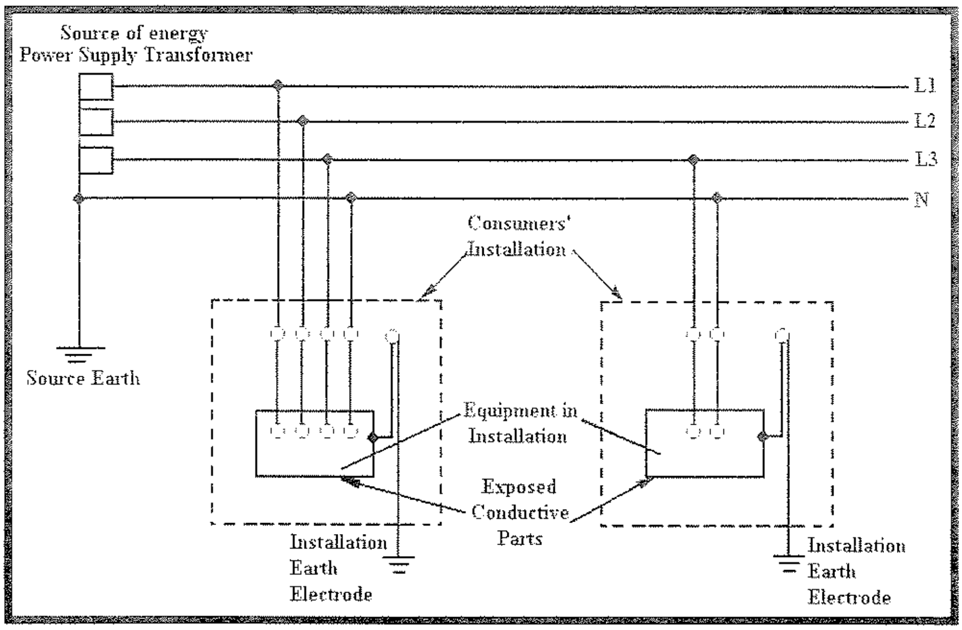


Figure 11. 2 TT Earthing System

All exposed-conductive-parts of an installation are connected to an earth electrode which is electrically independent of the source earth.

Definition for the Designation 'TT'

The first letter denotes the earthing arrangement at the source of energy, and
T = Direct connection of one or more points to Earth

The second letter denotes the relationship of the exposed conductive parts of the installation to earth, and

T = Direct electrical connection of the exposed conductive parts to Earth, independently of the earthing of any point of the source of energy.

(c) Earth fault loop impedance of TT earthing system as shown in Figure 11.3 is given as

$$\mathbf{Z_{ELFI} = Z_T + Z_P + Z_E + (R_B + R_A) + Z_{N/E}}$$
$$\mathbf{\approx (R_A + R_B)}$$

where Z_T = Transformer winding impedance
Z_P = Phase conductor's impedance
Z_E = Earth conductor's impedance
$Z_{N/E}$ = Neutral to Earth conductor impedance
R_A = Installation earth electrode resistance
R_B = Neutral earth electrode resistance

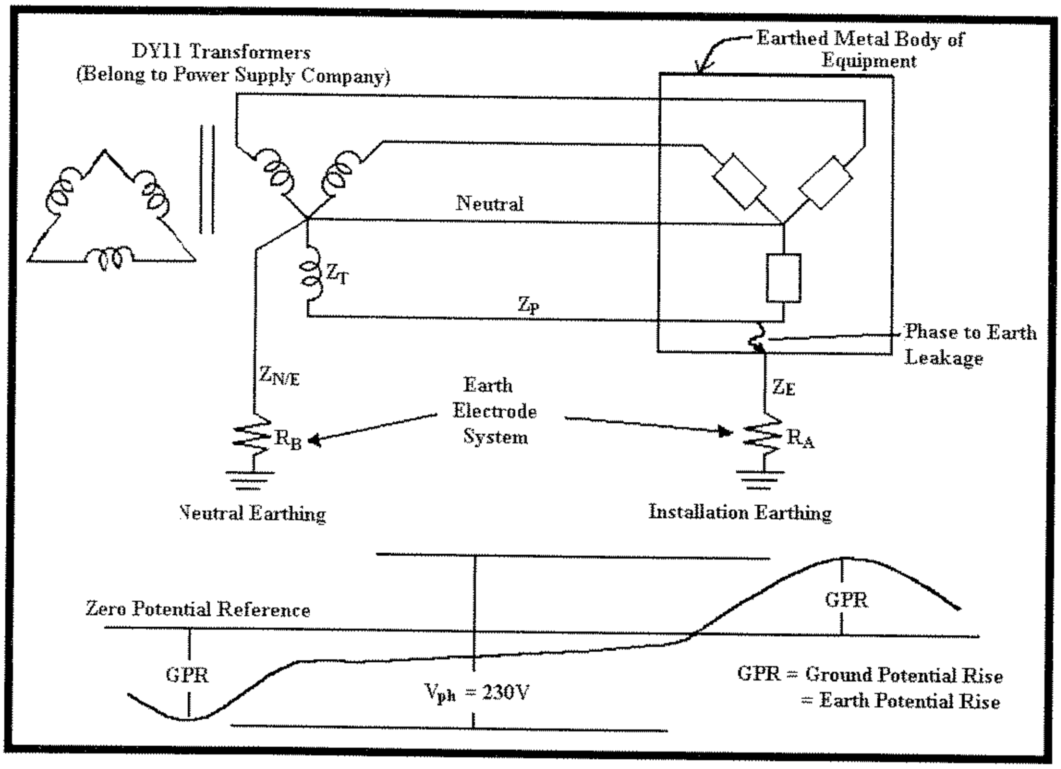


Figure 11. 3 TT Earthing System

Note:

Earth Fault Loop Impedance is defined as the total impedance in the path of the phase to earth fault current

$$\text{Therefore, } I_{E/F} = \frac{V_{ph}}{Z_{EFLI}}$$
$$= \frac{V_{ph}}{Z_T + Z_P + Z_E + (R_A + R_B) + Z_{N/E}}$$
$$\approx \frac{V_{ph}}{R_A + R_B}$$

$$I_{E/F} = \frac{230V}{R_A + R_B} = \frac{230V}{1\Omega + 1\Omega} = 115A \text{ to } 120A$$

if $R_A = R_B = 1\Omega$

&

$$I_{E/F} = \frac{230V}{R_A + R_B} = \frac{230V}{0.1\Omega + 0.1\Omega} = 1150A \text{ to } 1200A$$

if $R_A = R_B = 0.1\Omega$

As the phase to earth fault current has to pass through the two electrode systems in TT system, the Earth fault current $I_{E/F}$ is limited by R_A & R_B.

(d) As a result of the flow of earth leakage current and earth fault current to the electrode system, there would be an earth potential rise may be as high as 120V:

$$I_{E/F} \times R_A = 120A \times 1\Omega = 120V$$

TN-S EARTHING SYSTEM

(a) TN-S earthing system is used when the consumers receive electricity supply at high voltage (22kV or 6.6kV supply in Singapore and 11kV supply in Malaysia).

(b) As the distribution transformers are installed on the consumer side, system neutral earthing and installation earthing (i.e. safety earthing for consumer's electrical equipment) share the same electrode system.

The protective conductor (PE) is the metallic covering of the cable supplying the installations or a separate earth conductor.

All exposed-conductive-parts of an installation are connected to this protective conductor via the main earthing terminal of the installation.

Definition for the Designation 'TN- S'

The first letter denotes the earthing arrangement at the source of energy, and
T = Direct connection of one or more points to Earth

The second letter denotes the relationship of the exposed conductive parts of the installation to earth, and

N = Direct electrical connection of the exposed conductive parts to the Earth point of the source of energy, which, is usually the Neutral point.

The third letter 'S' denotes the separate conductors being used for Neutral and Earth.

S = Separate conductors for Neutral & Earth

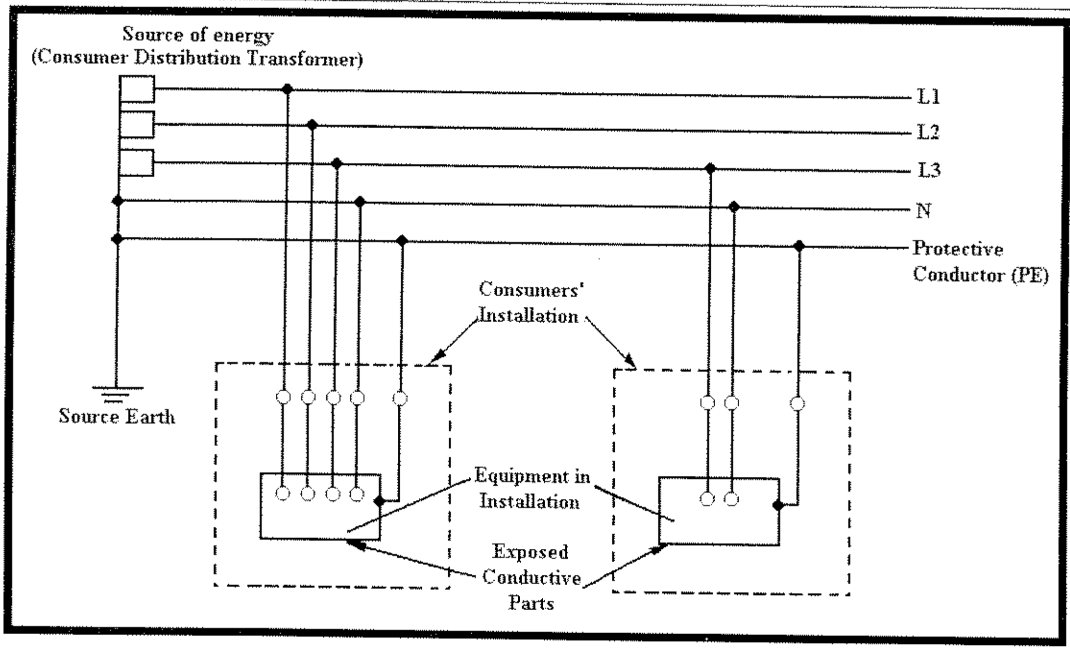


Figure 11. 4 TN-S System

(c) Earth Fault Loop Impedance of TN-S earthing system does not include any of the earth electrode system;

$$Z_{EFLI} = Z_T + Z_P + Z_E + Z_{N/E}$$

where Z_T = Transformer winding impedance
Z_P = Phase conductor's impedance
Z_E = Earth conductor's impedance
$Z_{N/E}$ = Neutral to Earth conductor impedance

Note that earth electrode resistance R_B for neutral earthing is not included in the Z_{EFLI} formula.

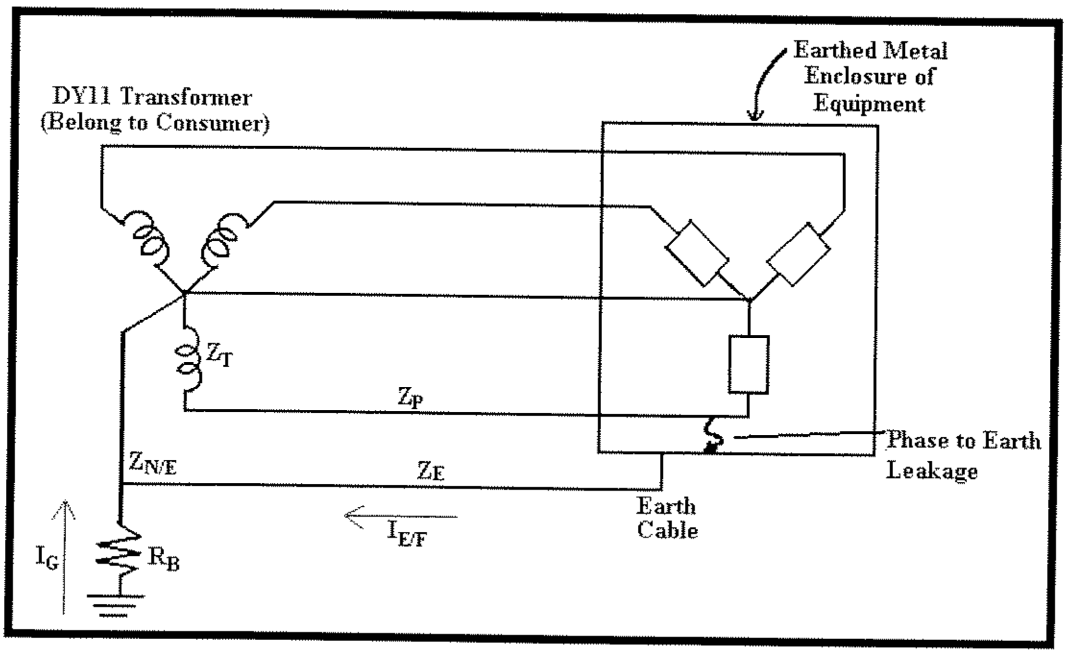


Figure 11. 5 TN-S Earthing System

Therefore Phase to Earth Fault current.

$$I_{E/F} = \frac{V_{ph}}{Z_{EFLI}} = \left(\frac{V_{ph}}{Z_T + Z_P + Z_E + Z_{N\,E}}\right)$$

Ground Potential rise or Earth potential rise at earth electrode terminal = I_g x R_B = 0Volts

Ground potential rise or Earth potential rise at metal enclosure = $I_{E\,F}$ x Z_E

11.3 TOUCH VOLTAGE CONCEPT

(a) Two forms of electric shocks are recognised:

(i) Direct Contact
(ii) Indirect Contact

(b) The touch voltage concept is concerned with "Indirect Contact". It is used to determine the magnitude of voltage to which the person at risk would be subjected to in the event of an earth fault occurring in an installation.

(c) One often hears or reads the statement that provided an item of electrical equipment (intended to be earthed) is properly earthed, it is not possible for a person to receive an electric shock in the event of a fault.

The touch voltage concept shows that such a statement to be totally incorrect.

(d) The connection of all exposed conductive parts to Earth terminal of the installation leads to the creation of 'touch voltage' in the event of an earth fault and hence, to the shock risk.

(e) The protective measure is automatic disconnection of supply. In the event of an earth fault, the speed of disconnection should be such that if the person at risk experiences an electric shock, it will not be a harmful one.

Comparison of Touch Voltage – TT & TN-S System

Example 11.1
TT Earthing System

Earth Fault Loop Impedance is

$$Z_S = Z_T + Z_P + Z_E + (R_A + R_B) + Z_{N\,E}$$
$$\approx (R_A + R_B) \approx (1+1)\ \Omega$$

Therefore $I_{E\,F} = \dfrac{230}{(1+1)\Omega} \approx 120A$

Therefore Touch Voltage = $I_{E\,F}$ x $(Z_E + R_B) \approx 120A \times 1\Omega$
= 120V

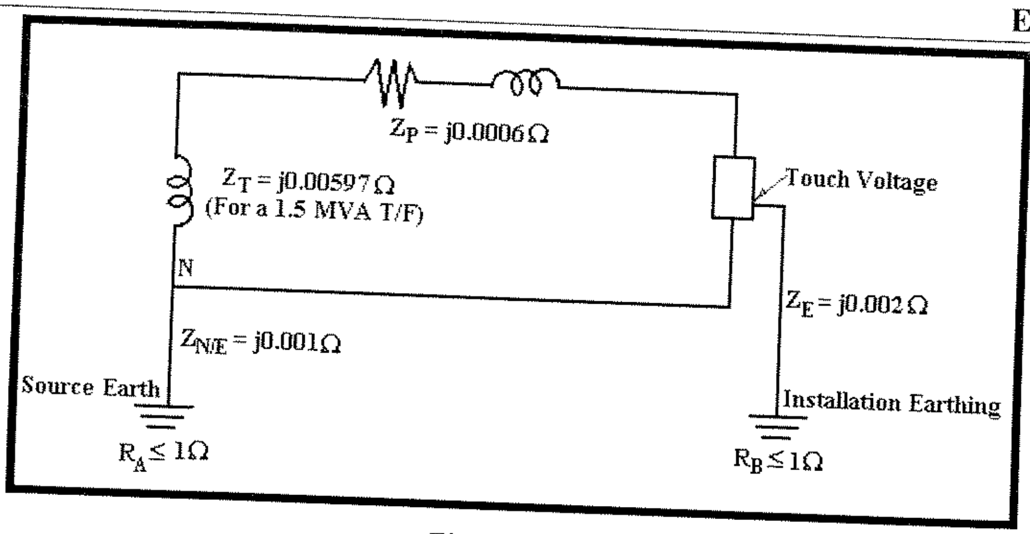


Figure 11. 6

<u>Example11.2</u>
TN-S Earthing System

Earth Fault Loop Impedance is

$$Z_S = Z_T + Z_P + Z_E + Z_{N/E}$$
$$= j\,(0.00597 + 0.0006 + 0.002 + 0.001) = j\,0.00957$$

$$\text{Therefore } I_{E/F} = \frac{230V}{0.00957} = 24033A$$

$$\text{Touch voltage} = I_{E/F} \times (Z_E) = 24033A \times 0.002\Omega = 48V$$

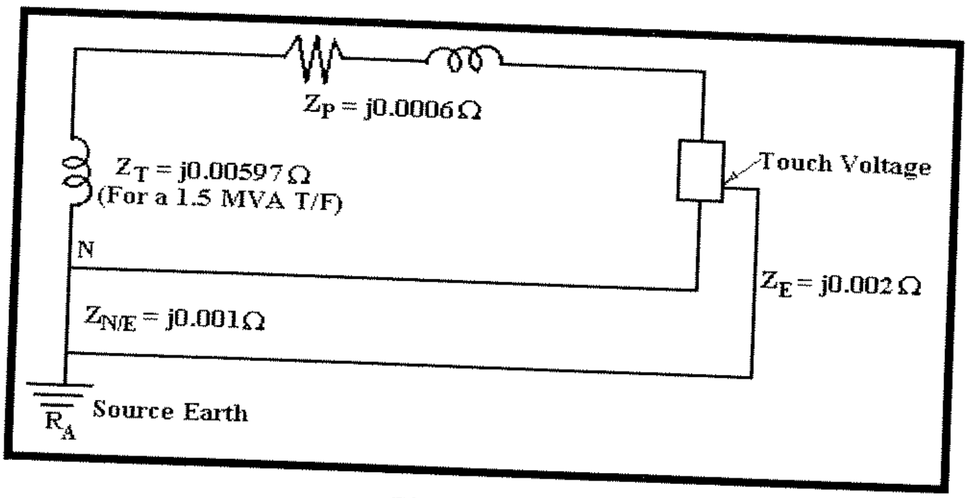


Figure 11. 7

11.4 INSTALLATION EARTHING

A typical earthing arrangement of an electrical installation is shown in Figure 11.8.

<u>Note:</u>

(a) Cross-sectional area of equipotential bonding cable shall not be less than half of the main Earth cable size.

(b) Cross-sectional area of earthing cable for cable tray and cable trunking shall not be less than the biggest CPC or earth cable within the cable tray and cable trunking.

Definitions:

(a) **Exposed Conductive Part**

Exposed Conductive Part is defined as a conductive part of electrical equipment which can be touched and which is not a 'Live' part but which may become live under fault conditions.

Exposed conductive parts of electrical installation essentially include:

(i) Metallic Enclosure of electrical equipment & electrical appliances
(ii) Metallic Enclosure of electrical Switchboard (MSB & SB) & Distribution Boards (DB)
(iii) Metallic cable tray & cable trunking
  - connection of cable tray & cable trunking are considered as earthing for electrical safety and not bonding.

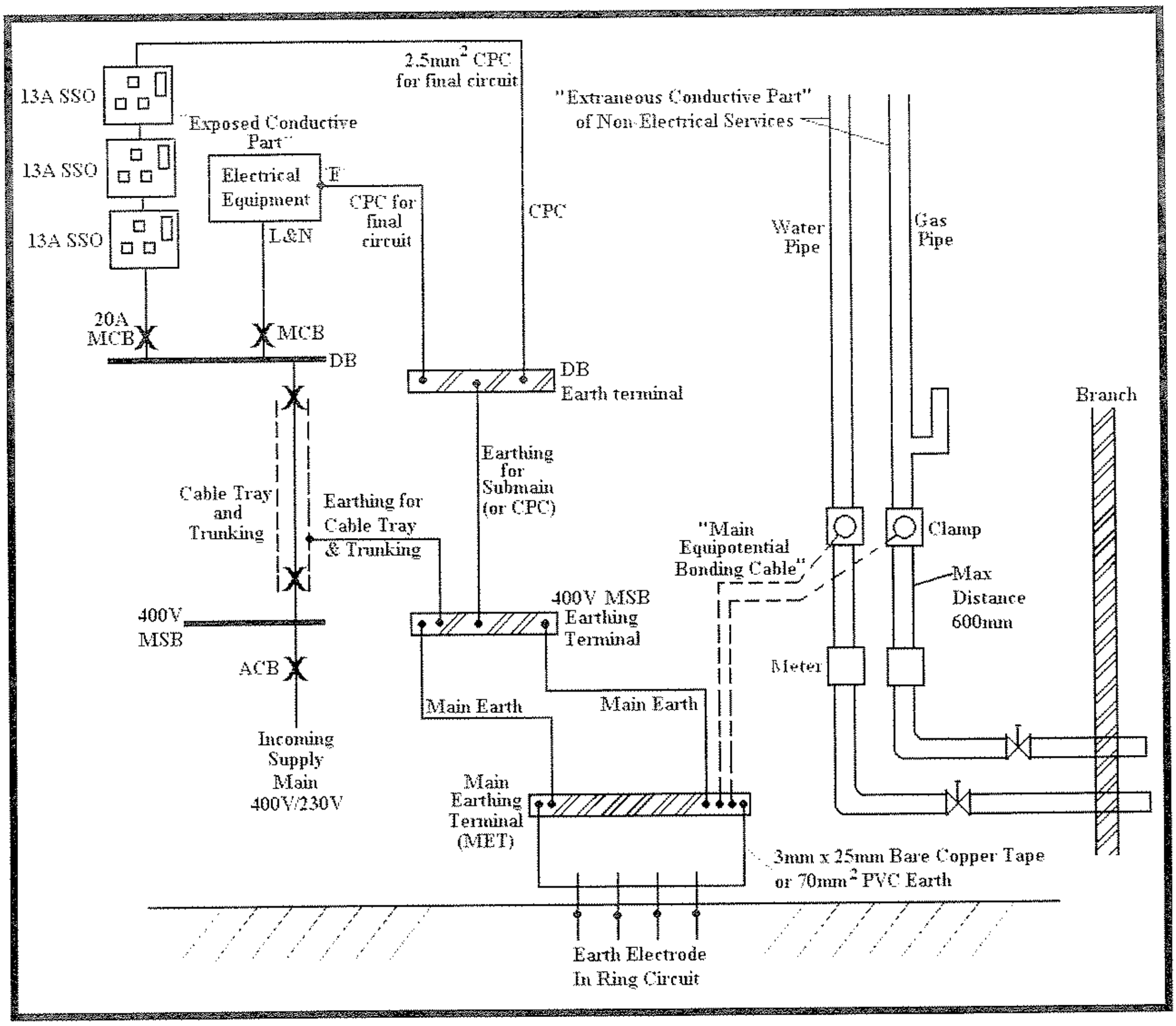


Figure 11. 8 Typical Earthing arrangement for TT System

(b) Extraneous Conductive Part

Extraneous conductive part is defined as a conductive part of non-electrical services which does not form part of the electrical installation, but is likely to introduce an earth potential.

Extraneous Conductive Parts in the buildings include non electrical services such as:

(i) Water pipes & gas pipes
(ii) Air-conditioning ducting
(iii) Fire protection, wet risers and sprinkler pipings

As these extraneous conductive parts form a separate earthing system in the building and introduce an earth potential, it is possible that a person could simultaneously touch the exposed conductive part (e.g. metal enclosure of electrical equipment) and the extraneous conductive part (e.g. the water pipe and gas pipe), which may introduce a potential difference especially when the electrical equipment develops a fault and becomes 'live' or partially 'live'.

(c) Main Equipotential Bonding Conductor

To eliminate or minimise the potential difference that may exist between exposed conductive part and extraneous conductive part. A bonding conductor is used to connect the extraneous conductive part such as a water pipe & gas pipe to the Main Earthing Terminals (MET) of the electrical system to create an equipotential zone. This is known as main equipotential bonding as shown in Figure 11.9.

Note: Clause 547-02-01L of SS CP5: 1998

- The main equipotential bonding conductor shall have a cross sectional area not less than half the cross sectional area required for the earthing conductor of the installation.

(d) Circuit Protective Conductors (CPC)

Circuit protective conductor (CPC) is defined as a protective conductor connecting exposed-conductive-parts of electrical equipment to the main earthing terminal.

Size of earth cable on circuit protective conductors (S mm^2) may be determined by the formula given in Clause 543-01-03 of SS CP5: 1998

$$K^2S^2 \geq I_{E/F}^{\ 2}\, t \quad \text{or} \quad S = (I_{E/F}\sqrt{t}) / K$$

where: S is the nominal cross-sectional area of the conductor in mm^2.

$I_{E/F}$ is the value in amperes (r.m.s. for a.c.) of fault current for a fault of negligible impedance, which can flow through the associated protective device, due account being taken of the current limiting effect of the circuit impedances and the limiting capability (I^2t) of that protective device. Account shall be taken of the effect, on the resistance of circuit conductors, of their temperature rise as a result of overcurrent – see Clause 413-02-05 of SS CP5:1998.

t is the operating time of the disconnecting device in seconds corresponding to the fault current / amperes.

k is a factor taking account of the resistivity, temperature coefficient and heat capacity of the conductor material, and the appropriate initial and final temperatures.

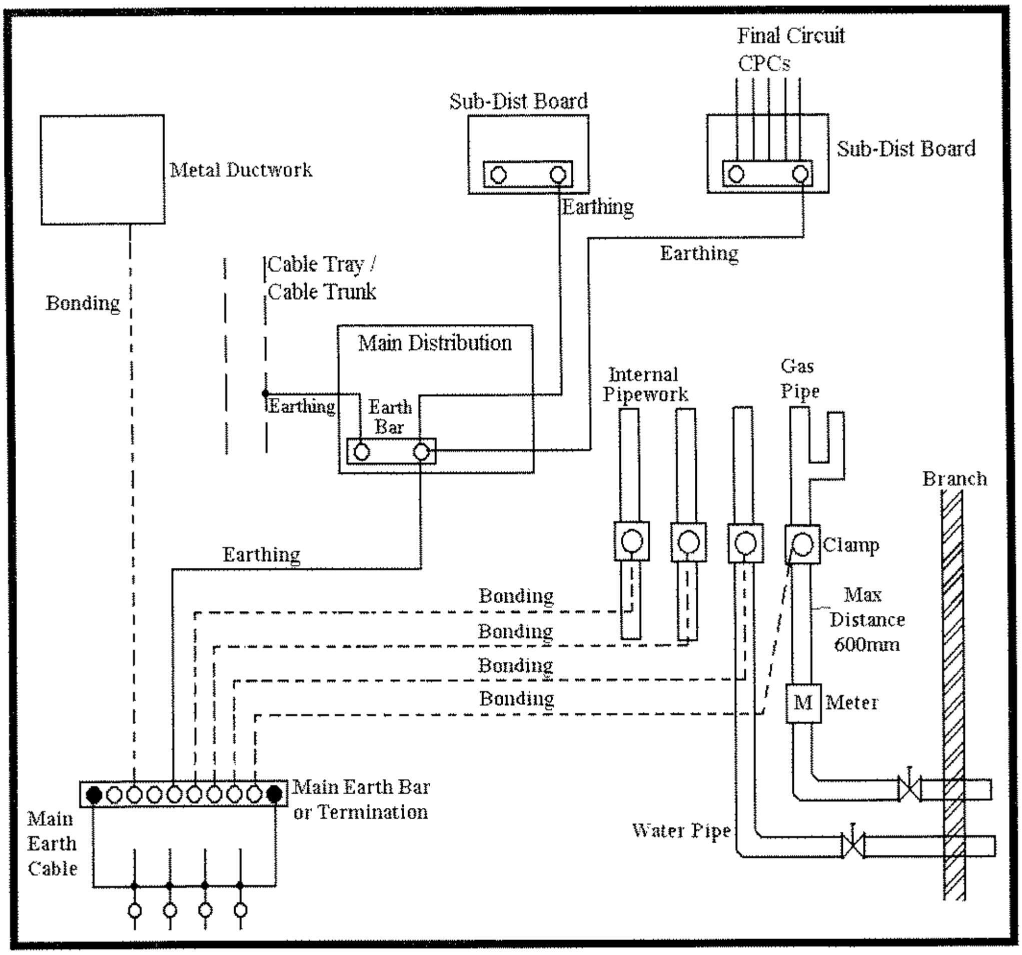


Figure 11. 9 Earthing & Main Equipotential Bonding

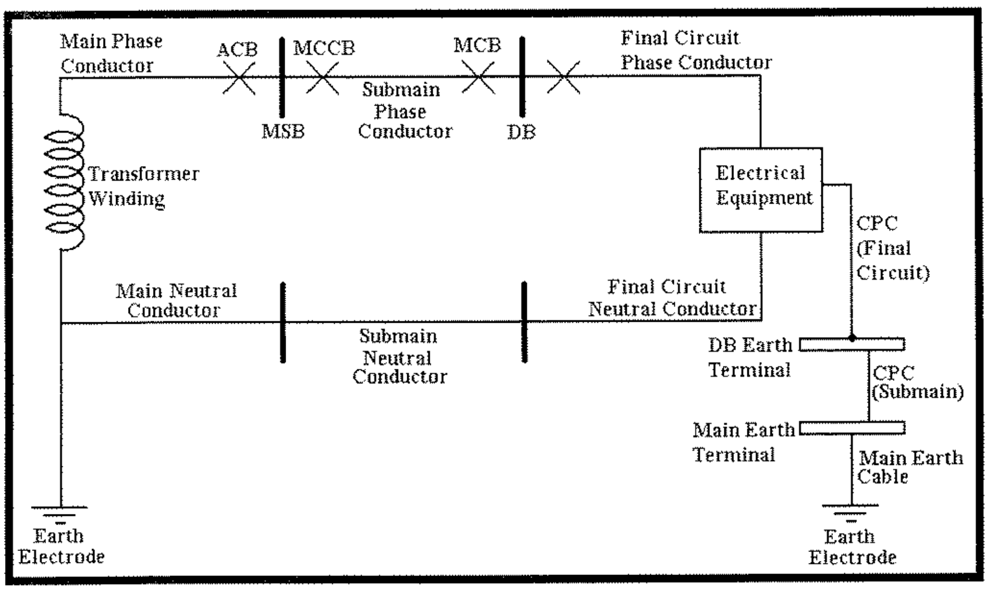


Figure 11. 10 CPC and Main Earth Cable in a TT Earthing System

Values of k for protective conductors in various use or service are as given in Tables 54B, 54C, 54D, 54E and 54F. The values are based on the initial and final temperatures indicated below each table.

For example: k = 143 for PVC insulated copper Earth cable or CPC not bunched with the phase conductors and k = 159 for bare copper earth cable or CPC where there is no risk of damage to neighbouring material.
Where the application of the formula produces a non-standard size, a conductor having the nearest larger standard cross-sectional area shall be used.

CPC for Final Circuits and Submains

However, due to the non-availability of t, the operating time of disconnection device, rule of thumbs as given by table 54G of SS CP5: 1998 is often used by designers as a guide to sizing of CPC for submains and final circuits. The size of CPC is determined based on the size of phase conductor in accordance with Table 54G.

From table 54G of CP5: 1998: -

Size of CPC in Relation to the Size of Phase Conductor

Phase conductor size (S), mm^2	Minimum CPC size, mm^2
$S \leq 16$	S
$16 < S \leq 35$	16
S >35	S / 2

Table 11.1 Minimum cross-sectional area of CPC in relation to cross-sectional area of phase conductors

Main Earth Cable

Cross-sectional area (S mm^2) for main earth cable should be determined carefully by the following considerations:

(a) Whether it is TT or TN-S earthing system

(b) Magnitude of prospective phase to earth fault current $I_{E/F}$

(c) Duration of the flow of prospective phase to earth fault current t seconds

If actual disconnection time of protective device is not known, maximum duration of 3 seconds or 1 second may be used.

(d) Thermal stress on earth cable

The main earth cable or protective conductor must be able to conduct the full prospective phase to earth fault current (magnitude and direction) without excessively raising the temperature of the earth cable or protective conductor and causing expulsion of sparks or arcs that could initiate a fire or explosion.

(e) Low impedance path

The impedance of the protective conductor must be low enough to accept the full phase to earth current without causing a voltage drop enough to be dangerous.

Criteria: Touch Voltage < 50 Volts (Limit)

(f) Earth Fault Loop Impedance: Operation of protective device

The total impedance of the earth fault loop circuit (Earth fault loop impedance) must permit sufficient earth fault current magnitude to operate the protective device in required disconnection time stipulated by SS CP5: 1998.

For example: For distribution circuit or submain, CP5: 1998 imposed **5 seconds** limit & for portable equipment connected to socket outlet CP5: 1998 imposed **0.4 seconds** limit. (Refer to relevant clauses of CP5: 1998).

These limits can be achieved by the use of appropriate Residual Current Device (RCD).

Supplementary Bonding Conductor

Supplementary bonding may be required at locations of increased electric shock risk as shown in Figure 11.11.

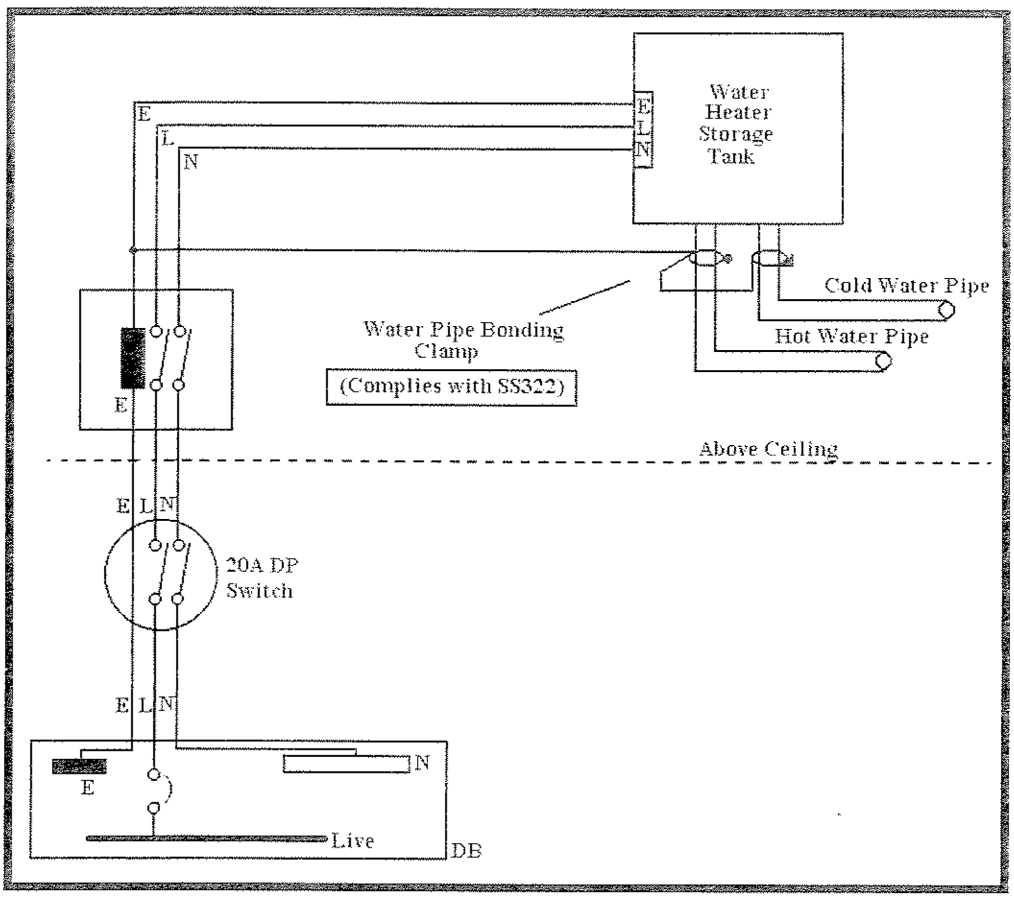


Figure 11. 11 Supplementary bonding of hot water pipe of water heater

The supplementary bonding conductor shall have cross-sectional area

- Not less than smallest protective conductor connected to the exposed conductive parts
- Minimum of 2.5 sqmm with mechanical protection
- Minimum of 4 sqmm without mechanical protection

11.5 EXAMPLES IN SIZING OF MAIN EARTH CABLE – TT Earthing System

Example 11.3

The Low Voltage Supply System to the 1st floor of a multi-storey building is shown in Figure 11.12.

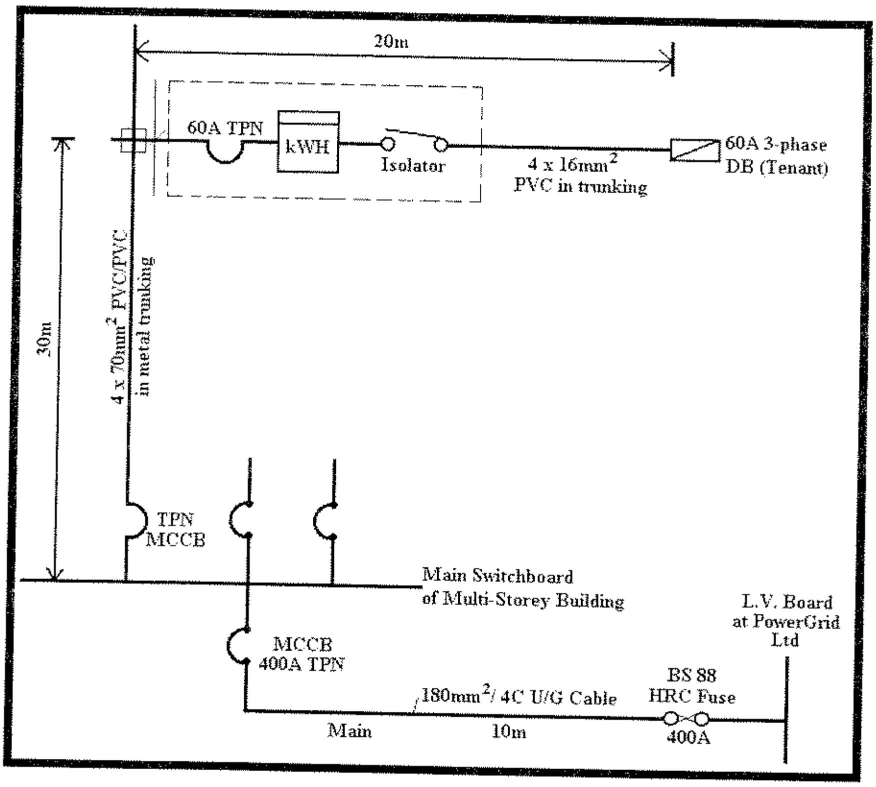


Figure 11. 12

The length and impedances of the cables are as follows: -

	Impedance Per Phase Per Metre	Length
185 mm²/4C XLPE/SWA/PVC main from Power Grid (Table 4E4A)	$\left(\frac{0.22}{\sqrt{3}} + \frac{j0.125}{\sqrt{3}}\right) \times 10^{-3}$	10m
4 x 70 mm² PVC/PVC single core riser	$\left(\frac{0.56}{\sqrt{3}} + \frac{j0.25}{\sqrt{3}}\right) \times 10^{-3}$	30m
4 x 16 mm² PVC single core service to tenant	$\left(\frac{2.4}{\sqrt{3}} + \frac{j0}{\sqrt{3}}\right) \times 10^{-3}$	20m

Table 11.2

Determine:

(a) The prospective 3-phase short circuit current at the MSB, tap-off unit and Tenant DB.
(b) The cross-sectional area of main earth cable at the MSB.

Solutions:

(a) Fault Level Calculation

(i) Calculation of Fault Level at the three-phase 400V MSB

The declared fault level at the PowerGrid intake is 36kA, this prospective short circuit current can be converted to an equivalent source impedance.

$$Z_{source} = \left(\frac{400V/\sqrt{3}}{36 \times 10^3}\right) = j0.00639 \text{ ohms (Reactive)}$$

∴ Total Impedance up to the MSB

$$\begin{aligned} Z_{total} &= Z_{source} + Z_{185} \\ &= j0.00639 + (0.127 + j0.0722) \times 10^{-3} \times 10 \\ &= j0.00639 + 0.00127 + j0.000722 \\ &= 0.00127 + j0.00711 \\ &= 0.00722 \end{aligned}$$

$$\therefore \text{ Prospective 3-}\phi \text{ short circuit current at the MSB} = \frac{400V/\sqrt{3}}{0.00722} = 33.24kA$$

Therefore a 400A MCCB with breaking capacity 36kA is recommended.

(ii) At the Tap-off unit

$$Z_{total} = Z_S + Z_{185} + Z_{70}$$

$$Z_{70} = \left(\frac{0.56}{\sqrt{3}} + \frac{j0.25}{\sqrt{3}}\right) \times 10^{-3} \times 30m$$

$$= 0.0097 + j0.00433 \text{ ohm}$$

$$\begin{aligned} \text{Therefore, } Z_{Total} &= j0.0039 + (0.00127 + j0.000722) + (0.0097 + j0.00433) \\ &= 0.01097 + j0.0114 = 0.0157\angle\phi \end{aligned}$$

$$I_{SC} = \left(\frac{400V/\sqrt{3}}{0.0158}\right) = 14.56 \text{ kA}$$

Prospective 3-phase short circuit level at tap-off units is 14.56kA. A 16kA MCCB is required.

(iii) At the tenant DB.

$$Z_{16} = \frac{2.4 \times 10^{-3} \times 20m}{\sqrt{3}}$$

Therefore, $Z_{Total} = Z_S + Z_{185} + Z_{70}$
$= (0.01097 + j0.001144) + 0.0278$
$= 0.0388 + j0.0114$
$= 0.04\angle\phi$

Therefore, $I_{SC} = \left(\frac{400V/\sqrt{3}}{0.04}\right) = 5.75\ kA$

Therefore, 6kA MCCB is required at the DB.

(b) Calculation of Earth Fault Loop Impedance

(i) At the Main Switchboard

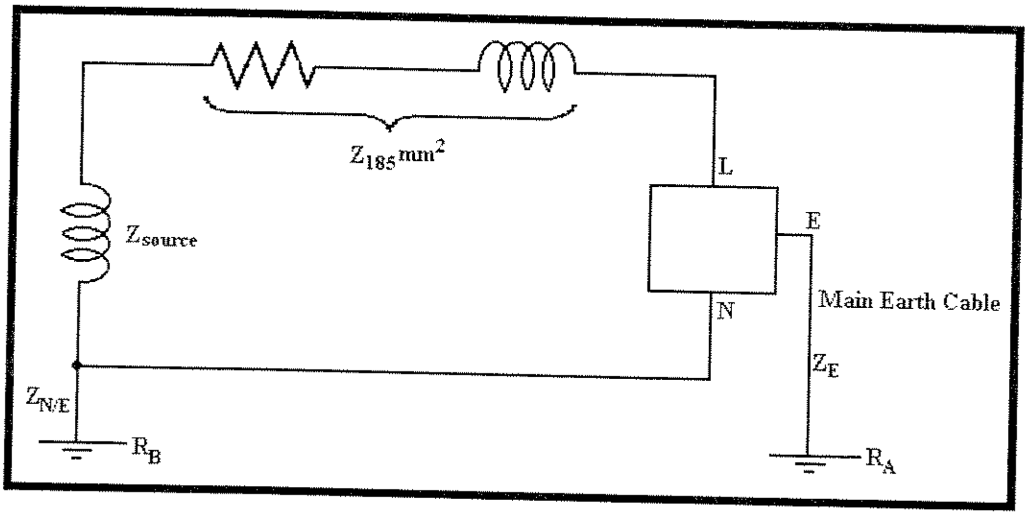


Figure 11. 13

Earth Fault Loop Impedance = $Z_{source} + Z_{185} + Z_E + R_B + R_A + Z_{N/E}$

where $Z_{source} = 0.00639\Omega$
$Z_{185} = 0.00127 + j0.000722$

$$Z_E = Z_{70} = \left(\frac{0.56}{\sqrt{3}} + \frac{j0.25}{\sqrt{3}}\right) \times 10^{-3} \times 10m = 0.00323 + j0.00144$$

Therefore, Z_{source} approx. $R_A + R_B$

If $R_A = R_B = 1\Omega$, $Z_{EFLI} = 1 + 1 = 2\Omega$

$I_{E/F} = \frac{400V/\sqrt{3}}{2\Omega}$ approx. 120A

If $R_A = R_B = 0.1\Omega$, $Z_{EFLI} = 0.1 + 0.1 = 0.2\Omega$

$$I_{E/F} = \frac{400V/\sqrt{3}}{0.2\Omega} \text{ approx. } 1200A$$

(ii) Main Earth Cable Sizing

$K^2S^2 > I_{E/F}^2 t$ and $S > \dfrac{I_{E/F}\sqrt{t}}{K}$

Assuming t = 1sec, $S > \dfrac{1200\sqrt{1}}{159} = 7.6mm^2$

where K = 159 for bare copper tape

Assuming t = 3sec, $S > \dfrac{1200\sqrt{3}}{159} = 13.1mm^2$

Therefore, bare copper tape of 3mm x 25mm = $75mm^2$ is selected.

(iii) Protection Against Indirect Contact by Automatic Disconnection of Supply

As $I_{E/F}$ may be as low as 120A to 1200A, it may not be sufficient to cause the overcurrent protection device (i.e. MCB, MCCB or overcurrent relay) to operate.

Therefore for TT earthing system, Clause 413-02-19 of SS CP5: 1998 recommended that Residual Current Device is preferred for protection against indirect contact.

11.6 EXAMPLE IN SIZING OF MAIN EARTH CABLE - TN-S Earthing System

Example 11.4

The High Voltage and Low Voltage supply system of a building receiving 22kV supply is shown in Figure 11.14.

(a) Determine the prospective 3-phase short circuit current at the Low Voltage MSB

(b) Determine the breaking current & making current at the 500A MCCB of the Motor Centre Control.

(c) Determine the cross-sectional area of the main earth cable at the MSB.

Solutions:

(a) Select Base MVA = 1MVA
Base Voltage (H.V.) = 22 kV (H.V)
Base Voltage (L.V.) = 0.4 kV

The utility fault level at 800 MVA has to be converted into p.u. value

$$Z_u = \frac{\text{Base MVA}}{\text{Fault MVA}} = j\left(\frac{1}{800}\right) = 0.00125 \text{ p.u. (Reactive)}$$

Transformer Impedance = j0.0575 p.u.

For the 500mm^2 / SC, 400V Cable

From Table 4DIB of CP5: 1998 (Column 8)
$r = 0.086/\sqrt{3}\ m\Omega/m$
$X = 0.21/\sqrt{3}\ m\Omega/m$

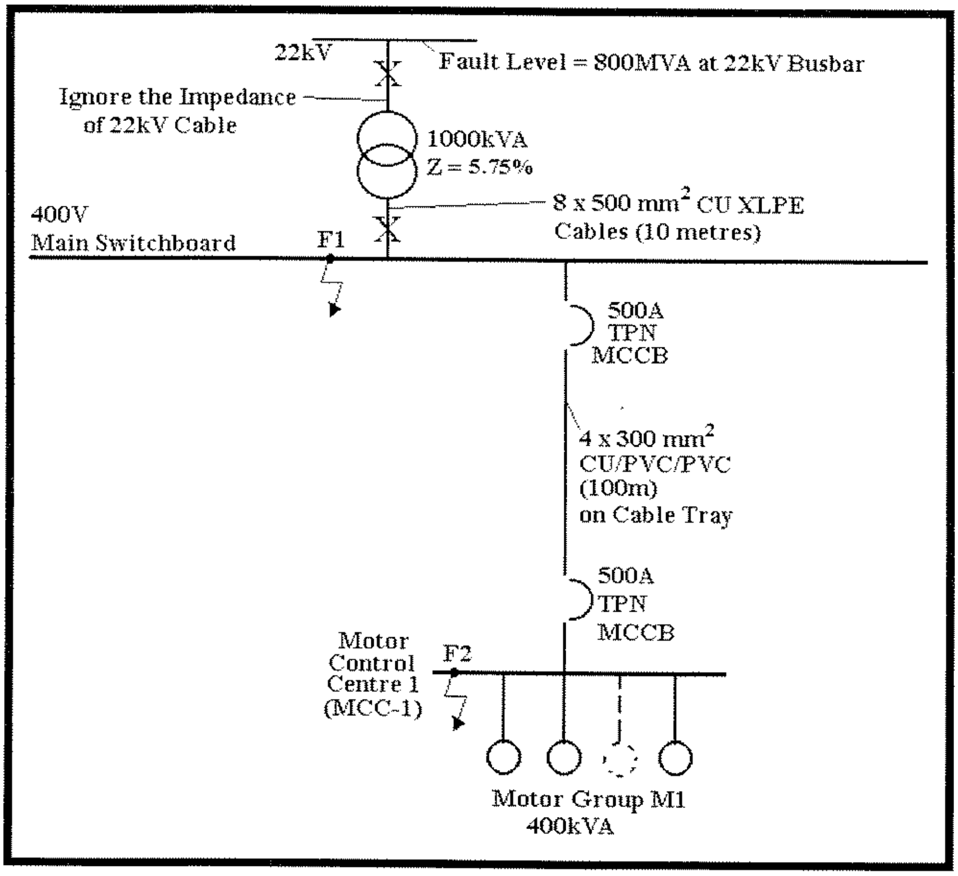


Figure 11. 14

Since two single core cables are connected in parallel in each Phase & Neutral

$$Z_{500} = \tfrac{1}{2}\,[0.086/\sqrt{3} + j0.21/\sqrt{3}] \times 10^{-3} \times 10$$
$$= [0.000248 + j0.0006]\Omega$$

$$\text{Base Impedance} = \frac{(\text{base kV})^2}{\text{base MVA}} = \frac{(0.4)^2}{1} = 0.16\Omega$$

$$Z_{500} = \frac{0.000248 + j0.0006}{0.16}$$
$$= (0.00155 + j0.00379)\ \text{p.u.}$$

$$\text{Total Impedance, } Z = j0.00125 + j0.0575 + j0.00379 + 0.00155$$
$$= 0.00155 + j0.0625$$
$$= 0.0625\ \angle\phi$$

Therefore, fault level at the MSB = $\frac{\text{Base MVA}}{Z} = \frac{1\text{ MVA}}{0.0625} = 16\text{MVA}$

$I_{SC} = \frac{16 \times 10^6}{\sqrt{3} \times 400} = 23.09\text{ kA}$

(b) At the Motor Control Centre

For the 300mm^2 / 4C Cable

From Table 4DI of SS CP5: 1998 (Column 8)

$r = 0.130/\sqrt{3}\ \text{m}\Omega/\text{m}$
$X = 0.22/\sqrt{3}\ \text{m}\Omega/\text{m}$

Therefore, $Z_{500} = \left(\frac{[0.130\sqrt{3} + j0.22/\sqrt{3}]}{0.16 \times 1000}\right) \times \left(\frac{1}{1000}\right) \times 100$

$= [0.0469 + j\ 0.0794]$ p.u.

Total Impedance $= 0.00155 + j0.0625 + 0.00469 + j0.0794$
$= 0.0485 + j0.149$
$= 0.1499\angle\phi 2$

Fault Level = $\frac{\text{Base MVA}}{Z} = \frac{1\text{ MVA}}{0.1499} = 6.67\text{ MVA}$

$I_{SC} = \frac{6.67 \times 10^6}{\sqrt{3} \times 400} = 9.63\text{ kA}$

The breaking capacity of the 500A MCCB must be at least 10kA.

For X/R Ratio = 5, Making Capacity = $1.5 \times (\sqrt{2} \times 10\text{ kA})$
$= 21.21$ kAp

(c) Phase to Earth Short Circuit

The transformer room and 400V Main switchroom are located adjacent to each other. (TN-S earthing system is adopted).

If the following earth cables are used for the earthing system:

T/F Neutral earthing cable:	2 x 120 mm^2/SC PVC insulated copper cable (10 metres)
400 MSB protective earth cable:	2 x 120 mm^2/SC PVC insulated copper cable (10 metres)

and the earth electrode system has an overall earth electrode resistance, $R_A = 0.5\Omega$

(i) Determine the total earth fault loop impedance at the 400V MSB and the magnitude of the earth fault current at the 400V MSB.

(ii) Determine whether the 2 x 120 mm^2/single core PVC insulated PVC earth cable can withstand the thermal stress produced by earth fault current for one sec. (Thermal constant of PVC Cu earth cable is K = 143)

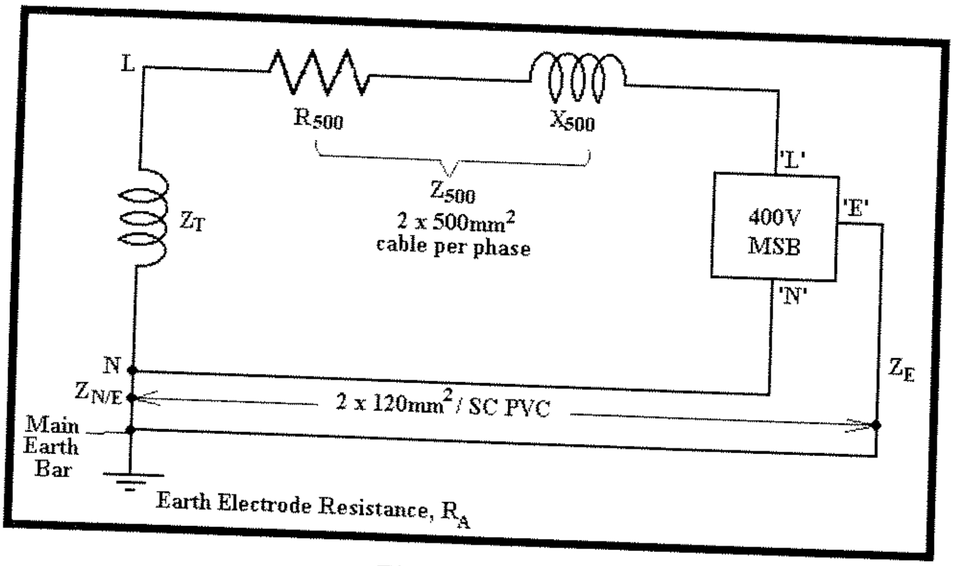


Figure 11. 15

Solution:

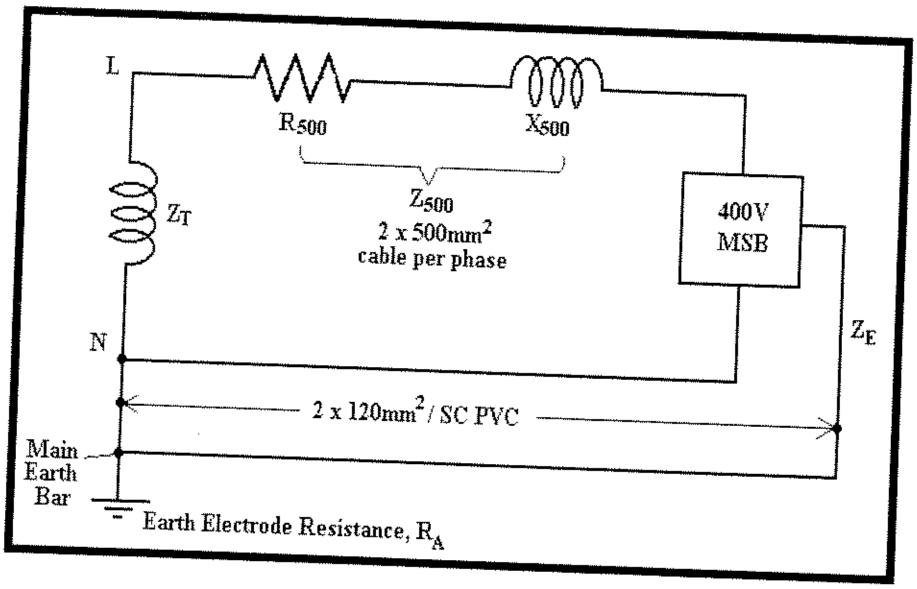


Figure 11. 16

(i) Total Earth Fault Loop Impedance

$Z_{EFLI} = Z_T + Z_{500} + Z_E + Z_N$

Earth Electrode Resistance R_A is not included because it is not in the earth fault loop path.

$$\text{Fault Level} = \frac{1 \text{ MVA}}{0.05} = 20 \text{ MVA}$$

$$I_{SC} = \frac{20 \times 10^6}{\sqrt{3} \times 400} = 28.87 \text{ kA}$$

Therefore, $Z_r = \left(\frac{j400/\sqrt{3}}{28 \times 87 \times 10^3}\right) = j0.0083\Omega$

For 500 mm^2 cable: From Table 4E1B of CP5: 1998

$r = 0.086/\sqrt{3}$ mΩ/m
$X = 0.21/\sqrt{3}$ mΩ/m

Therefore, $Z_{500} = ½ [0.086\sqrt{3} + 0.21/\sqrt{3}] \times 10^{-3} \times 10$ metre
$= 0.000248 + j0.0006\Omega$

For 120mm^2 cable

From Table 4D1B for 120mm^2 cable (flat spaced)
$r = 0.32/\sqrt{3}$ mΩ/m
$X = 0.30/\sqrt{3}$ mΩ/m

$Z_{120} = ½ [0.32/\sqrt{3} + j0.30/\sqrt{3}] \times 10^{-3} \times [10m + 10m]$
$= [1.848 + j1.732] \times 10^{-3}$
$= (0.001848 + j0.001732)\ \Omega$

$Z_{EFLI} = (j0.0083\Omega) + (0.000248 + j0.0006) + (0.001848 + j0.001732)$
$= 0.002096 + j0.01063$
$= 0.01084 \angle\phi$

Therefore, $I_{E/F} = \frac{230V}{0.01084} = 21.22kA$

(b) For K = 143, t = 1 sec & $I_{E/F}$ = 21.22 kA

The minimum cable size which is able to withstand the thermal stress for 1 second is

$S = \frac{I\sqrt{t}}{K} = \frac{21.22 \times 10^3 \times 1}{143}$
$= 148$ mm^2

Since S = 148 mm^2 which is smaller than 2 x 120 mm^2, the main earth cable at (2 x 120 mm^2) is able to withstand the thermal stress for 1 sec.

11.7 COMMON TYPES OF EARTH ELECTRODES

Pipes or Rods

Solid copper or steel plated copper rods of sizes from 13mm to 20mm in diameter.

These rods are available in 1.8 metres long sections with threaded ends for the coupling of two sections.

The rods are driven directly into the ground. Additional sections are added if the required earth resistance cannot be obtained. However, a number of earth rods driven in at different locations and then connected in parallel are preferred to a single deeply driven rod.

The resistance of a pipe or rod electrode is given by:

$$R = \frac{\rho}{2.72L} \mathrm{Log}_{10} \frac{4000L}{d}$$

where L is length in metre
d is diameter in mm
ρ is resistivity of the soil in ohm m (assumed uniform).

Strips or Horizontal Conductor Electrodes

These strips or horizontal earth conductors have special advantage where high-resistivity soil underlines shallow surface layers of low resistivity. They are frequently in the form on untinned copper strip of not less than 2.5mm x 1.6mm in section, but may be of bare copper conductor as used for overhead lines. The resistance is given by:

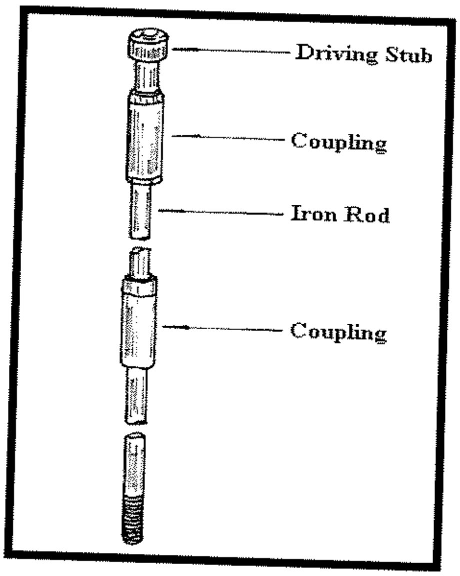


Figure 11. 17 Rod Electrode

The resistance is given by:

$$R = \frac{\rho}{2.72L} \mathrm{Log}_{10} \frac{2000L^2}{wt}$$

where ρ is resistivity of the soil in ohm m (assumed uniform).
L is length in metre
w is the width (in case of strip) or twice the diameter (incase of circular conductors) in mm
t is the depth in m

Care should be taken in positioning these electrodes especially to avoid damage by excavation works.

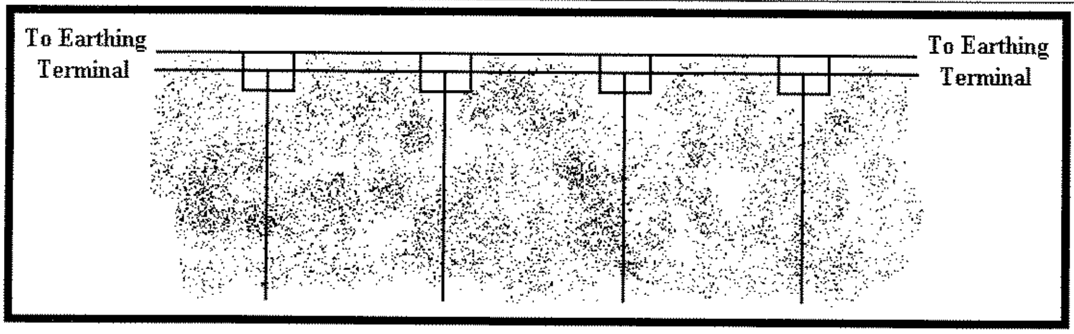


Figure 11. 18 Strip or Horizontal Earth Conductors

Earth Plates

The approximate resistance to earth of a plate can be calculated from:

$$R = \frac{\rho\sqrt{\pi/A}}{4}$$

where ρ is sensitivity of the soil (assumed uniform) in ohm m
A is the total area of the two sides of the plate in m^2

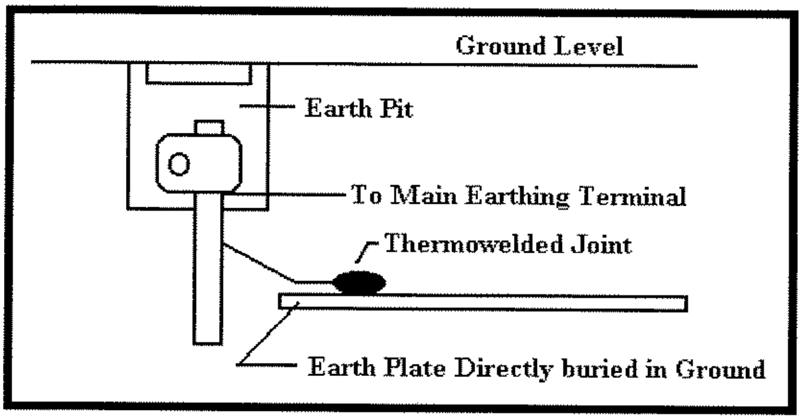


Figure 11. 19 Earth Plates

Connection of Earth Electrodes to Main Earth Terminal (MET)

Typical Installation of

(a) Electrodes
(b) Earthing Conductors
(c) Main Earth Terminals (MET)

are shown in Figure 11.20 and Figure 11.21: -

Example 11.5:

For the Earth Mesh System as shown in Figure 11.22, determine the resistance of each electrode and the horizontal $95mm^2$ bare conductor. Assuming that this apparent soil resistivity is 56 ohm-m.

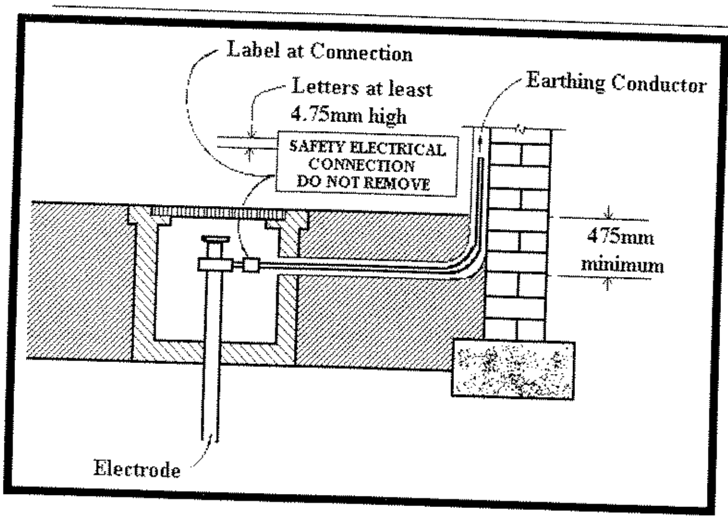


Figure 11. 20 Connection of Earthing Conductor to Earth Electrode

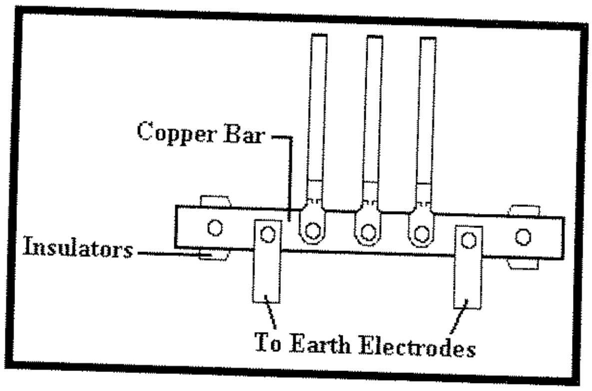


Figure 11. 11 Main Earthing Terminal

Example: Determine the earth resistance value of the earth mesh system as shown in Figure 11.22.

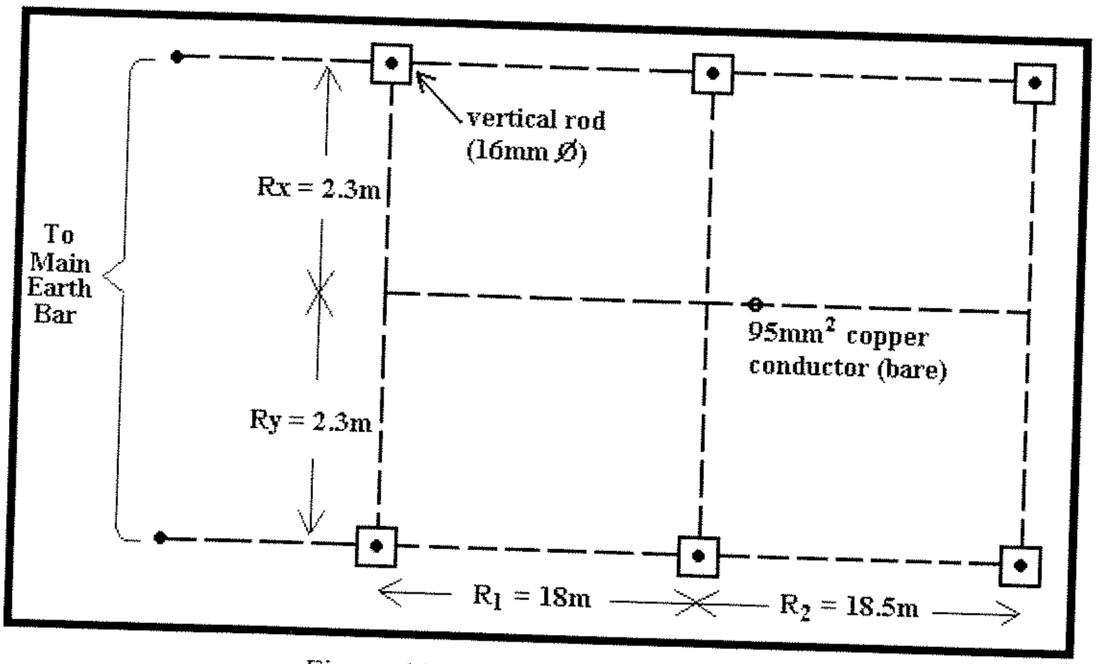


Figure 11. 22 Earth Mesh system

(a) Based on CP16: 1991, the resistance of a rod electrode (R_r) is given by: -

$$R_r = \frac{\rho}{2.72L} \text{Log}_{10} \frac{4000L}{d}$$

where ρ is soil resistivity in ohm-m

L length of rod in m (1.8m rod is used) and using 2 rods per earth point

D diameter of rod in mm (16mm ϕ copper bond rod is used)

The soil resistivity measurement gave an average value of 55.44 ohm-m The resistance of each earth rod is:

$$R_r = \frac{56}{2.72L} \text{Log}_{10} \frac{4000 \times 1.8 \times 2}{d}$$
$$= 5.72 \times \log_{10} 900$$
$$= 5.72 \times 2.95$$
$$= 16.9 \text{ ohm}$$

(b) The stranded earth conductor is 95 mm^2 and in accordance with CP16: 1991, the resistance of strip conductor (Rc) is given by:

$$R_C = \frac{\rho}{2.72L} \text{Log}_{10} \frac{2000L^2}{Wt}$$

where
- ρ is soil resistivity in ohm-m
- L length of strip conductor in m
- W twice the diameter of conductor in mm
- t is the depth conductor in soil in m (0.3m is specified)

Based on the layout in Figure 11.22, the resistance of strip conductor:

$$R_1 = \frac{56}{2.72 \times 18.00} \text{Log}_{10} \frac{2000 \times 18.00 \times 18.00}{2 \times 12.46 \times 0.3}$$
$$= 1.14 \times \log_{10} 86677.37$$
$$= 1.14 \times 4.94$$
$$= 5.63 \text{ ohm}$$

$$R_2 = \frac{56}{2.72 \times 18.50} \text{Log}_{10} \frac{2000 \times 18.50 \times 18.50}{2 \times 12.46 \times 0.3}$$
$$= 1.11 \times \log_{10} 91559.66$$
$$= 1.11 \times 4.96$$
$$= 5.51 \text{ ohm}$$

$$R_X = \frac{56}{2.72 \times 2.3} \text{Log}_{10} \frac{2000 \times 2.3 \times 2.3}{2 \times 12.46 \times 0.3}$$
$$= 8.95 \times \log_{10} 1415.20$$
$$= 8.95 \times 3.15 = 28.19 \text{ ohm}$$

Therefore, $R_X = R_Y = 28.19$ ohm

11.8 MEASUREMENT OF SOIL RESISTIVITY

Typical Variations in Soil Resistivity

The resistance to earth of an earth electrode is influenced by the resistivity of the surrounding soil. The resistivity depends upon the nature of the soil and its moisture content and can vary enormously as seen in the Table 11.3.

Material	Resistivity in Ω-metre
Ashes	3.5
Coke	0.2 – 8
Peal	45 – 200
Garden earth – 50% moisture	14
Garden earth – 20% moisture	48
Clay soil – 40% moisture	7.7
Clay soil – 20% moisture	33
London Clay	4 – 20
Very dry clay	50 – 150
Sand – 90% moisture	130
Sand – normal moisture	3000 – 8000
Chalk	50 – 150
Consolidated Sedimentary rocks	10 – 500

Table 11.3 Table of Soil Sensitivity

Because it is impossible to forecast the resistivity of the soil with any degree of accuracy, it is often advantageous to make a preliminary survey of the soil resistivity of the surrounding site before sinking of the electrodes. This will enable decisions to be made on the best position for the electrode(s), the number of electrodes required, and to decide whether any advantage can be gained by driving rods to a greater depth. Such a survey may produce considerable savings in electrode and installation costs incurred trying to achieve a required resistance.

The 4-pin Wenner Method

The 4-pin Wenner method is shown in Figure 11.23. Four electrodes (pins) are inserted into the ground, at fixed spacing of *a*. Electric current is applied by the outer two electrodes (Current Electrodes, C1 & C2), and voltage is measured by the inner two electrodes (Potential Electrodes, P1 & P2). The 4-pin Earth resistivity tester read the value of earth resistance.

Resistivity can be calculated by the formula:

$$\rho = 2\pi a R$$

where ρ is apparent resistivity
R is measured resistance by the 4-pin method

Without further processing, the apparent resistivity measured at spacing *a* may be considered as an estimate of the resistivity at depth of *a* at the center of the array. Resistivity at different depth can be estimated by conducting the test with varying pin spacing *a*. In this example, *a* will be 2m, 4m, 6m, 8m, and 10m.

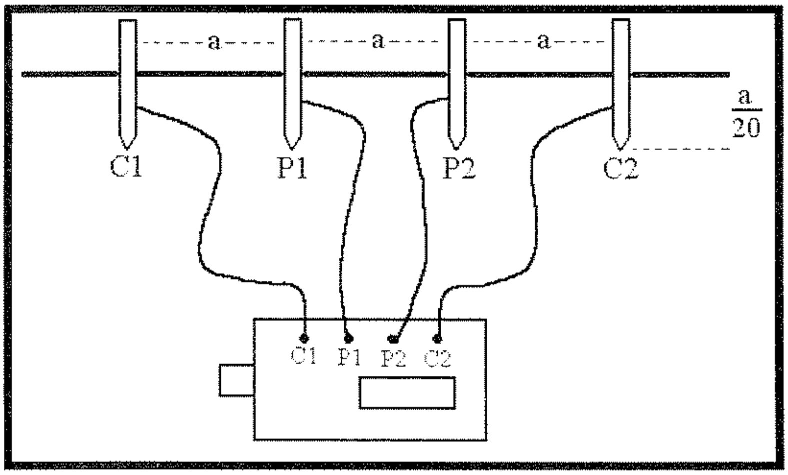


Figure 11. 23 Soil Resistivity Measurement

Example 11.7
Soil Resistivity Test (Wenner's Four Electrodes Tests)

Spacing (m) a	**Penetration Depth (m) D**	**Measured Resistance (ohm) R**	**Apparent Resistivity (ohm.m) $\rho = 2\pi aR$**
2.0	0.1	5	62.83
4.0	0.2	2	50.26
6.0	0.3	1.5	56.55
8.0	0.4	0.8	40.21
10.0	0.5	0.5	31.42
Mean Apparent Resistivity			56
Soil Type			Clay
Weather			Good

Table 11.4

1. With the aid of appropriate diagrams, explain briefly why Earth Fault Relay for TT Earthing System must not be set more than 120A.

2. Explain briefly the definitions of the following components of an earthing system:-

   (a) Exposed Conductive Part
   (b) Extraneous Conductive Part
   (c) Circuit Protective Conductor (CPC)

3. Explain briefly whether cable trays and cable trunkings are considered as exposed conductive part or extraneous conductive part and what is the appropriate cross-sectional area (S mm^2) of cable to connect the cable trays or trunking to earth?

4. Explain briefly with a diagram on the objectives of

   (a) Neutral Earthing
   (b) Installation Earthing

5. Draw proper diagrams to show how TT Earthing System and TN-S Earthing System are implemented and determine the Earth Fault Loop Impedance of the 2 systems.

6. The High Voltage and Low Voltage Supply System of a building receiving 22kV supply is shown in Figure 11.24, and the earthing system is TN-S system.

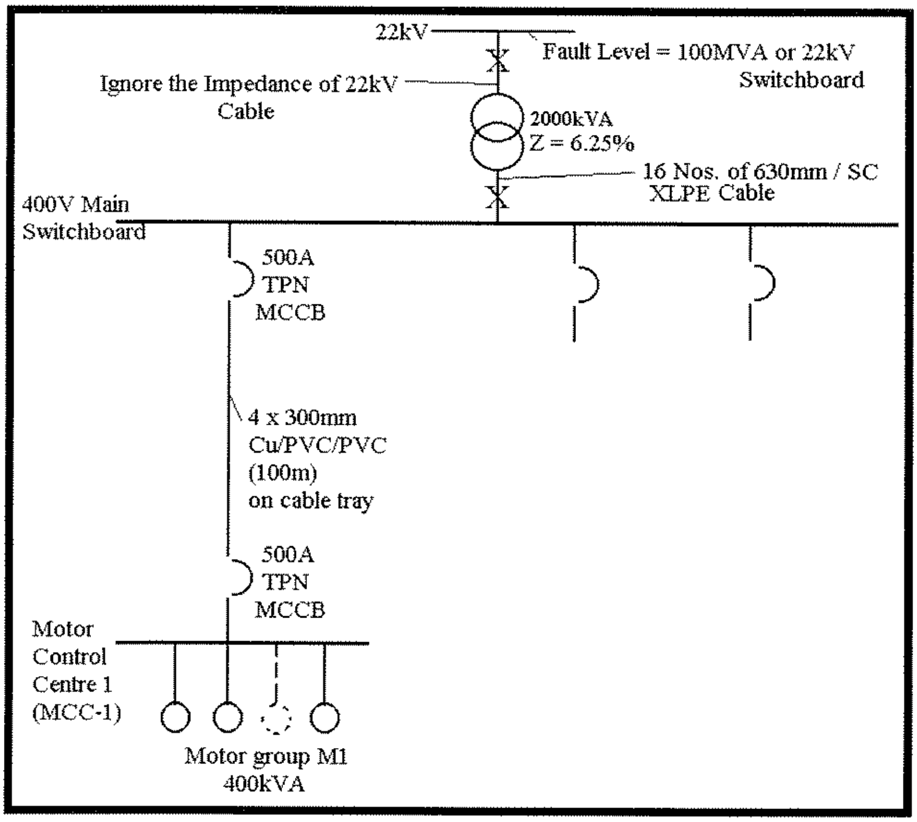


Figure 11. 24 Straight-line Diagrams of an Electrical Installation

Determine:

(a) the ohmic value of the transformer impedance

(b) the Earth Fault Loop Impedance at the 400V MSB
(c) the cross-sectional area of main earth cable at the MSB
(d) the cross-sectional area of the CPC for 4 x 300mm^2 Cu PVC/PVC submain

7. For the following final circuits and submains of an electrical installation with TT earthing system, determine the appropriate cross-sectional area of circuit protective conductors (CPC).

2 x 1.5 mm^2 PVC Cu. + ________ mm^2 CPC in conduit and trunking
2 x 2.5 mm^2 PVC Cu. + ________ mm^2 CPC in conduit and trunking
4 x 6 mm^2 PVC Cu. + ________ mm^2 CPC in conduit and trunking
4 x 16 mm^2 PVC Cu. + ________ mm^2 CPC in conduit and trunking
4 x 25 mm^2 PVC Cu. + ________ mm^2 CPC in conduit and trunking
4 x 35 mm^2 PVC Cu. + ________ mm^2 CPC in conduit and trunking
4 x 50 mm^2 PVC Cu. + ________ mm^2 CPC in conduit and trunking
4 x 120 mm^2 PVC/PVC Cu. + ________ mm^2 CPC in cable tray
4 x 185 mm^2 PVC/PVC Cu. + ________ mm^2 CPC in cable tray
4 x 300 mm^2 PVC/PVC Cu. + ________ mm^2 CPC in cable tray

8. For the following final circuits and submain of an electrical installation with TN-S Earthing System, determine the appropriate cross-sectional area of circuit protective conductors (CPC), the main earth cable used in the MSB room is 2 x 120mm^2 PVC Cu cable.

2 x 2.5 mm^2 PVC Cu. + ________ mm^2 CPC in conduit and trunking
2 x 4 mm^2 PVC Cu. + ________ mm^2 CPC in trunking
4 x 50 mm^2 PVC Cu. + ________ mm^2 CPC in trunking
4 x 95 mm^2 PVC Cu. + ________ mm^2 CPC in trunking
4 x 120 mm^2 PVC Cu. + ________ mm^2 CPC in trunking
4 x 185 mm^2 PVC Cu. + ________ mm^2 CPC in trunking
4 x 300 mm^2 PVC Cu. + ________ mm^2 CPC in trunking
8 x 500 mm^2 PVC/PVC Cu. + ________ mm^2 CPC in cable tray
12 x 630 mm^2 PVC/PVC Cu. + ________ mm^2 CPC in cable tray

CHAPTER 12
PROTECTION RELAYS

12.1 INTRODUCTION

Protection Relay

A relay is a device which makes a measurement or receives a signal which causes it to operate and to effect the operation of other equipment.

A protection relay is a device which responds to abnormal condition in an electrical installation system to operate a circuit breaker to disconnect the faulty section of the system with the minimum interruption of supply.

Current Transformers

Current transformer is used for transforming current from a high primary value to a low secondary value for protective relaying purpose.

The secondary ratings are of the order of 5A or 1A. Primary current ratings vary from 10 to 1600A or more.

The VA rating of current transformer is low (5-150VA) as compared with that of power transformers (kVA to MVA).

Example:

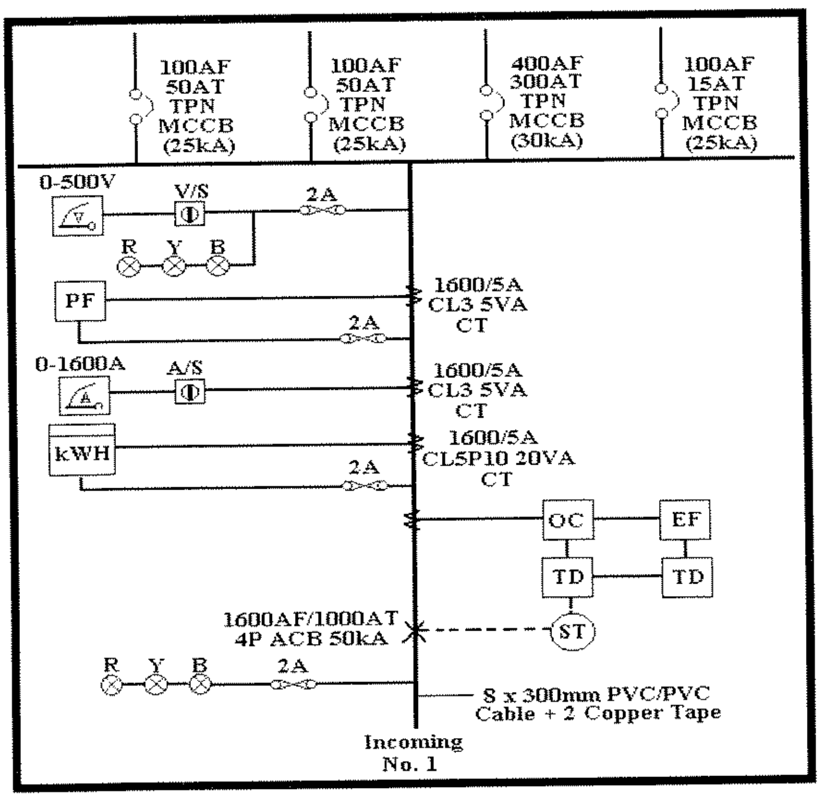


Figure 12. 1

A current transformer of ratio 1600/5A will transform the primary power current of 1600A in the primary circuit to a 5A current in the secondary circuit for the relay. A primary current of 800A will be transformed or reduced to 2.5A in the secondary circuit.

12.2 OVERCURRENT AND EARTH FAULT PROTECTION FOR LOW VOLTAGE (400V) SYSTEM

Overcurrent Protection

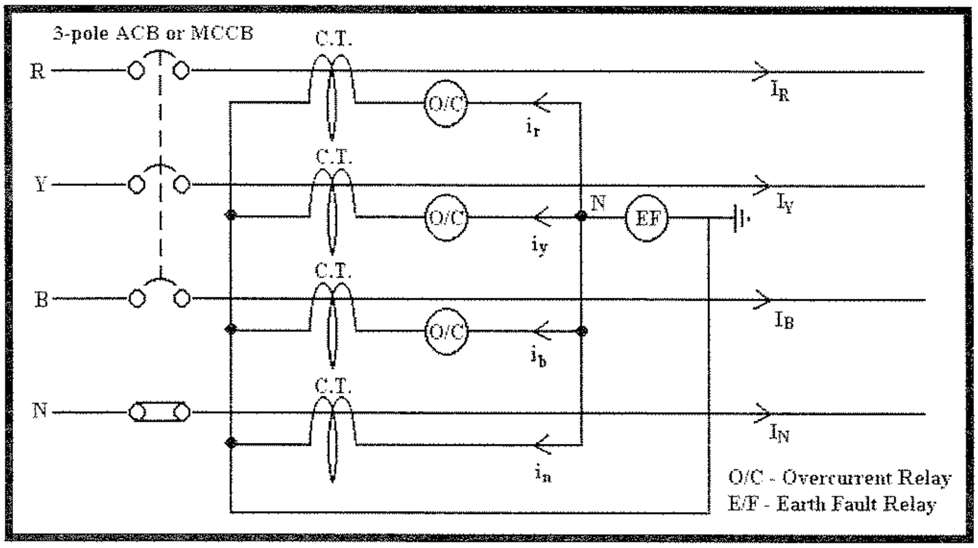


Figure 12. 2 Overcurrent Protection

(a) In the overcurrent and earth fault protection system for low voltage installation (400V system), four current transformers are used to transform current from a high primary value to a low secondary value for the protective relays. The current transformers are coupled to R, Y, B lines and the neutral line.

(b) An overcurrent relay is connected in series with the current transformer in each of the 3-phase. When a primary power current I_R, I_Y, I_B and I_N flow in each phase and neutral line, a replica secondary current at a reduced level, i_r, i_y, i_b and i_n will flow in each current transformer in opposite direction.

In this case, secondary currents flowing in the relays are scaled down to:

$$I_r = \frac{I_R}{\text{CT Ratio}}$$

$$I_y = \frac{I_Y}{\text{CT Ratio}}$$

$$I_b = \frac{I_B}{\text{CT Ratio}}$$

(c) Consequently, the overcurrent relay connected in series with each current transformer will pass a current in the phase concerned. The overcurrent relays can than be set to operate at any desired level. The relays would afford overcurrent and overload protection.

(d) The overcurrent relays are normally set to 100% of the designed and approved load for the incoming circuit.

Earth Fault Protection

Earth fault current occurring in any phase, however, can be detected by a separate relay known as earth fault relay.

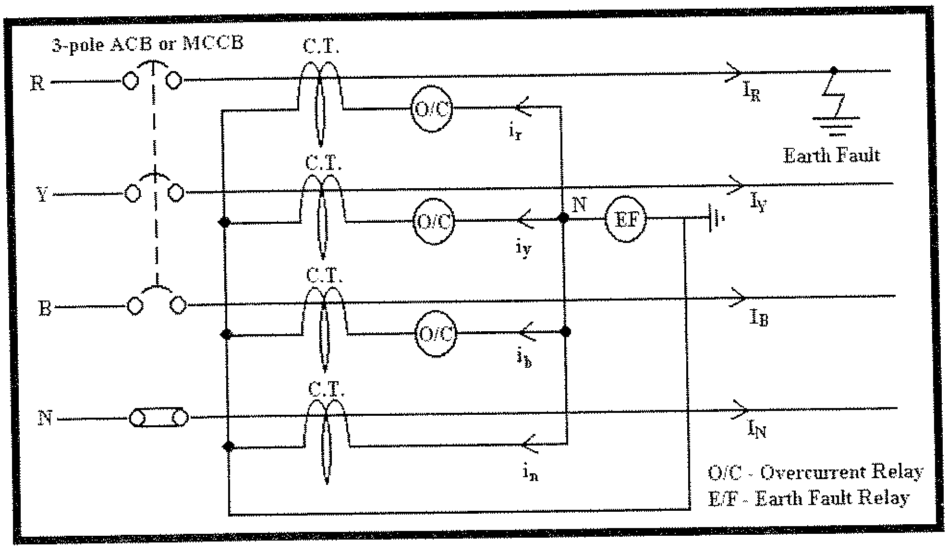


Figure 12. 3 Earth Fault Protection

(a) In a healthy L.V. electrical installation, the summation of the vector quantities of phase current and neutral current must be equal to zero.

$$\vec{I_R} + \vec{I_Y} + \vec{I_B} + \vec{I_N} = 0 \qquad \text{----------} (1)$$

Consequently, at the secondary level of the current transformer, the vector sum must also be equal to zero.

$$\vec{i_r} + \vec{i_y} + \vec{i_b} + \vec{i_n} = 0 \qquad \text{----------} (2)$$

However, at Neutral point N, following Kirchhoff's current law, $\sum i = 0$:-

$$\vec{i_r} + \vec{i_y} + \vec{i_b} + \vec{i_n} + \vec{i_{e/f}} = 0 \qquad \text{----------} (3)$$

comparing equations (2) & (3),

At neutral point N, $i_{e/f} = 0$

The earth fault relay therefore would not operate under healthy condition.
Based on the same analysis, the earth fault relay will also not operate under a balanced three-phase short circuit or a two-phase short circuit condition.

(b) When an earth fault (a short circuit in one of the phase to earth) occurs, for example, a short circuit between Red-phase and Earth, a short circuit current flows from Red-phase to Earth.

Consequently, at neutral point N, following Kirchhoff's current law,

$$\vec{i_r} + \vec{i_{e/f}} = 0$$

Therefore, $\vec{i_{e/f}} = - \vec{i_r}$

a current will therefore flow in the earth fault relay to cause it to operate.

(c) As earth fault current can be quite small sometimes due to the high earth fault impedance, earth fault relay is normally set about 10 to 20% of the rated current of the incoming circuit subject to a maximum of 120A.

Tripping Circuit

Tripping circuit is the control circuit to enable the tripping operation (or opening operation) of the circuit breaker. It consists of:-

(a) Circuit Breaker Trip Coil (Shunt Trip Coil)

A coil which produces magnetic force to trigger the tripping mechanism of the circuit breaker.

(b) Auxiliary Contact

A normally open contact to enable the 'emergency tripping' of the circuit breaker.

(c) Relay Contacts

Contacts for overcurrent relays and earth fault relays to cause the breaker to trip.

In most low voltage systems (400V system), the tripping circuit takes power supply from a 230V source. In most high voltage system, the tripping circuit takes supply from a 30V D.C. or 110V D.C. battery. A simplified circuit diagram of a tripping circuit is shown in Figure 12.4.

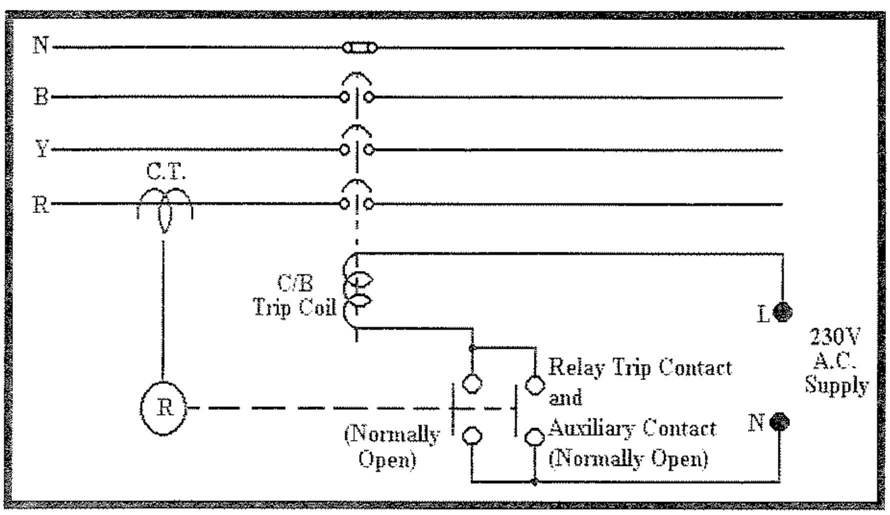


Figure 12. 4 A Simplified Diagram of a Tripping Circuit.

A typical overcurrent and earth fault protection scheme complete with shunt trip circuit is shown in Figure 12.5.

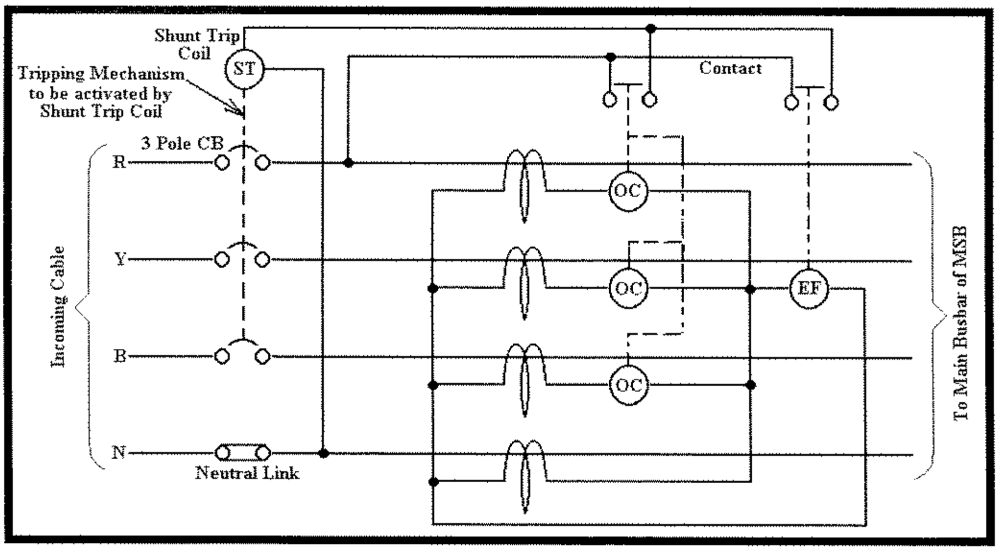


Figure 12. 5 Overcurrent and Earth Fault Relays and Shunt Trip Circuit

12.3 DEFINITE TIME LAG RELAYS (DTL RELAYS)

Definite Time Lag Relay can be seen as a relay combination of an instantaneous overcurrent element and a timing element (timer).

The operating current of the relay can be set by fixing the setting current at the instantaneous overcurrent element. The operating time of the relay can be set by fixing the time setting at the timing element.

When a fault current exceeding the current setting of the relay is detected by the instantaneous overcurrent element, the overcurrent element operated instantaneously and cause the timer to operate, the contact of timer will cause the circuit breaker to trip after a definite time lag determined by the time setting. The characteristic of DTL relay is shown in Figure 12.6 (a).

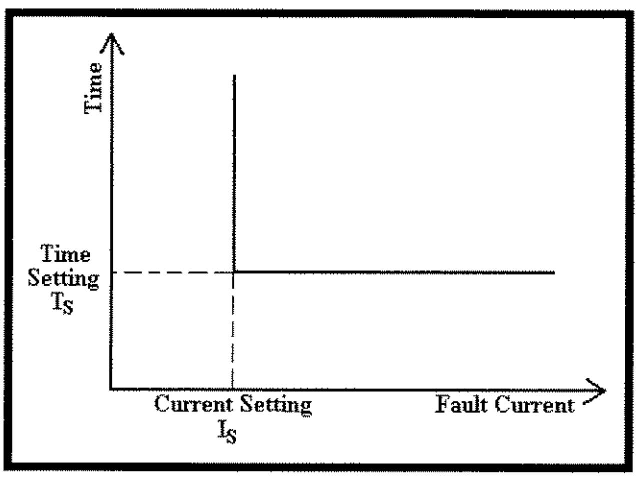


Figure 12. 6 (a) Time / Current Characteristic of DTL Relay

DTL overcurrent relays and earth fault relay are popular because of the simplicity to set. Its main application is in systems where the fault levels at the various locations do not vary greatly and hence the inverse type of relay cannot be used.

Figure 12.6 (b) illustrates the application of DTL relays in a time graded overcurrent protection system.

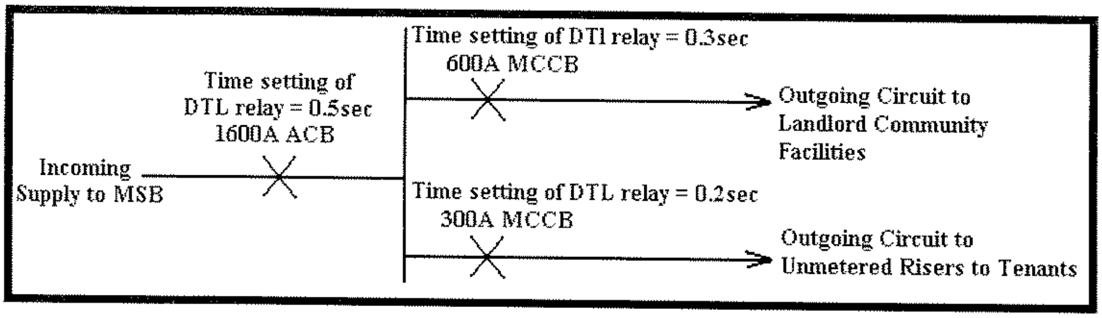


Figure 12.6 (b) Application of DTL Relays in a Time Graded System

12.4 TYPICAL SPECIFICATIONS OF DTL RELAYS

Electronic type of DTL overcurrent relays and earth fault relays are popular because they are easy to set, compact and easy to install.

Overcurrent Relay

Normally, the overcurrent relay is made to be a combination of 3 sets of overcurrent relay and a timer.

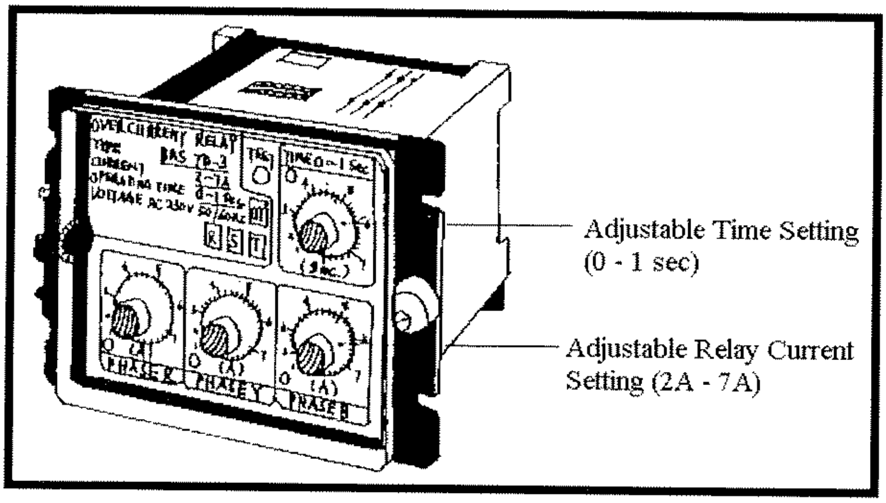


Figure 12. 7 (a) Overcurrent Relay

Typical specifications are as follows: -

Supply Voltage for Relay	:	AC, 230V, 50/60 Hz
Current Setting	:	Adjustable from 2A to 7A
Time Setting	:	Adjustable from 0 to 1 second

Earth Fault Relay

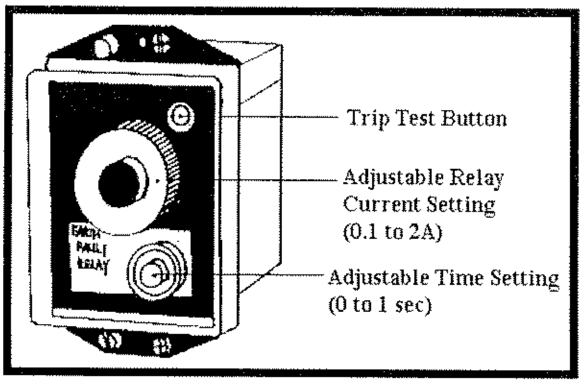


Figure 12.7 (b) Earth Fault Relay

Typical specifications are as follows:-

Supply Voltage for Relay	:	AC, 230V, 50/60 Hz
Current Setting	:	Adjustable from 0.1A to 2A
Time Setting	:	Adjustable from 0 to 1 second

12.5 PROTECTION REQUIREMENTS FOR L.V. MAIN SWITCHBOARD (MSB)

The requirements of DTL overcurrent relay and earth fault relay for main switchboard are as follows:-

Overcurrent Relay

DTL overcurrent relay (O/C) shall be set at 100% of approved load and a time lag not more than 0.5 second.

Earth Fault Relay

DTL earth fault relay (E/F) shall be set not more than 20% of approved load subject to a maximum of 120Amp and a time lag not more than 0.5 second.

Direct Acting Trip

Main incoming circuit breaker using shunt trip shall be provided with series trip (direct acting trip) device that operates with no time lag under shunt-circuit condition. The direct acting trip is normally built-in in the form of magnetic tripping.

The maximum direct acting trip settings recommended for various ranges of approved loads are as shown in Table 12.1.

Alternatively, HRC (High Rupturing Capacity) fuse can be installed in series with the circuit breaker so that the fuse will operate to cut off electricity supply under severe short circuit condition.

Range of Approved Load	Maximum Allowable Direct Trip Setting
200A & below	1200A
200A to 260A	2000A
260A to 400A	2400A
400A to 1500A	3200A
Above 1500A	4500A

Table 12.1 Recommended Direct Acting Trip Setting

12.6 WHY IS DIRECT ACTING TRIP NECESSARY?

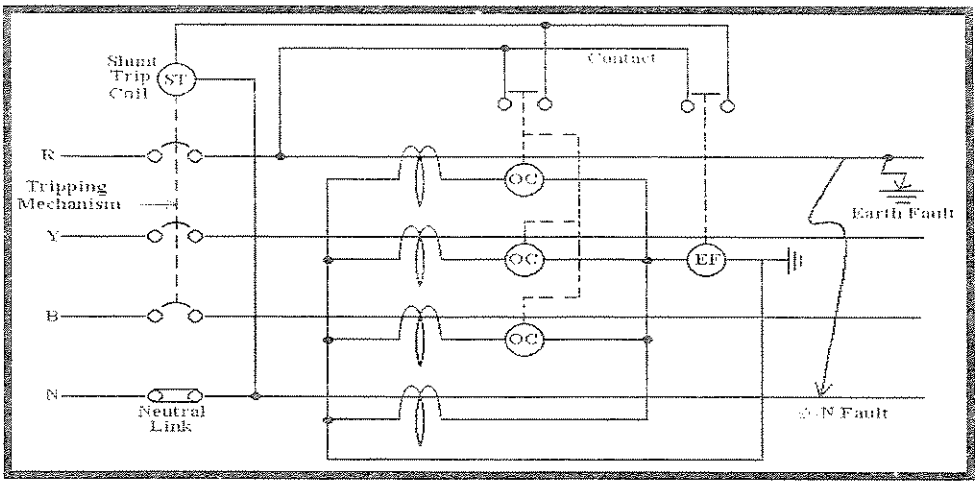


Figure 12. 8 Phase to Earth Fault & Phase to Neutral Fault

Circuit breaker using shunt trip as tripping coil for external protective relays must be provided with internal Direct Acting Trip device in series with the circuit breaker or back-up HRC fuse (High Rupturing Capacity Fuse) in series with the breaker.

This is necessary because a circuit breaker without built-in short circuit protection will not operate on Direct Phase to Earth Fault or Direct Phase to Neutral Fault on Red-phase as the shunt trip coil loses its 230V A.C. supply momentarily during the short circuit.

Example 12.1:

The incoming 1600A ACB of a 400V 3-phase main switchboard (MSB) is provided with DTL overcurrent relays and DTL Earth fault relay. The particulars of the protection equipment on the main incoming are as follows:-

Protection Current Transformers	Ratio 1600/5A
	Class 5P10
	Burden 20VA
Overcurrent Relay	Adjustable setting 2A-7A
	Time setting 0-1 sec
Earth Fault Relay	Adjustable setting 0.1A-2A
	Time setting 0-1 sec

If the approved load of the electrical installation is 1200A, 3-phase at 400V, determine the settings of overcurrent relay and earth fault relay according to the authority's requirements.

Solution:

(a) Overcurrent Relay Settings

According to the authority's requirements, the overcurrent relays current setting can only be set to 100% of approved load 1200A.

Therefore, primary trip current = 1200A

$$\text{Overcurrent relay setting} = \frac{1200A}{\text{CT Ratio}} = \frac{1200}{1600/5}$$

$$= 1200 \times \frac{5}{1600A} = 3.75A$$

Therefore the overcurrent relays are set to trip

at primary current	=	1200A
at secondary relay current	=	3.75A
with time lag	=	0.5 second

(b) Earth Fault Relay Setting

The current setting of earth fault relay is allowed to be set to 10% to 20% of the approved load subject to a maximum current of 120Amp.

$$20\,\% \times 1600A = \frac{20}{100} \times 1600 = 320A$$

Since the 20% setting exceeds 120A, the maximum allowable earth fault setting is 120A primary current.

Corresponding secondary current setting at the earth fault relay

$$= \frac{120A}{\text{CT Ratio}} = \frac{120}{1600/5} = 120 \times \frac{5}{1600} = 0.38A$$

Therefore, the earth fault relay is set to trip

at primary earth fault current	=	120A
or secondary earth fault current	=	0.38A
with a time lag	=	0.5 sec

(c) Direct Acting Trip

Direct acting trip element in the form of magnetic trip or back-up HRC fuse must be provided to operate with no time lag under severe short circuit condition.

From Table 12.1, for an approved load of 1200A, the maximum allowable direct acting trip setting is 3200A.

Example 12.2:

The electricity supply to a tenant in a multi-storey flatted factory is taken from a 2000A, 3∅, 400V main switchboard as shown in Figure 12.9.

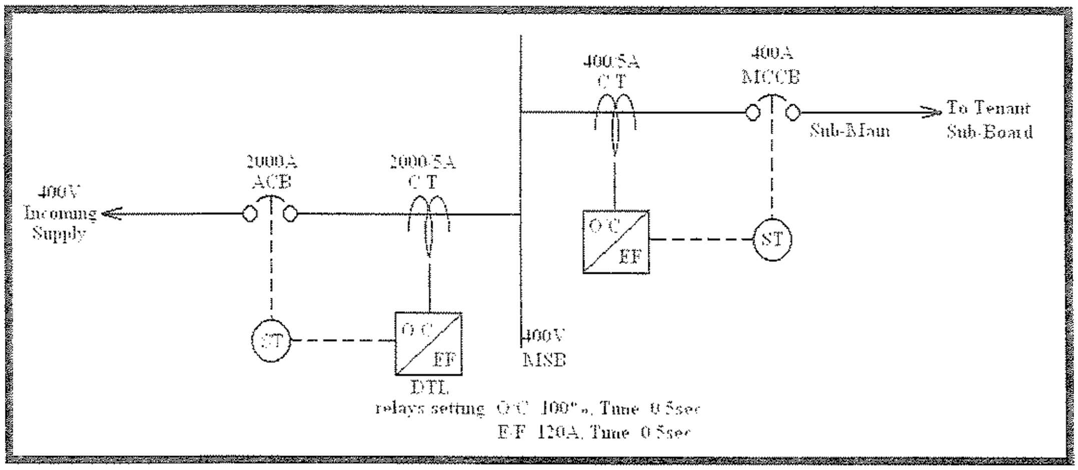


Figure 12. 9 Supply to Tenant's Switchboard

If the approved load for the tenant is 400A, 3-phase at 400V and the particulars of the protection equipment for the sub-main breaker are as follows:

Protection CT	:	Ratio 400/5A
		Class 5P10, Burden 15VA
Overcurrent Relay	:	Adjustable setting 2A-7A
		Time setting 0-1 sec
Earth Fault Relay	:	Adjustable setting 0.1A-2A
		Time setting 0-1 sec

Determine the settings of overcurrent relay and earth fault relay for the breaker of the tenanted sub-main if the settings of overcurrent relays and earth fault relays of the main incoming supply are as follows:-

Overcurrent relays: 100% of 2000A,
Time setting = 0.5sec

Solution:

(a) Overcurrent Relay Settings

Overcurrent relay shall be set to 100% of the approved load.
Therefore primary trip current = 400A

$$\text{Overcurrent relay setting} = \frac{400A}{\text{CT Ratio}} = \frac{400A}{400/5} = 5A$$

To maintain fault discrimination between the incoming ACB and the sub-main breaker, the time setting of the sub-main breaker is to be set to 0.2 sec.

Therefore grading margin = 0.5 sec – 0.2 sec
= 0.3 sec

Therefore the overcurrent relay for sub-main breaker are set to trip

at primary current	=	400A
or at secondary relay current	=	5A
with a time lag	=	0.2 second

(b) Earth Fault Relay Setting

Earth fault relay shall be set at about 10% to 20% of the approved load.

At 10%, the primary trip current
= 10% x 400A = 40A
which is lower than maximum limit of 120A

Corresponding Earth Fault relay current

$$= \frac{40A}{\text{CT Ratio}}$$

$$= \frac{40A}{400/5}$$

$$= 0.5A$$

Therefore the earth fault relay is set to trip

at primary current	=	40A
at earth fault relay current	=	0.5A
with a time lag	=	0.2 second

12.7 IDMTL RELAYS (Inverse Definite Minimum Time Lag Relays)

IDMTL relays have been evolved for use for discrimination by both time and current. With the characteristic of the IDMTL relays, the time of the operation of relay is inversely proportional to the fault current level. The actual characteristic of the relay is also a function of both the 'time' and 'current' settings.

The typical characteristics of a 3/10 and a 1.3/10 IDMTL relays are shown in Figure 12.10 (a) and Figure 12.10 (b).

Type of IDMTL Relays

(a) Normal inverse time IDMTL relay, CDG11-3 is produced by GEC measurement, the followings are the features of the relay.

(i) CDG11 characteristic conforms to BS 142 and is known as the 3/10 characteristic as shown in Figure 12.11.

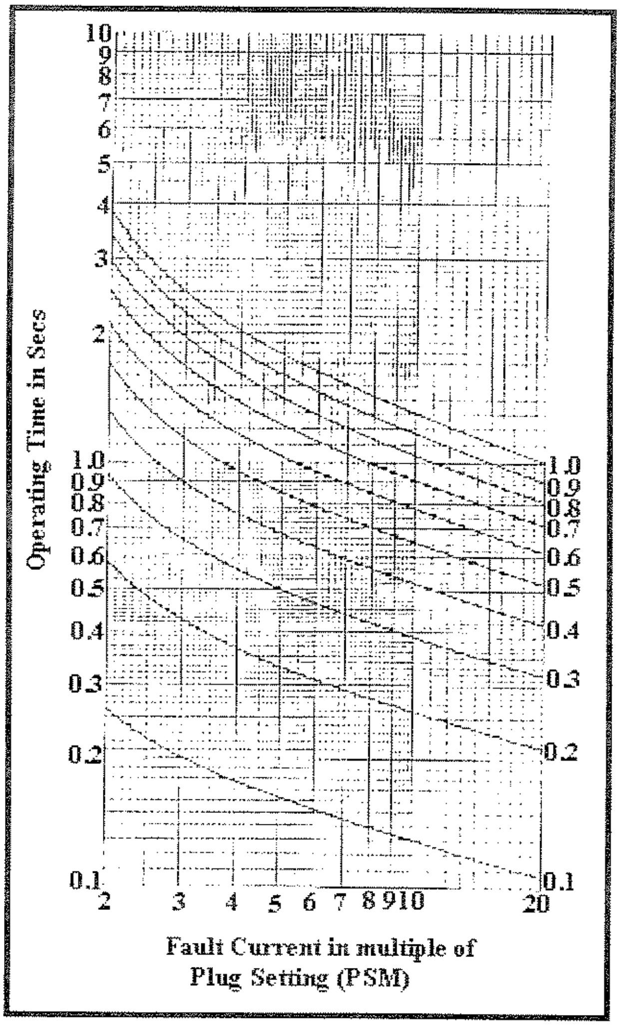


Figure 12. 10(a) Time/current characteristic of 1.3/10s IDMTL relay.

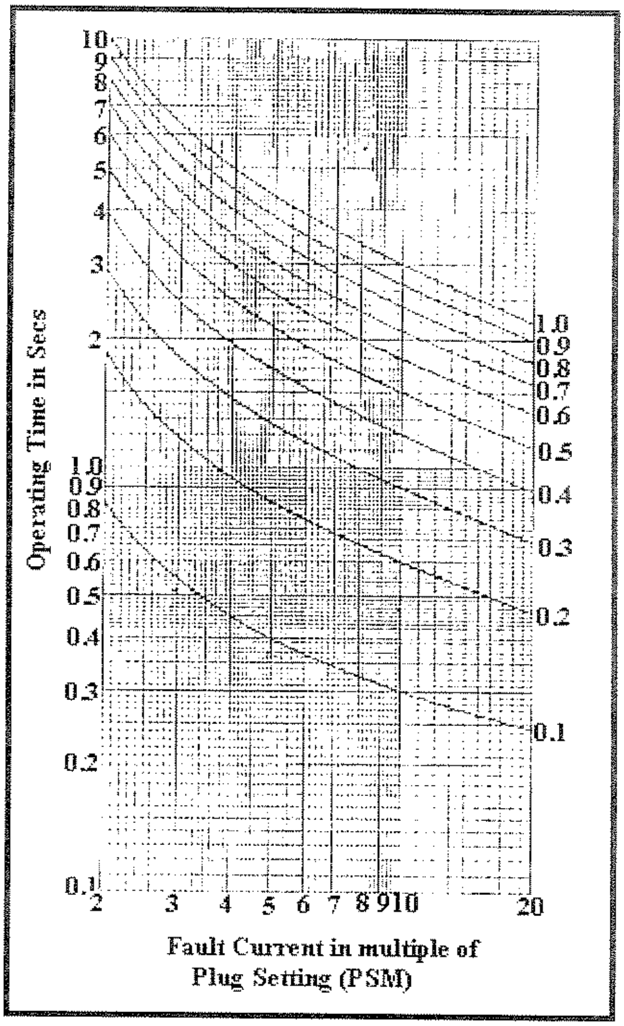


Figure 12.10 (b) Time/current characteristic of 3/10 IDMTL relay.

(ii) At ten times plug setting current and TMS of one, the relay will operate in 3 seconds.

(iii) The relay is fitted with a single disc contact.

(iv) If required, the relay can be fitted with two disc contacts (which are electrically separate). The relay is then designated CDG16. Top contact for tripping and bottom contact for alarm.

(v) The plug settings are available only in fixed discrete percentages at 25%, 50%, 75%, 100%, 125%, 150% and 175%.

(b) Normal inverse time IDMTL relay, CDG11-1.3 is also available from GEC Measurement, the followings are the features of the relays:-

(i) An alternative characteristic is available in CDG11 range and is referred to as the 1.3/10 characteristic.

(ii) It has a similar shape to 3/10 characteristic but the operating time at 10 (ten) times plug setting is 1.3 seconds (when TMS = 1).

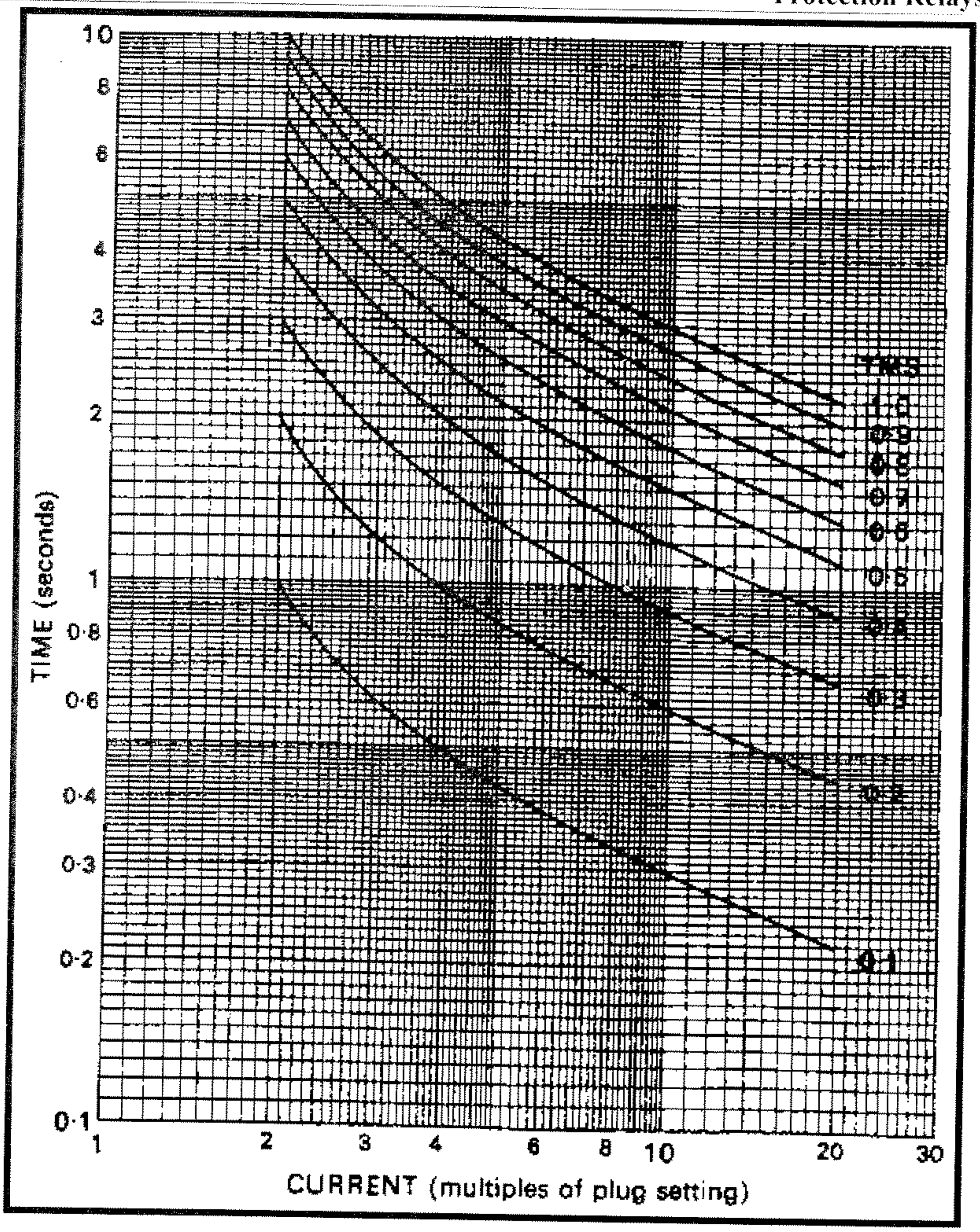


Figure 12. 11 Typical Time/Current Characteristics of 3 seconds Standard IDMTL Relay

Plug Setting and Time Multiplier Setting of IDMTL Overcurrent Relay

(a) Time Multiplier (TMS)

The spindle of induction disc IDMTL relay carries a moving contact which closes the fixed contacts, when the disc rotates through an angle (which is adjustable between 0 to 360°).

By adjusting the angle, the travel distance of the moving contact can be adjusted so that the relay can be given any desired time setting. The adjustment in the form of setting dial is known as time multiplier setting.

The time multiplier does not represent the actual operating time, but are multipliers to be used to convert the time known from the relay time/current characteristic.

As some of the terminology may be unfamiliar to many not closely conversant with relay technique, the following definitions may be of value.

Time setting multiplier is a mean of adjusting the movable back-stop which controls the travel of the disc and thereby varies the time in which the relay will close its contacts for given values of fault current.

(b) Plug Setting (P.S.)

The IDMTL relay coil is connected to the secondary of C.T. in the line to be protected and is provided with tappings. These current tappings are connected to a plug setting bridge which is normally arranged to give seven selections of tapping; these tapping values are % of the current rating of the relay.

A relay can therefore be set to operate at 5A if p.s. is set at 100% or set to operate at 2.5A if p.s. is set to 50%.

Plug setting bridge is device providing a range of current settings at which the relay will start to operate.

Pick-up errors are allowable errors in the current value at which the disc starts to move and at which its contacts close, expressed as a multiple of the plug setting.

Overshoot is the time allowed for the relay disc to continue to travel after the fault has been cleared (by the preceding relay), before it closes its contacts.

An IDMTL relay shows the adjustments of Time Multiplier (T.M.) and Plug Setting (P.S.) is shown in Figure 12.12

Time Multiplier Setting (TMS)

In order to apply the relay in a graded system, it is necessary to be able to modify the time scale of the time/current characteristic. This can be achieved by control of the amount of disc movement, since the operating time is proportional to such movement at any given current value. This adjustment is known as the time multiplier and is adjustable from 0.05 to 1.0.

This means that at time multiplier TMS = 1.0, if the time taken to operate is S second, then for TMS = 0.1, the relay will operate in 0.1 x S seconds,

For TMS = 0.8, the relay will operate in 0.8 x S seconds.

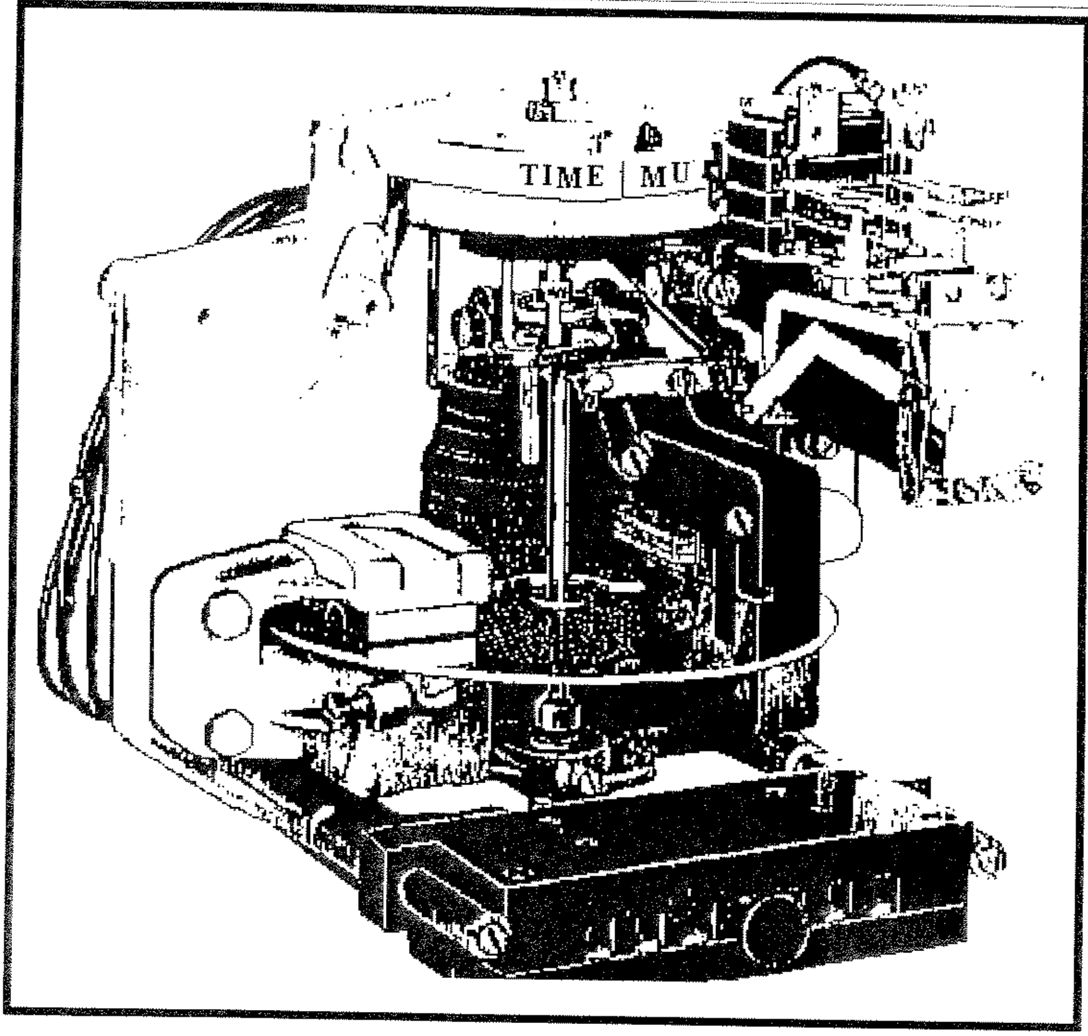


Figure 12. 12 An example of IDMTL relay

Therefore, the time multiplier setting for an IDMTL relay is defined as

$$TMS = \frac{T}{TM}$$

T - the required time of operation
TM - the time obtained from the relay characteristic curve at TMS = 1.0

<u>Plug Setting</u>

IDMTL relays are rated at 5A, which is also the rated secondary current of the current transformer (e.g. 300/5, 50/5 ratio, etc.).

Plug Settings are the adjustments in the form of tapped plug bridge for changing the relay current settings.

i.e. Relay Current Setting = Plug Setting (%) x 5A

or $$\text{Plug Setting (\%)} = \frac{\text{Relay Current Setting}}{5A}$$

Example 12.3:

If Plug Setting = 50%, Relay Current Setting = $\frac{50}{100}$ x 5A = 2.5A

If Plug Setting = 200%, Relay Current Setting = $\frac{200}{100}$ x 5A = 10A

Plug Setting Multiplier (PSM)

Plug Setting Multiplier (PSM) or multiplies of plug setting current, which appears on the X axis of the IDMTL relay characteristic, is the multiple of the actual secondary fault current flow in the relay against the relay current setting.

i.e. $$PSM = \frac{\text{Actual secondary current flow in the relay}}{\text{Relay current setting}}$$

Example 12.4:

Fault current in the primary circuit is 2400A, if C.T. ratio is 300/5A and relay plug setting is 200% (of 5A). What is the multiples of plug setting current (PSM)?

Solution:

Relay current setting = 200% x 5A
= 10A

Actual secondary current flowing in the relay = 2400A ÷ $\frac{300}{5}$
= 2400A x $\frac{5}{300}$
= 40A

Therefore, Multiplies of Plug Setting (PSM) = $\frac{40A}{10A}$ = 4 times

Example 12.5:

The 1400A incoming cable to a 400V Main Switch Board (MSB) is protected by an IDMTL overcurrent relay with 3/10 characteristic and a DTL earth fault relay. The settings of the relays are as follows:-

IDMTL O/C Relay	:	Plug setting (P.S.) = 100% Time Multiplier Setting (TMS) = 0.05
DTL E/F Relay	:	Current setting = 120A Tripping time = 0.5 sec
C.T. Ratio	:	1400A/5A

Determine:

(i) The tripping time of the overcurrent relay if a 2800A fault current passes through the incoming cable.

(ii) The maximum Earth Loop Impedance value allowable for this installation.

Solution:

$$PSM = \frac{2800A}{100\% \times 1400} = 2$$

At TMS = 1, PSM = 2, Tripping time = 10 seconds
At TMS = 0.05, Tripping time = 10 x 0.05 = 0.5 sec

Earth Fault Relay Setting = 120A
Safe Touch Voltage = 50V

Therefore, Earth Fault Loop Impedance $= \frac{50V}{120A} = 0.42\Omega$

12.8 GRADING MARGIN

The time interval between the operation of two adjacent relays depends upon a number of factors:

(a) The fault current interrupting time of the circuit breaker.
(b) The overshoot time of the relay.
(c) Errors
(d) Final margin on completion of operation – safety margin.

0.5 sec is normally recommended as the grading margin for the co-ordination of protective relays.

12.9 HIGH SET ELEMENT

IDMTL relays are normally added with a high set instantaneous overcurrent element. With the high set element, tripping time is reduced at high fault levels, overall system grading is also improved by allowing the 'discriminating curves' behind the high set instantaneous elements to be lowered.

As shown in Figure 12.13, one of the advantages of the high set elements is to reduce the operating time of the circuit protection by the shaded area below the 'discriminating curves'.

Figure 12.13 also clearly illustrates the important point that the grading with the relay immediately behind the instantaneous elements is carried out at the current setting of the instantaneous element and not at the maximum fault level that would be required for grading standard IDMTL relays. For example, relay R_2 is graded with relay R_3 at 500A and not 1100A, allowing relay R_2 to be set with a 0.15 TMS instead of 0.2 while maintaining a grading margin between relays about 0.4-0.5 of 0.2 while maintaining a grading margin between relays of about 0.4-0.5 second. Similarly, relay R_1 is graded with R_2 at 1400A and not at 2300A.

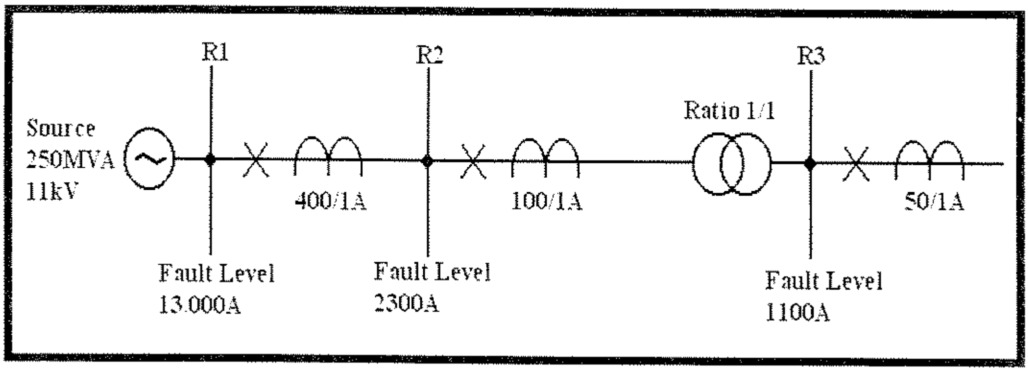


Figure 12. 13 (b) IDMTL relays with High Set Instantaneous Overcurrent Element.

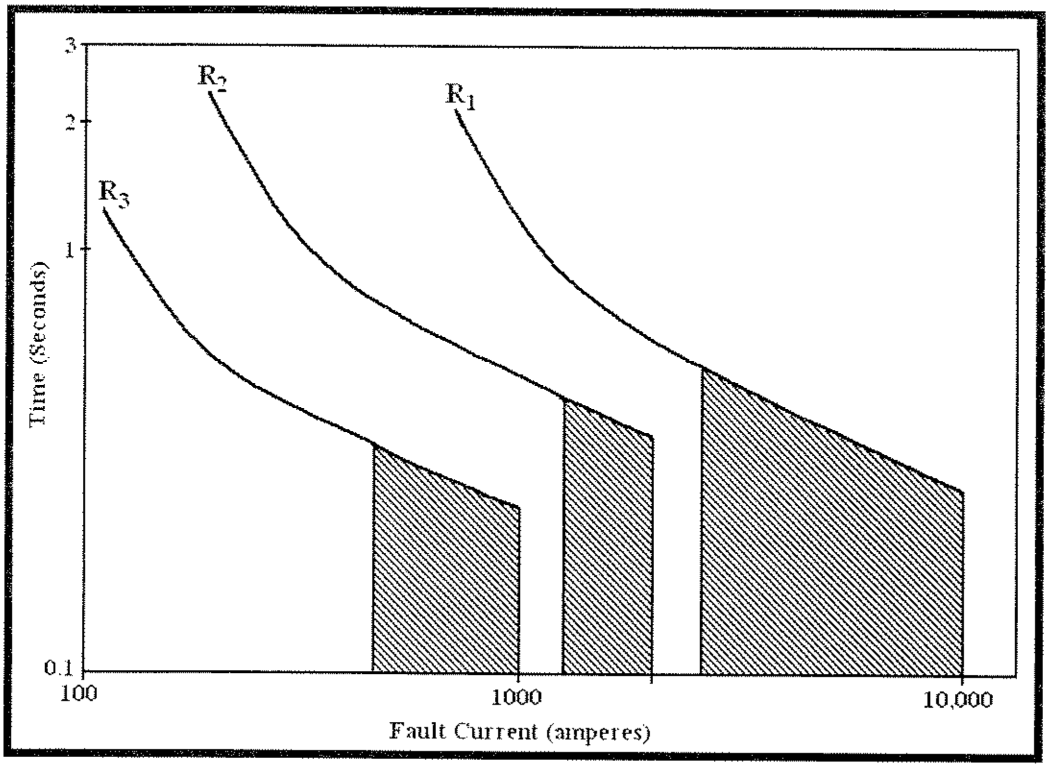


Figure 12.13 (a) Characteristic of IDMTL relays with Hi-set

Example 12.6

For the High Voltage and Low Voltage installation, study the plug setting (P.S.) and time multiplier setting (TMS) of the respective protection relays as shown in Figure 12.14.

Determine the setting for the O/C and E/F relays and the high set element for the Consumer's 22kV switchboard and the 400V Main Switchboard.

Solution:

(a) $I_{F.L.}(400V) = \dfrac{1500kVA}{\sqrt{3} \times 0.4kV} = 2165A$

$I_{F.L.}(22kV) = \dfrac{1500kVA}{\sqrt{3} \times 22kV} = 39.37A$

(i) Therefore, Plug setting (400V) = $\dfrac{\text{Maximum Allowable Load Current}}{\text{Primary Rated Current to CT}}$

$= \dfrac{2165A}{2500A} = 86.6\%$

i.e. O/C relay setting at 400V ACB = 86.6% x 5A = 4.32A

As rotating disc relay which is on fixed discrete tapping at 25%, 50%, 75%, 100%, etc., it cannot be used if we wish to set at 86.6%, alternatively electronic type relay which can be set at any percentage may be used.

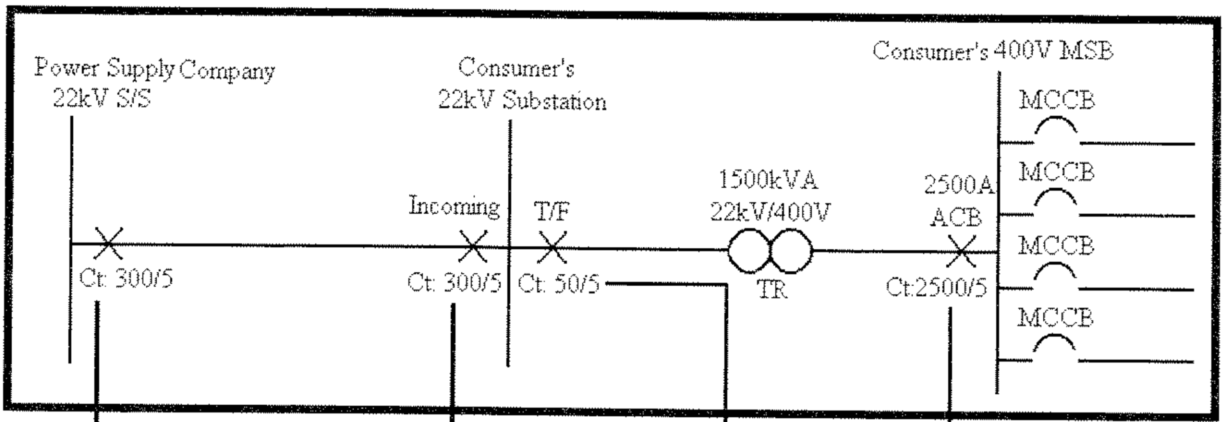


Figure 12. 1

Ct: 300/5	Ct: 300/5	Ct: 50/5	Ct: 2500/5
O/C relay	**O/C relay**	**O/C relay**	**O/C relay**
(3/10 IDMTL)	(3/10 IDMTL)	(3/10 IDMTL)	(3/10 IDMTL)
P.S. – 200%	P.S. – 100%	P.S. – 100%	P.S. = (2165A/2500A x 100%) = 86.6%
T.M.S. – 0.1 (maybe 0.2 under special circumstances)	T.M.S – 0.1	T.M.S – 0.1	T.M.S – 0.1 (or 0.05)
	High Set – 4 to 9 times	High Set – 4 to 9 times (set to avoid through fault current from LT fault to trip Incoming)	Recommended: Direct Acting Trip = 4500A to 5000A
E/F relay	**E/F relay**	**E/F relay**	**E/F relay**
(3/10 IDMTL)	(3/10 IDMTL)	Voltage operated (Instantaneous)	(DTL)
P.S. – 60%	P.S. – 40% (Maybe consider 20%) (i.e. relay current 1A)	Operating Voltage = 20V	P.S. – 100A (Maybe 120 – 250A)
T.M.S – 0.1	T.M.S – 0.1		TD = 0.5 sec
	High Set – 5 times		

(ii) $I_{F.L.}\ (22kV) = \frac{1500kVA}{\sqrt{3} \times 22kV} = 39.37A$

As C.T. ratio on T/F panel normally come in 100/50/5A or 150/75/5A and the O/C relay normally come in the form of rotating disc relay with discrete Tapping 25%, 50%,75%, 100%, etc. It is difficult to set O/C relay exactly at $I_{F.L.} = 39.37A$. In this case CT ratio at 50/5A is selected and the nearest P.S. available is 100% x 50A (Primary rated current of C.T.) = 50A. It means overloading must be limited by the protection on L.V. side.

(b) Calculation of Prospective 3-phase short circuit current on 400V MSB

$$\text{Fault Level} = \frac{1.5MVA}{6\%} = 25MVA$$

$$I_{SC}\ (3\varnothing) = \frac{25 \times 10^6}{\sqrt{3} \times 400} = 36{,}000A$$

Through fault current on 22kV side of transformer,

$$I'_{SC} = \frac{25 \times 10^6}{\sqrt{3} \times 22 \times 10^3} = 656A$$

(c) At $I_{SC} = 36{,}000A$, how fast will the O/C relay of the 400V MSB operate?

$$PSM = \frac{I_F}{P.S.} = \frac{36{,}000A}{2165A} = 17 \text{ times}$$

At TM = 0.1, operating time = 0.26 sec

(d) At $I'_S = 656A$, how fast will the O/C relay of the 22kV side of the transformer operate?

$$PSM = \frac{I_F}{P.S.} = \frac{656A}{50A} = 13 \text{ times}$$

At TM = 0.1, operating time = 0.28 sec

(e) Since both O/C relays almost trip at the same time when a 3-phase short occurs on the 400V MSB, other means must be provided on the O/C relay and ACB of the 400V side to enable the ACB to trip faster than the H.T. switchgear.

To add Direct Acting trip on ACB (set at 5000A to trip) or to set the Hi-set element of the O/C Relay of the 400V side to operate at 5000A.

Questions – Chapter 12

1. Draw a wiring diagram to show the connections of an overcurrent and earth fault protection system using 4 current transformers in a 3-phase 400A, 4-wire system. Your wiring diagram should include a 230V shunt trip circuit.

   Briefly explain the operation of overcurrent relay and earth fault relay.

2. Explain the meaning of the following abbreviated descriptions used for current transformers:-

(a) 1600A/5A CL5P10	15VA
(b) 800A/5A CL5P5	20VA
(c) 400A/5A CL0.1	15VA
(d) 600A/5A CL1	20VA

3. The incoming 1000A ACB of a 400V 3-phase main switchboard (MSB) is provided with DTL overcurrent relays and DTL Earth fault relay. The particulars of the protection equipment on the main incoming are as follows:-

Protection current transformers:	Ratio 1000/5A
	Class 5P10
	Burden 20VA
Overcurrent relay:	Adjustable setting 2A-7A
	Time setting 0-1 sec
Earth fault relay:	Adjustable setting 0.1A-2A
	Time setting 0-1 sec

   If the approved load of the electrical installation is 800A, 3-phase at 400V, determine the settings of overcurrent relay and earth fault relay according to the authority's requirements.

4. The electricity supply to a tenant in a multi-storey flatted factory is taken from a 1000A, 3-phase, 400V main switchboard as shown in Figure 12.15.

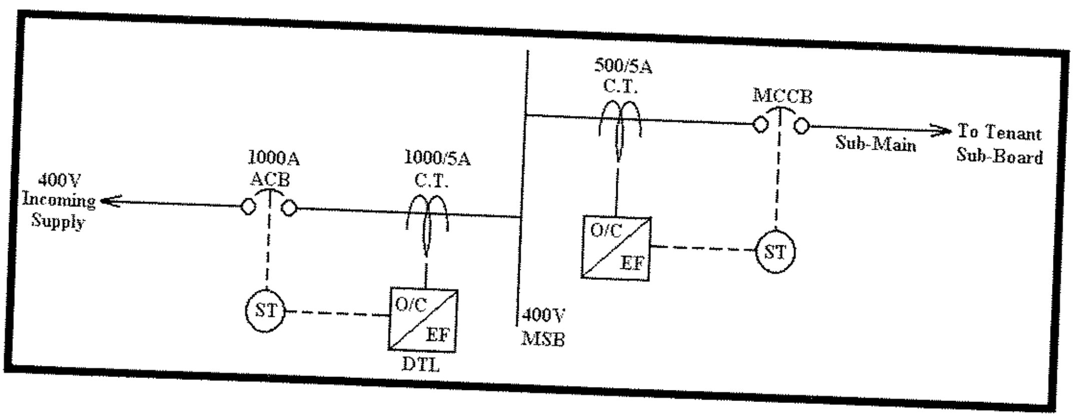


Figure 12. 15 Supply to Tenant's Switchboard

If the approved load for the tenant is 400A, 3-phase at 400V and the particulars of the protection equipment for the sub-main breaker are as follows:

Protection current transformers:	Ratio 500/5A
	Class 5P10, Burden 15VA

Overcurrent relay:	Adjustable setting 2A-7A Time setting 0-1 sec
Earth fault relay:	Adjustable setting 0.1A-2A Time setting 0-1 sec

Determine the settings of overcurrent relay and earth fault relay for the breaker of the sub-main.

5. For a 1.3/10 characteristic IDMTL relay,

   (a) If Time Multiplier Setting (TMS) = 1
   & Multiple of Plug Setting (PSM) = 10

   Find the tripping time, T from the characteristic.

   (b) For Time Multiplier Setting (TMS) = 0.5
   & Multiple of Plug Setting (PSM) = 10

   Calculate the tripping time, t and check with the characteristic to see whether your answer is correct.

6. For a 3/10 characteristic IDMTL Relay,

   (a) If TMS = 1 and PSM = 10, find the tripping time, t from the characteristic.

   (b) For TMS = 0.2 and PSM = 10
   Calculate the tripping time, t and check with the characteristic to see whether your answer is correct.

7. For a 3/10 characteristic IDMTL relay, if the plug setting (P.S.) is 40%.

   (a) Determine the relay current setting.

   (b) If the fault current is 3000A and the C.T. ratio of the feeder being protected is 300/5, calculate the actual secondary current flowing in the relay. Calculate the PSM for the amount of fault current.

   (c) Determine (from relay characteristic) the actual operating time of relay if T.M.S. is set at TMS = 0.2.

8. The 1000A incoming cable to a 400V main switchboard (MSB) is protected by an IDMTL overcurrent relay with 3/10 characteristic and a DTL earth fault relay. The settings of the relays are as follows:

IDMTL O/C relay:	Plug setting (P.S.) = 100% Time Multiplier Setting (TMS) = 0.1
DTL E/F relay:	Current setting = 120A Tripping time = 0.5 sec
C.T. Ratio:	2000A/5A

Determine:

(a) The tripping time of the overcurrent relay for the following fault currents:
  (i) 2000A
  (ii) 4000A
  (iii) 6000A
  (iv) 20,000A
  (v) 36,000A

(b) The secondary relay current setting of the DTL earth fault relay.

(c) Whether the O/C relay will operate for an earth fault current, $I_{E/F} = 240A$.

9. The 800A incoming cable to a 400V main switchboard (MSB) is protected by an IDMTL overcurrent relay with 3/10 characteristics. The settings of the relays are as follows:

IDMTL O/C relays:	Time Multiplier Setting (TMS) = 0.05
C.T. Ratio:	1000A/5A

(a) Determine the appropriate plug setting of the relays.

(b) Using the time current characteristics for 3/10 IDMTL relay, determine the tripping time of the overcurrent relay if a 1600A fault current passes through the incoming cable.

10. The 1500A incoming cable to a 400V main switchboard (MSB) is protected by an IDMTL overcurrent relay with 3/10 characteristic. The settings of the relays are as follows:

IDMTL O/C relays:	Plug Setting (P.S.) = 75%
	Time Multiplier Setting (TMS) = 0.1
C.T. Ratio:	2000A/5A

Using the time current characteristics for 3/10 IDMTL relay, determine the tripping time of the overcurrent relay if a 4500A fault current passes through the incoming cable.

11. The 1400A incoming cable to a 400V main switchboard (MSB) is protected by an IDMTL overcurrent relay with 1.3/10 characteristic and a DTL earth fault relay. The settings of the relays are as follows:

IDMTL O/C relays:	Plug Setting (P.S.) = 100%
	Time Multiplier Setting (TMS) = 0.15
DTL E/F relay:	Current Setting = 120A
	Tripping Time = 0.5 sec
C.T. Ratio:	1400A/5A

Determine:

(a) The tripping time of the 1.3/10 overcurrent relay for the following fault current:
   (i) 2800A
   (ii) 5600A
   (iii) 28,000A
   (iv) 36,000A

(b) If the earthing system of this electrical installation is TN-S. Determine the maximum earth fault loop impedance allowable.

12. A 15MVA, 33kV/11kV distribution transformer with an impedance of 10% is connected to an 11kV switchboard which supplies electricity to a number of 11kV feeders. The transformer is allowed to be overloaded by 15% for short duration.

(a) Determine the appropriate current transformer ratio and plug setting for the IDMTL relays on the 33kV and 11kV sides of the transformer (the plug settings available are 50%, 75%, 100%, 125%, 150%, 175% and 200%).

(b) Neglecting the impedance of the source and cables, calculate the fault current on the 33kV and 11kV sides when a 3-phase short circuit occurs on the 11kV side of the transformer.

(c) Determine the time multiplier setting (TMS) of the IDMTL overcurrent relays on the 33kV side if a 0.4 second grading margin is required and the time multiplier setting (TM) on the 11kV side is 0.1.

Use 3/10 IDMTL characteristic for your analysis.

13. (a) Explain what you understand by:

   (i) time multiplier setting, and

   (ii) plug multiplier setting in an IDMTL induction relay.

(b) The "incoming mains" circuit breaker of a low voltage 400V main switchboard is connected to a 2MVA, 22kV/400V transformer having an impedance of 6.25%. The transformer is allowed to operate up to 100% full load continuously. The protection on the L.V. side and the H.V. side are provided by the IDMTL relays. The relays are rated at 5A.

   (i) Determine the appropriate C.T. ratio for the current transformers on the 22kV side and 400V side.

   (ii) Choose a suitable plug setting for the IDMTL relays on the 22kV side and L.V. side. (The plug settings available are 50%, 75%, 100%, 125%, 150%, 175% and 200%).

   (iii) Calculate the fault current on the H.V. side when a 3-phase short circuit occurs on the L.V. side of the transformer. Neglect the source impedance and impedance of all the cables.

(iv) If the time multiplier setting of the IDMTL relay on the 400V side is 0.1 seconds, select the time multiplier setting for the IDMTL relay on the 22kV side if a time discrimination of 0.4 seconds is required to co-ordinate the relay operations.

14. For the 3-phase, 400V motor control centre for an air-conditioning plant,

(a) Determine the trip rating of all outgoing MCCBs.
(b) Determine the trip rating of the incoming ACB.
(c) Determine the CT ratio for each circuit breaker.
(d) Calculate the motor full load currents, motor starting currents and motor inrush current for each motor and determine the appropriate P.S. (%) and T.M. of the 3/10 IDMTL overcurrent relay for the main breaker.

Assume power factor = 0.85 and efficiency at 90% for each motor at full load.

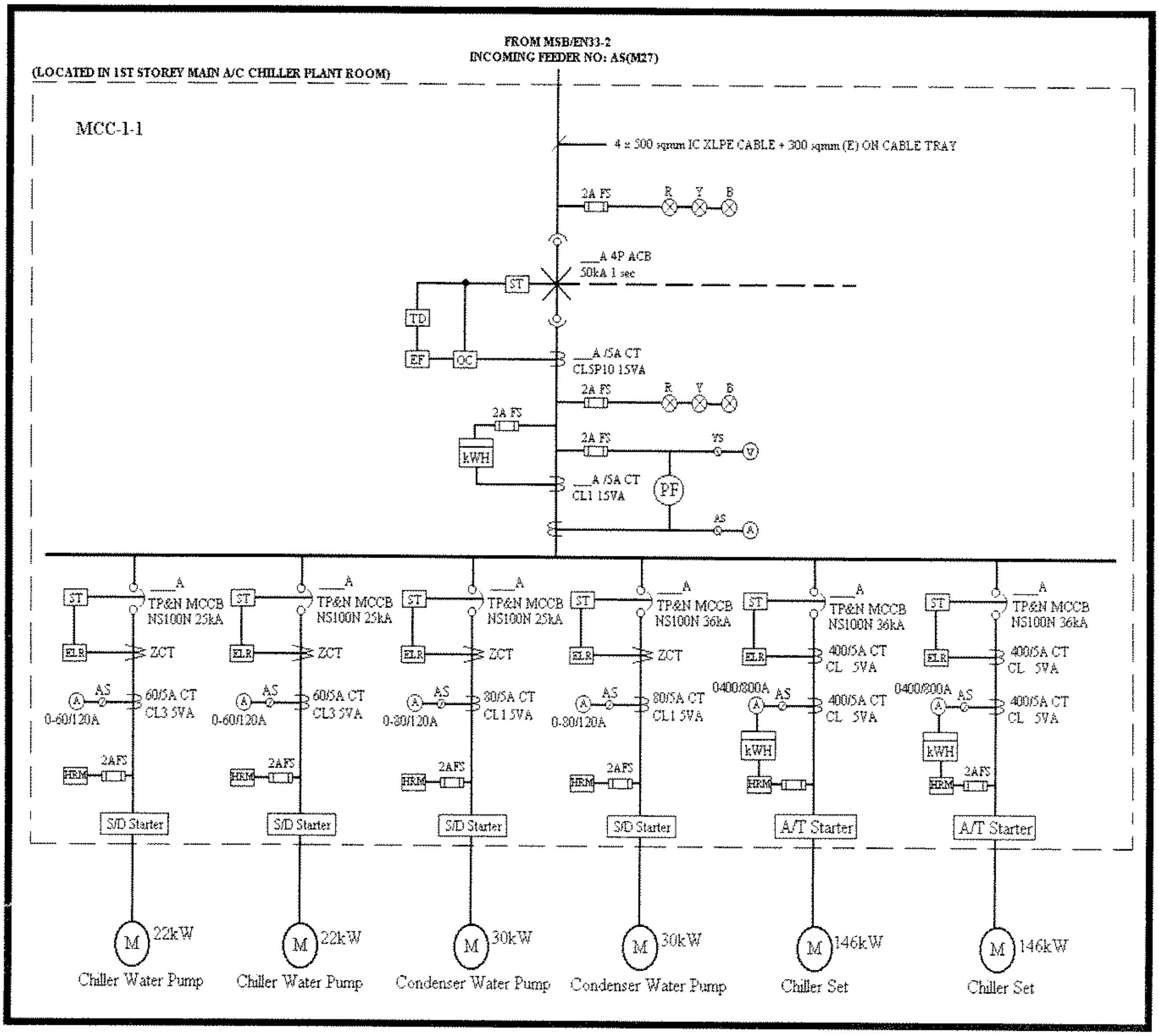


Figure 12. 16 Single Line Diagram of MCC-1-1

CHAPTER 13
FAULT CALCULATION BY OHMIC VALUE METHOD

13.1 INTRODUCTION

Short Circuit

Short-circuit faults in an electrical installation can arise as a result of: -

(a) Failure of insulation within equipment or distribution feeders.
(b) Wrong connection of terminations.
(c) Negligence.

Effects of Short Circuit Current

When a short-circuit occurs, a very high fault current flows from the source of supply to the fault point; the two effects of this high short-circuit are: -

(a) Dissipation of a tremendous amount of heat energy (thermal energy) in the complete distribution system.

Thermal energy = (I^2R) x Duration of the fault

(b) Setting up of a very high oscillating mechanical force (proportional to I^2) between two conductors, which may cause severe mechanical damage to the installation.

Protection against Short Circuit

The application of short-circuit protective devices is dependent on the knowledge of short-circuit current levels at the various locations in the power distribution system.

Short-circuit protective devices are circuit breakers or fuses at all voltage levels. The circuit breakers or fuses selected must be capable of interrupting the fault current at the rated voltages that may flow under any of the following short-circuit conditions: -

(a) Single phase to Earth Fault
(b) Phase to Neutral Fault
(c) Phase to Phase Fault
(d) Two (2) Phase to Earth Fault
(e) Three (3) Phases Fault
(f) Three (3) Phase to Earth Fault

Interrupting Capacity of Protective Device

When subjected to a short-circuit, protective devices having inadequate interrupting capacity may explode resulting in injury to personnel and causing serious damage to the installation.

The short-circuit rating of a protective device is the maximum fault current that the device can interrupt safely and must therefore not be less than the calculated short circuit current at the point of installation.

13.2 PROSPECTIVE SHORT CIRCUIT CURRENT

Consider an industrial installation customer taking its supply from the Supply Authority at the main intake receiving station and then distribution to loads substations through feeder cables and step-down transformers for supplies to various types of loads. The configuration in its simplest forms is as shown in Figure 13.1.

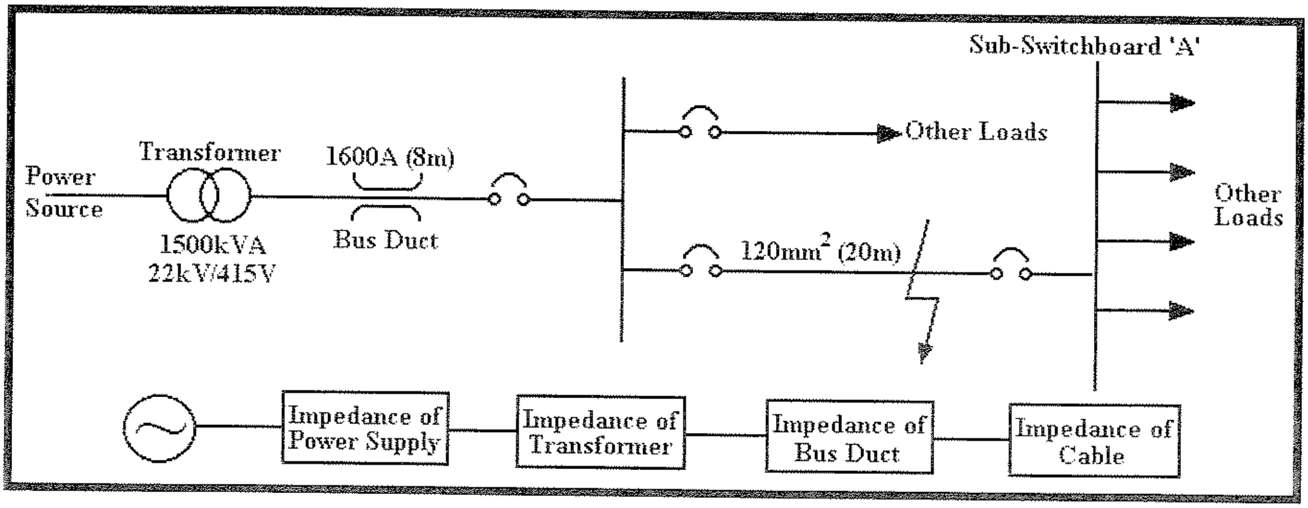


Figure 13. 1 Total system impedance which limits the short circuit current

The 'prospective' level of fault current at the point of installation is the r.m.s. symmetrical current that would flow in a circuit due to the nominal applied voltage when a short-circuiting occurs at that point.

Total System Resistance R_T = [Resistance of Power Source] + [Resistance of Transformer] + [Resistance of Bus Duct] + [Resistance of Cable]

Total System Reactance R_T = [Reactance of Power Source] + [Reactance of Transformer] + [Reactance of Bus Duct] + [Reactance of Cable]

Total System Impedance $Z_T = \sqrt{R_T^2 + X_T^2}$

Therefore, r.m.s. value of a 3-phase symmetrical short-circuit current

$$I_r = \frac{\text{Line Voltage}}{\sqrt{3} \times Z_T}$$

Ohmic Value Method

The above calculation makes use of the ohmic value of impedance of the power source, transformer, bus duct and cables for the fault current calculation and it is therefore known as ohmic value method.

Ohmic value method for fault current is effective for simple system with one voltage level only (i.e. 400V 3-phase or 230V single phase system).

Example:

The impedance of the components, in the electrical installation as shown in Figure 13.1 are given as follows: -

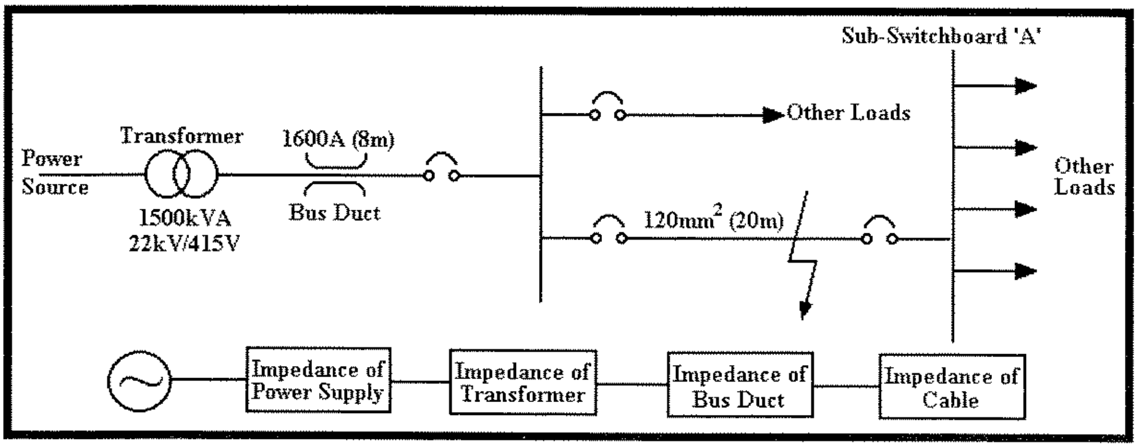


Figure 13.1 Total System Impedance Which Limits the Short Circuit Current

$R_S = 0.8\ m\Omega$, $X_S = 5\ m\Omega$ } Impedance of Power Source and Transformer

$R_B = 0.023 \times 8 = 0.184\ m\Omega$, $X_B = 0.045 \times 8 = 0.36\ m\Omega$ } Impedance of Bus Duct

$R_c = 0.14 \times 20 = 2.8\ m\Omega$, $X_c = 0.13 \times 20 = 2.6\ m\Omega$ } Impedance of the 120 mm² L.V. Cable

Determine the prospective 3-phase short circuit current at the sub-switchboard 'A'

$R_T = R_S + R_B + R_C = 0.8 + 0.184 + 2.8 = 3.784\ m\Omega$

$X_T = X_S + X_B + X_C = 5 + 0.35 + 2.6 = 7.96\ m\Omega$

} Total impedance up to the point of short circuit

Total System Impedance = $Z_T = \sqrt{3.784^2 + 7.96^2} = 8.8\ m\Omega$

The prospective short-circuit current at point 'A'

$$I_{sym} = \frac{\text{Line Voltage}}{\sqrt{3} \times Z_T} = \frac{400}{\sqrt{3} \times 8.8 \times 10^{-3}} = 26{,}000\text{A} = 26\text{kA}$$

13.3 MAIN OBJECTIVES OF FAULT CALCULATIONS

(a) To determine maximum 3-phase short-circuit currents for the selection of suitable circuit breakers with the necessary interrupting capacities.

(b) To determine the time co-ordination of protective relays with the knowledge of the fault currents that must be protected.

(c) To ensure that busbars are adequately braced against the short-circuit forces produced by the high fault currents. Short-circuit forces are proportional to the square of the fault current.

(d) To select cables with ability to withstand short-circuit heating for the time required to clear circuit by the circuit breakers or fuses.

13.4 SYMMETRICAL SHORT-CIRCUIT CURRENT

A normal load current is said to be symmetrical if the peaks of the envelopes of the load current wave are symmetrical about the zero axis as shown in Figure 13.2(a).

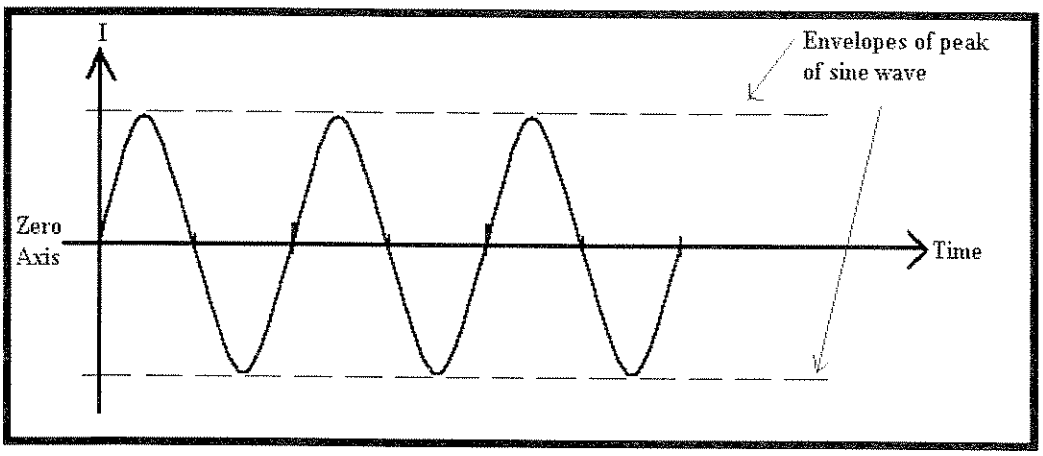


Figure 13. 2(a) Symmetrical Wave of a Normal Load Current

For symmetrical short-circuit current, the current wave can be seen in Figure 13.2(b)

13.5 ASYMMETRICAL FAULT CURRENT

Power circuits can be seen as a combination of simple resistors, inductors and capacitors. A sudden application of a sinusoidal voltage source on these components like in the case of a circuit breaker closing onto a short circuit, will produce the typical transient current waveform as shown in Figure 13.3.

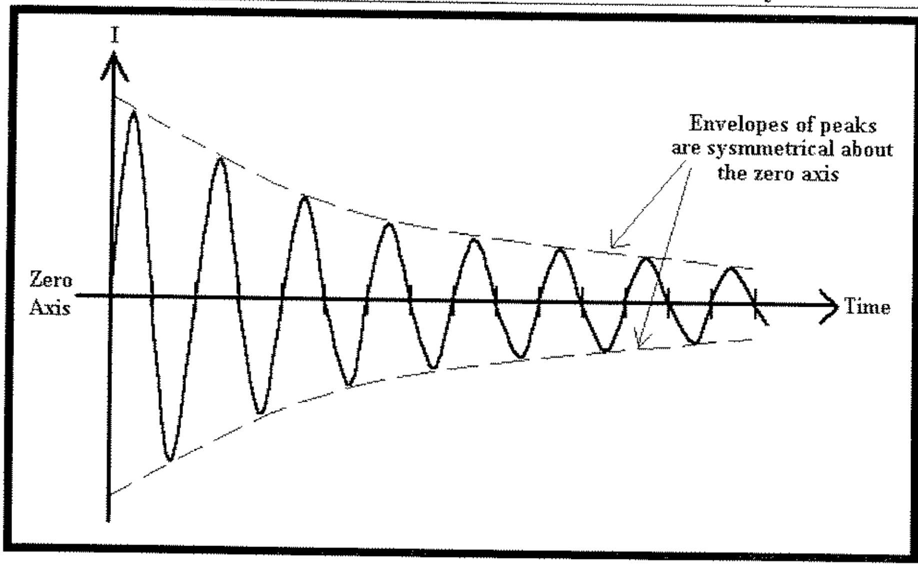


Figure13.2(b) Symmetrical Short-Circuit Zero Axis Current Wave

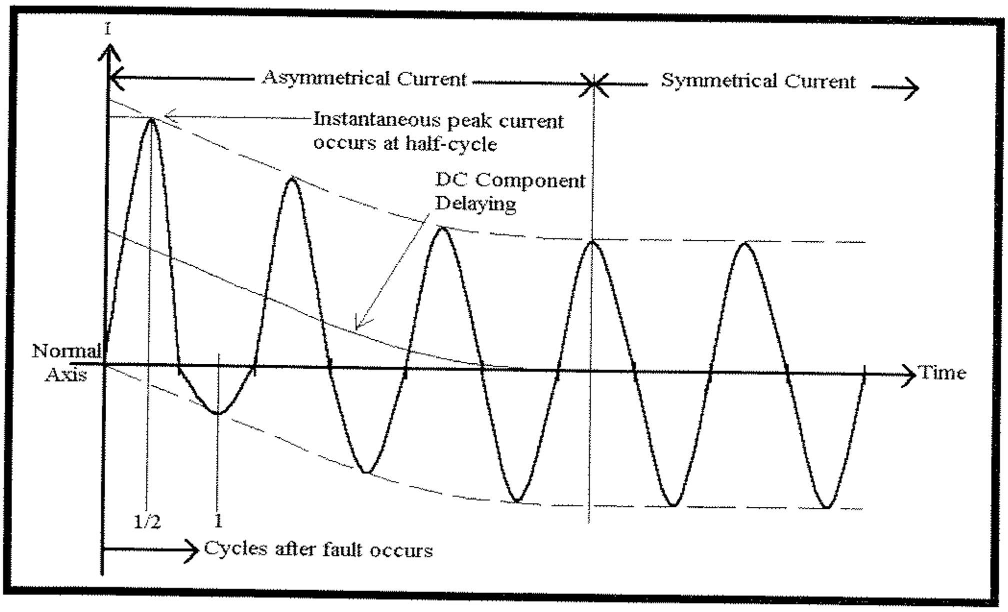


Figure 13. 3 Asymmetrical fault current due to Inductive Nature of Power System

The current is displaced from the zero axis for the first few cycles and then gradually assumes a symmetrical waveform after the subsidence of the transient.

The asymmetry of the short circuit current waveform depends on 2 things: -

(a) Presence of circuit reactance X in power system and the X/R ratio in the system.
(b) The exact time that the fault occurs.

X/R Ratio

In low voltage systems where X/R ratio tends to be lower, the rate of decaying of the DC components is faster. Conversely, with high voltage systems, the X/R ratio tends to be higher and the rate of decay is slower.

Multiplying Factor

Studies have been done on typical power systems and multiplying factors have been recommended to account for asymmetrical fault currents in the design of electrical system and equipment.

Prospective Asymmetrical Peak Short Circuit Current

The asymmetrical peak short-circuit current is responsible for the mechanical damage which results from the high oscillating mechanical forces (proportional to I^2) set up between two conductors which are adjacent and parallel to each other.

(a) For more severe cases, the prospective peak current can be $2\sqrt{2}$ x r.m.s. value of the symmetrical fault current.

Therefore, Asymmetrical peak fault current
= 2 x (Peak Value of Symmetrical Fault Current)
= 2 x ($\sqrt{2}$ x r.m.s. Value of Symmetrical Fault Current)
= 2 x 1.414 x r.m.s. Symmetrical Value
= 2.828 x r.m.s. Symmetrical Value

(b) However, for L.V. System where the power factor of the system is about 0.15 to 0.2: -

Ratio of X/R = 1/0.2 = 5

The multiplying factor is about 1.5 x $\sqrt{2}$ = 2.2

Asymmetrical peak fault current = 2.2 x r.m.s. symmetrical value (in kA)

(c) For H.V. System (above 1000V), the recommended multiplying factor is 1.8 x $\sqrt{2}$ = 2.55

Asymmetrical peak fault current = 2.55 x r.m.s. Symmetrical fault current (in kA)

Example 13.1:

The supply authority's fault level at a consumer's intake is 50kA at 400V, a BS 88 200A fuse is installed. 100m of 240 mm^2 PVC/SWA/PVC cable is installed from the intake to the consumer's main switchboard.

if cables resistance R = 0.09×10^{-3} Ω per metre
reactance = 0.076×10^{-3} Ω per metre

(a) Calculate the prospective symmetrical short circuit current at the Main Switch Board (MSB).

(b) Calculate the Asymmetrical peak fault current at the MSB.

(c) Draw the waveform of the short circuit current.

Solution:

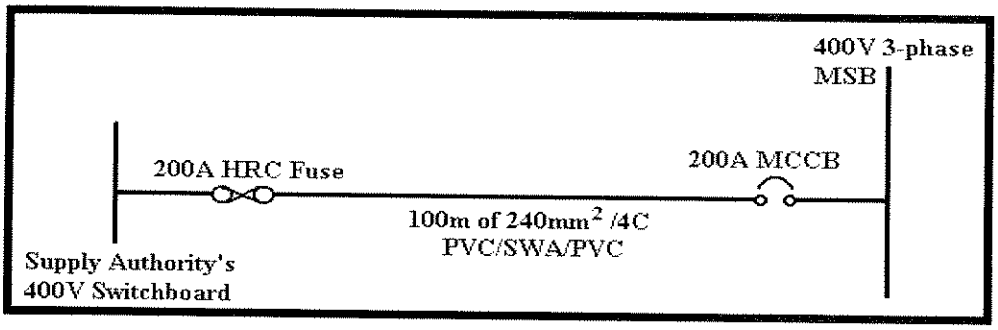


Figure 13. 4

(a) Impedance on supply authority's network

$$= \frac{400V/\sqrt{3}}{50{,}000A} = \frac{230}{50{,}000} = j0.00048\ \Omega \text{ (generally reactive)}$$

Impedance of $240mm^2$ cable = R + jX

$R = 0.09 \times 10^{-3}\ \Omega/m \times 100m = 0.009\ \Omega$
$X = 0.076 \times 10^{-3}\ \Omega/m \times 100m = 0.0076\ \Omega$

$\therefore$ Total Impedance $Z_T = R_T + X_T$

$R_T = 0 + 0.009\Omega = 0.009\ \Omega$
$X_T = 0.00048\Omega + 0.0076\Omega = 0.00808\ \Omega$

Total Impedance $Z_T = 0.009 + j0.00808$

$$|Z_T| = \sqrt{0.009^2 + 0.00808^2}$$

$$\text{Prospective Symmetrical Fault Current} = \frac{400/\sqrt{3}}{|Z_T|} = \frac{230}{\sqrt{0.009^2 + 0.00808^2}} = 15{,}600A = 15.6kA$$

$\therefore$ The Rated Breaking Capacity of the circuit breaker at the MSB must be at least 16kA or 22kA.

(b) Asymmetrical Peak Fault Current = Multiplying Factor x r.m.s. symmetrical fault current

$$= 1.5 \times \sqrt{2} \times (15.6kA)$$
$$= 2.2 \times 15.6kA$$
$$= 35\ kA_p$$

$\therefore$ The rated making capacity of the circuit breaker at the MSB must be at least $35kA_p$.

(c)

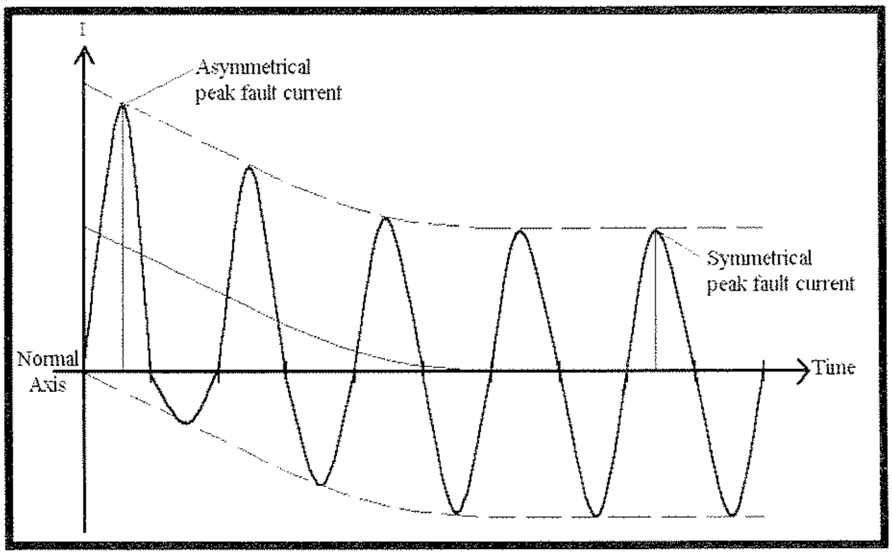


Figure 13. 5

13.6 SOURCES OF FAULT CURRENT

In order to obtain the magnitude of short-circuit current, it is necessary to consider all the possible sources (together with their reactances) which can feed the fault current. There are mainly 2 sources which can feed short-circuit current into the fault point, viz.

(a) Generators
(b) Synchronous Motors and Induction Motors

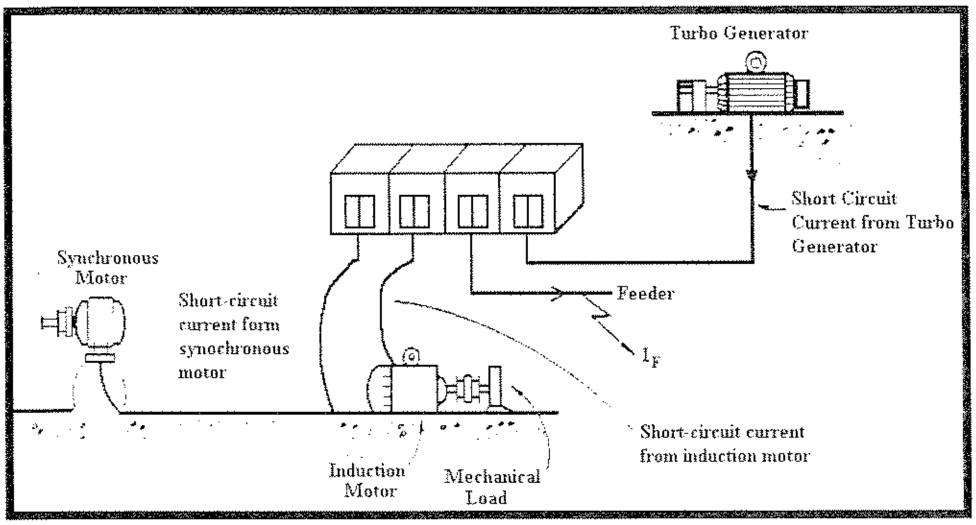


Figure 13. 6 Sources of Fault Current

When a fault occurs in a power network, the current flowing into the fault is determined by

(a) the internal EMFs of the machines in the network;
(b) the impedances of the machines;
(c) the impedances in the network between the machines and the fault including impedances of transformers, cables, etc.

Generators

On the occurrence of a short-circuit current, the generator (driven by prime movers) will continue to run at rated speed and the excitation is also maintained. So the normal voltage is still being generated and this voltage feeds a large amount of short-circuit current into the fault point.

As fault current continues to flow, the generator impedance increases rapidly as a result of increased winding temperature, voltage imbalance and changes in machine speed. As a result, the fault current decreases to a steady state condition within a few cycles.

To simplify fault calculations, the decrease in fault current is treated as an increase in reactance. Industry standards divide reactance of rotating machines under short-circuit condition into three (3) values: -

(a) Sub-transient reactance (X"d)

During the first cycle after a fault, the sub-transient reactance determines the fault current.

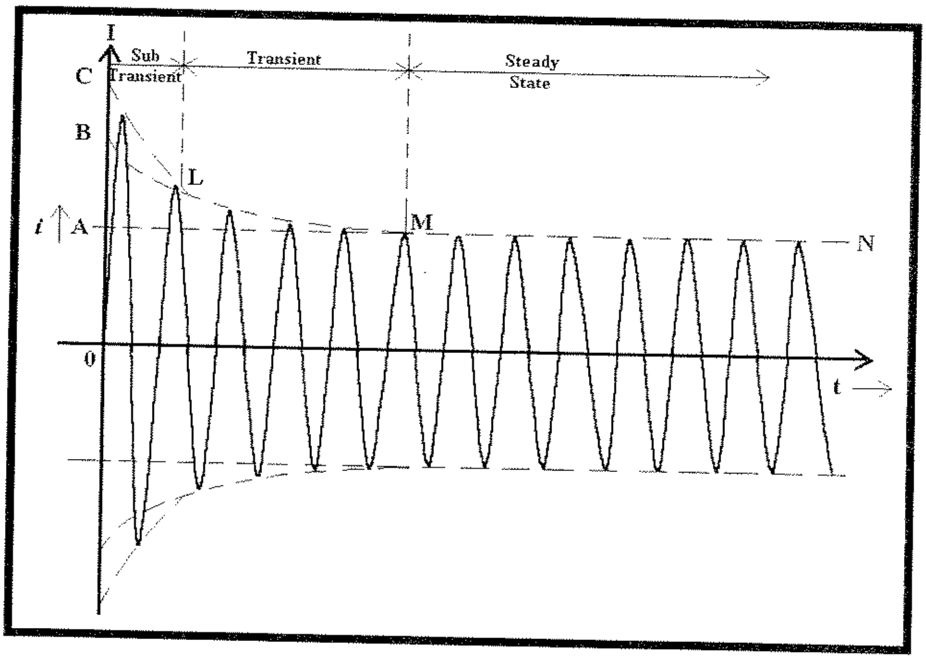


Figure 13. 7 Oscillogram of current in the phase having zero DC component.

(b) Transient Reactance (X'd)

From 0.1 second up to 0.5 second after the fault occurrence, machine reactance is termed transient reactance.

(c) Steady State or Synchronous Reactance (X_d)

Machine reactance for time in excess of 0.5 second after the occurrence of the fault. In power systems where generators are involved, the value of the reactance to be used depends on the type of fault current to be calculated. Hence, sub-transient reactance (X") must be used to calculate the sub-transient fault current, and the transient reactance (X'_d) must be used to calculate the transient fault current. Similarly, the synchronous reactance (X_d) must be used to calculate the steady state fault current.

Synchronous Motors and Induction Motors

When a short-circuit occurs, the power supply to the motor will be cut off immediately. However, the motor will continue to run due to the inertia of the motor. Also, the magnetic flux in the air gap of the motor will not be reduced to zero instantly. Hence, the back emf of the motor will still be there for a short period of time. During this time, the motor behaves like an alternator and feeds current into the fault.

Therefore, $I_{SC} = I_T + \sum I_M$

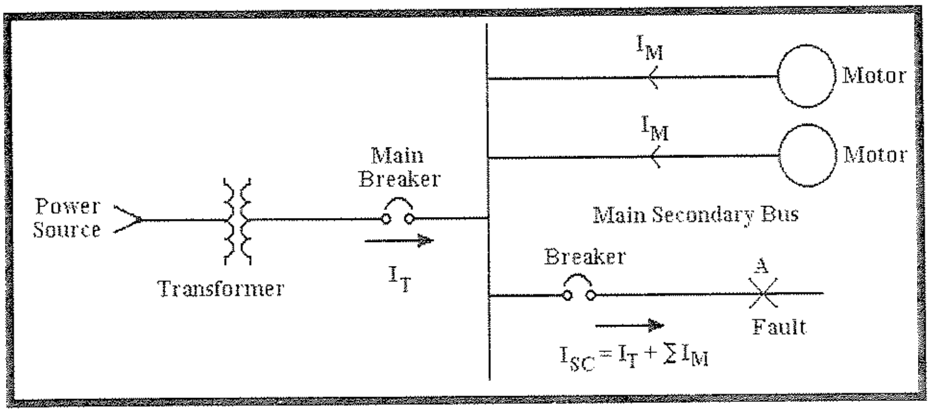


Figure 13. 8 Fault Current Contributed By Motors

Sub – Transient Reactance and Transient Reactance of Motors

As in the case of generators, the value of reactance (sub–transient or transient) to be used for motors depends on the type of fault current (sub–transient or transient) to be calculated. Within a short time, the motor will come to a complete stop and hence there will NOT be any steady state fault current contributions from synchronous or induction motors.

13.7 CALCULATION OF THREE-PHASE BALANCED FAULT CURRENTS

Single-phase to ground faults are the most common whereas three-phase short-circuit faults are the most severe faults.

Three-phase short-circuit faults are less complex to calculate since a balanced 3-phase system can be simplified to a simple single-phase representation.

Single-Phase Representation of a 3-phase Systems (Applicable to Balanced 3-Phase Systems Only)

Figure 13.9 shows a generator supplying a balanced load over a transmission line where

Z_g is Impedance of the generator winding

Z_L	is Impedance of the load
R	is Resistance of the transmission line
L	is Inductance of the transmission line
N	is Neutral Conductor between the generator neutral and the star-point of the load

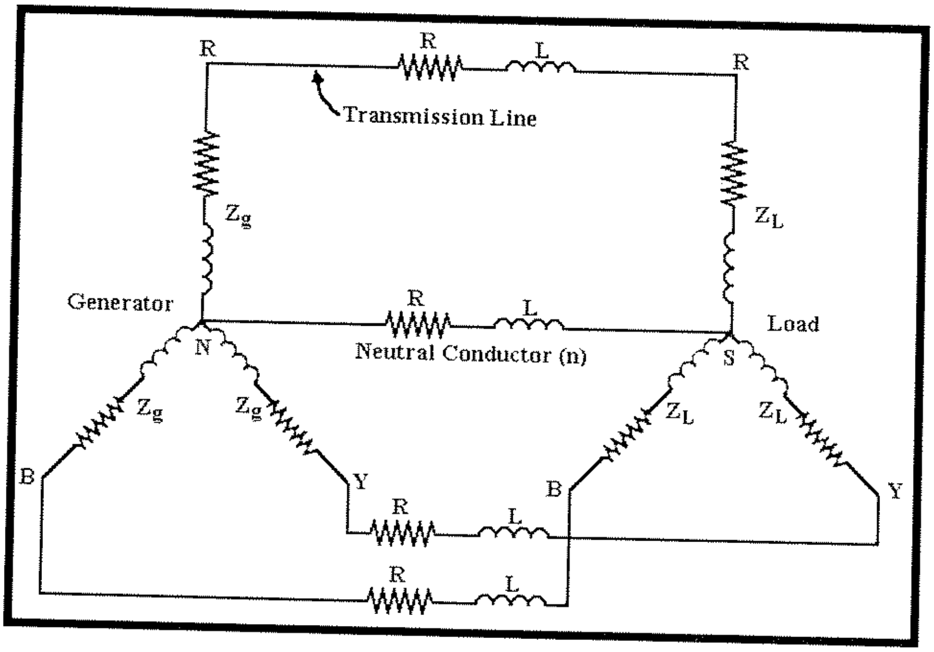


Figure 13. 9 A Balanced 3-Phase System

Since the system is balanced, the current in all the 3 phases are of the same magnitude, and there is no current in the neutral conductor.

Also, the voltages of all the 3 phases with respect to the neutral are of the same magnitude. The only difference is that the voltage across and the currents in the various phases have a phase displacement of 120°.

For the purpose of solving the problem, the above system may be represented by its single-phase equivalent circuit as shown in Figure 13.10.

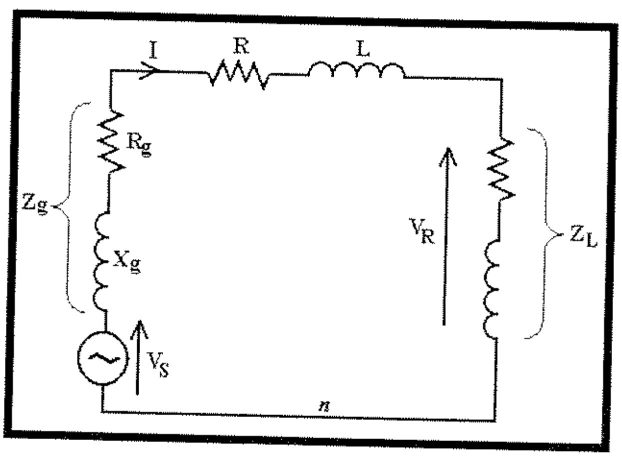


Figure 13. 10 Single-Phase Equipment Circuit

In this equivalent circuit,

I	is the line current
V_S	is the voltage of the generator per phase
V_R	is the voltage per phase across the load

Note that although the neutral conductor does not carry any current, it must be included in the single-phase equivalent circuit to complete the circuit. However, it should be emphasised that the resistance and reactance of the neutral conductor must NOT be taken into consideration when carrying out the fault calculations.

Important Points to Note:

Important points to remember when representing a 3-phase system by its single-phase equivalent circuit: -

(a) Voltages selected are line to neutral voltages of phase voltage.

(b) Current selected is the line current

(c) Resistance and inductive reactance are calculated for each phase only.

(d) There is no current in the neutral conductor (as a balanced system is being considered here) and its resistance and reactance should NOT be taken into consideration.

(e) The power calculated is power per phase.

(f) Calculations based on the single-phase equivalent circuit could be extended for all the 3 phases by noting that the currents and voltages for the other phases are equal in magnitude and displacement by 120° and 240°.

(g) Total 3-phase power = 3 x power per phase.

(h) A 3-phase delta-connected system could be replaced by an equivalent star-connected system. Hence, the above method is applicable for both the star-connected and delta-connected systems.

Symbols for Single-Line Diagrams Used in Fault Calculations

Some of the standard symbols used in single-line diagrams for fault calculations are show in Figure 13.11.

Single-line Drawing and Corresponding Impedance Diagram (Without Transformers)

Example 13.2:

The data of the power system as shown in Figure 13.12 are as follows:-

Generator 1	20,000 kVA, 6.6 kV, X" = 0.655 Ω
Generator 2	10,000 kVA, 6.6 kV, X" = 1.31 Ω
Generator 3	30,000 kVA, 6.6 kV, X" = 0.1452 Ω

Transmission Line - X = 17.4Ω

Load A 15,000 kVA, 6.6 kV, power factor 0.9 lagging
Load B 30,000 kVA, 6.6 kV, power factor 0.9 lagging

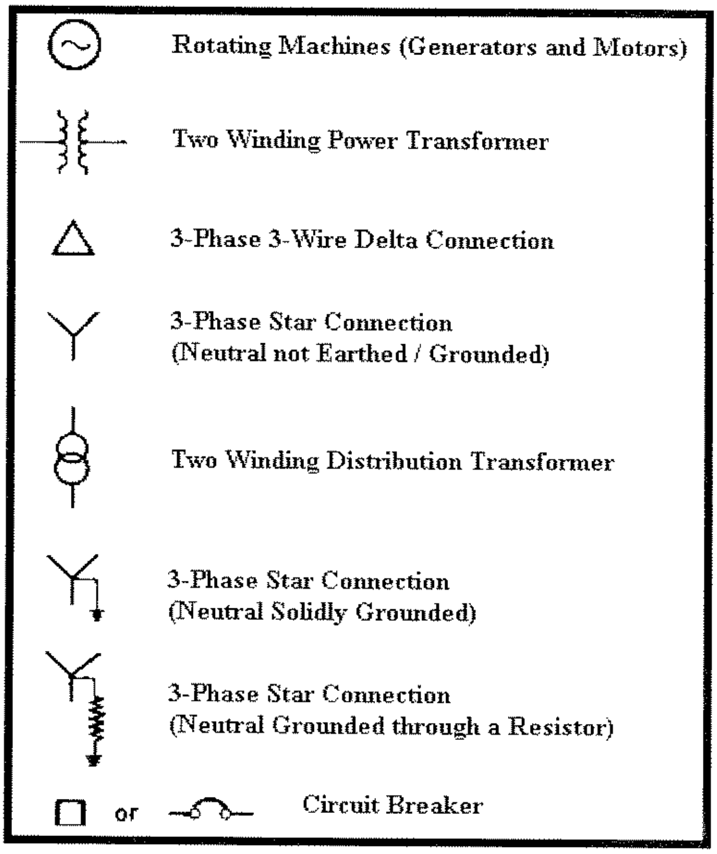


Figure 13. 11 Standard Symbols used in Single-Line Diagrams

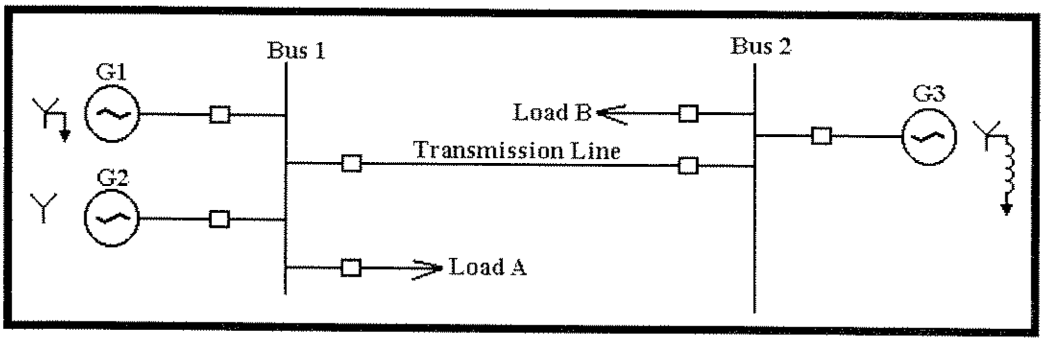


Figure 13. 12 Single Line Diagram of a Power System

Generators G1 and G2 are connected by a transmission line to another generator G3. A load is connected to each bus. All the three generators are star-connected. The star-point of G1 is solidly grounded, that of G2 is ungrounded, and that of G3 is grounded through a reactor.

Solution:

The power system shown in Figure 13.12 can now be represented by the following impedance diagram: -

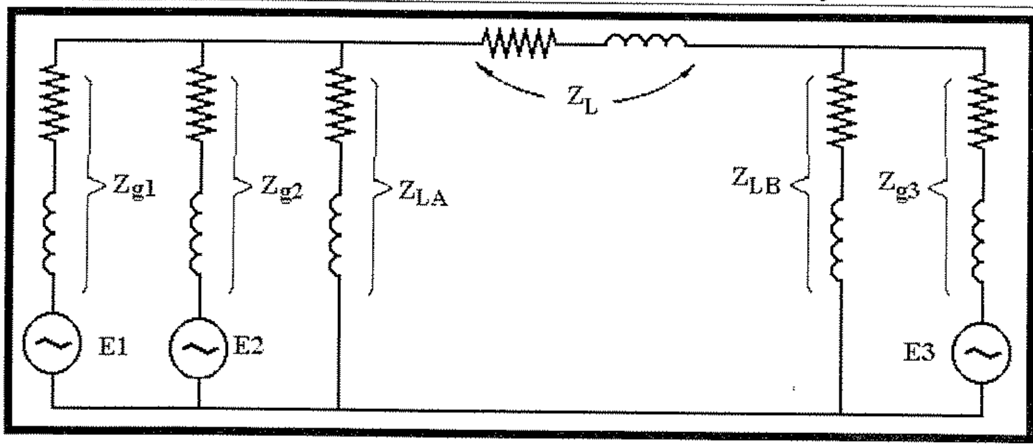


Figure 13. 13 Impedance Diagram for the Power System shown in Figure 13.12

(a) In Figure 13.13 above:

E_1, E_2, E_3 are emf's of the generator Z_{g1}, Z_{g2}, Z_{g3} are impedances of the three generators. Z_{LA}, Z_{LB} are impedances of loads A and B. Z_L is the impedance of the transmission line. Note that in general, resistances of the motors, generators and transmission lines (and cables) are small when compared with their reactances. Hence, these resistances may be neglected for the purpose of fault calculations.

(b) Also, the load impedance has no effect on the fault current and may be ignored.

If the resistances and load impedances are neglected, the resulting diagram is called the "reactance diagram". The reactance diagram for the power system shown in Figure 13.12 is given below: -

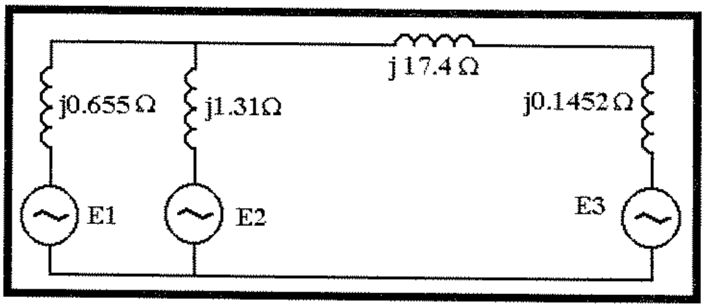


Figure 13. 14 Reactance Diagram for the Power system shown in Figure 13.12

Single-line Drawing and Corresponding Reactance Diagram (With Transformers Connected in the Circuit)

Example 13.3:

The data of the power system network are as follows: -

Generator 1 20,000 kVA, 6.6 kV, X" = 0.655 Ω
Generator 2 10,000 kVA, 6.6 kV, X" = 1.31 Ω
Generator 3 30,000 kVA, 6.6 kV, X" = 0.1452 Ω
Transformers T_1 and T_2 – 30,000 kVA, 6.6/38.1 kV,

and reactance X = 14.52Ω referred to the high tension side.
Transmission line – reactance = 17.4 Ω

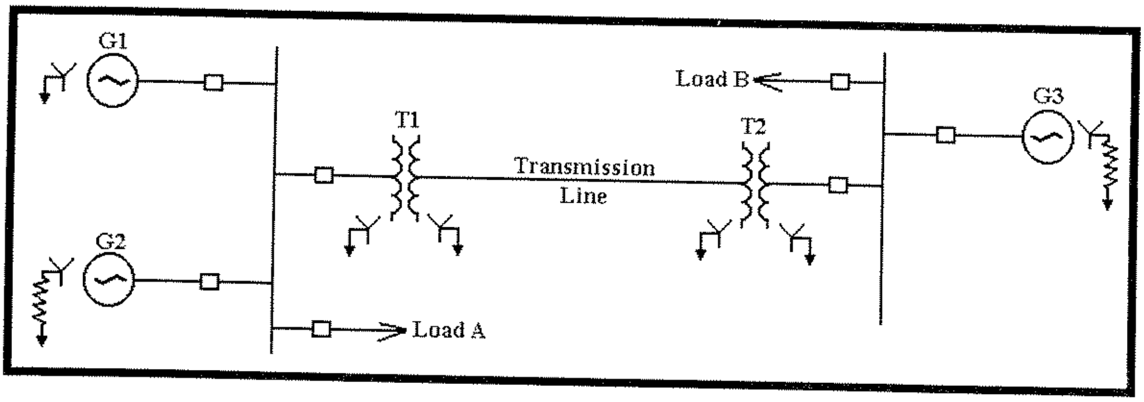


Figure 13. 15 Single Line Drawing of a Power System

Solution:

To draw the reactance diagram for the system, the reactances of the generators and transformers must be referred to the same side of the transformer.

The transformer theory shows that the impedance on the secondary side of a transformer may be referred to the primary side by multiplying the impedance on the secondary side by the square of the ratio of the primary turns to the secondary turns of the transformer.

$$\text{That is } Z_1 = Z_2 \frac{(N_1)^2}{(N_2)^2}$$

Let us refer all the general impedances to the HT side (38.1 kV) of the transformer.

Reactance of G1 referred to HT side = $0.655 \times \frac{(38.1)^2}{(6.6)^2} = 21.85\ \Omega$

Reactance of G2 referred to HT side = $1.31 \times \frac{(38.1)^2}{(6.6)^2} = 43.65\ \Omega$

Reactance of G3 referred to HT side = $0.1451 \times \frac{(38.1)^2}{(6.6)^2} = 4.84\ \Omega$

Both the transformer reactance and the transmission line reactance are already referred to the HT side, so no correction is required. The diagram referred to the HT side can now be drawn:

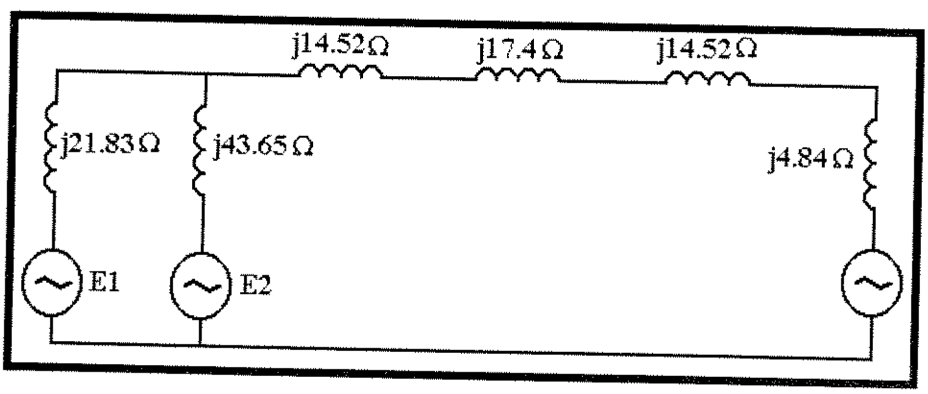


Figure 13. 16 Reactance Diagram referred to HT side

From the above, it can be seen that in the case of a power system with a large number of network components involving many transformers, the task of having to refer reactances to the same side of a transformer becomes very complicated. To overcome this problem, a new method of representation needs to be adopted – "the per unit system".

Example 13.4:

(a) Describe briefly the effects of short circuit current.

(b) Give the definitions of the following: -

(i) Rated making capacity
(ii) Rated breaking capacity of circuit breakers

(c) The Low Voltage Supply to a residential unit at the 1st floor of a multi-storey apartment building is shown in Figure 13.17.

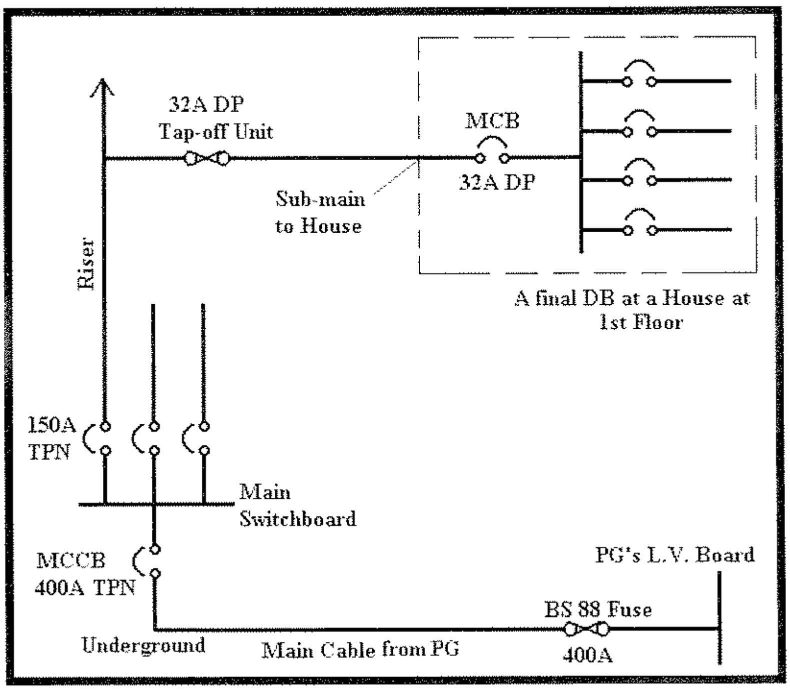


Figure 13. 17

The lengths and impedances per phase of the 3-phase main cable from PG, the 3-phase riser and the single-phase sub-main to the residential unit are as shown in Table13.1.

	Impedances per phase / per metre	**Length**
185mm²/4C PVC/SWA/PVC main from PG	$0.12 \times 10^{-3} + j0.07 \times 10^{-3}\ \Omega$ per phase	100m
4 x 70 mm² PVC/PVC single core riser	$0.32 \times 10^{-3} + j0.14 \times 10^{-3}\ \Omega$ per phase	30m
2 x 6 mm² PVC/PVC single core sub-main to House	$3.6 \times 10^{-3}\ \Omega$ per phase	20m

Table 13.1

If the declared fault level at the PowerGrid's L.V. Switch Board is 36kA,

(i) Determine the prospective 3-phase short-circuit current at the Tap-off unit

(ii) Determine the prospective phase-to neutral short circuit current at the DB. If the available MCBs are of M6 and M9 type, determine whether a M6 or M9 MCB would be appropriate.

Solution:

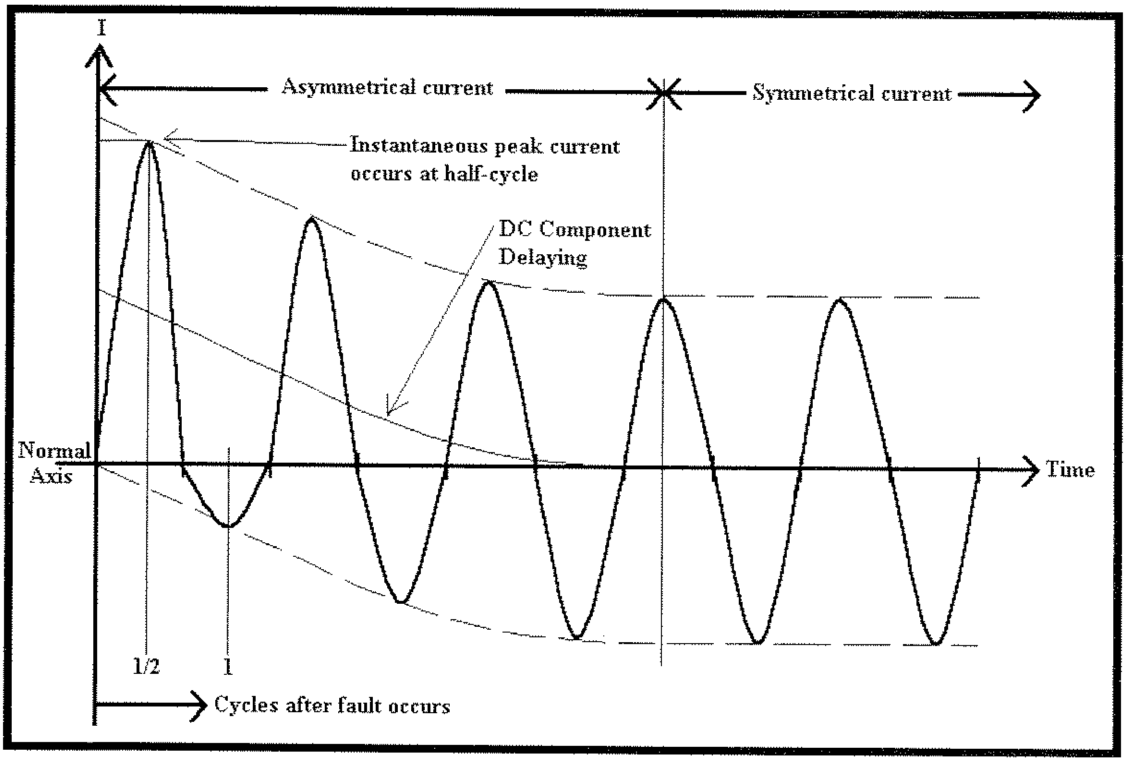


Figure 13. 18

(a) When a short-circuit occurs, a very high fault current flows from the source of supply to the fault point; the two effects of this high short-circuit current are: -

(i) Dissipation of tremendous amount of heat energy (thermal energy) in the complete distribution system.

Thermal energy = (I^2R) x Duration of the fault, t

(ii) Setting up of a very high oscillating mechanical force (proportional to I^2) between two conductors which may cause severe mechanical damage to the installation. This mechanical force is related to the initial peak current.

(b) (i) Rated Short Circuit Making Capacity

The prospective peak current the circuit breaker is capable of making at rated voltage, rated frequency and rated power factor. Rated short-circuit making current is related to the prospective asymmetrical peak short circuit current.

(ii) Rated Short-Circuit Breaking Capacity or known as Interrupting Rating or Interrupting Capacity

The r.m.s. value of the a.c. component of current at the initiation of arc which the circuit breaker can break under the specified conditions of voltage and power factor.

(c) Fault Calculation

(i) Phase Impedance of the source $= \dfrac{400V/\sqrt{3}}{36000A} = j0.0064\Omega$ (General Reactive)

Impedance of the 185 mm^2 / 4C PVC/SWA/PVC underground cable,

$R = 0.12 \times 10^{-3}\ \Omega/m \times 100m$
$= 0.012\Omega$ per phase

$X = j0.07 \times 10^{-3}\ \Omega/m \times 100m$
$= j0.007\Omega$ per phase

Impedance of the 4 x 70 mm^2 PVC/PVC single core cable riser,

$R = 0.32 \times 10^{-3}\ \Omega/m \times 30m$
$= 0.0096\Omega$ per phase

$X = j0.14 \times 10^{-3}\ \Omega/m \times 30m$
$= j0.0042\Omega$ per phase

Total Impedance per phase at the tap-off unit,

$R_T = 0.012\Omega + 0.0096\Omega = 0.0216\Omega$

$X_T = j(0.0064 + 0.007 + 0.0042)\ \Omega$
$= j0.0176\Omega$

$\therefore Z_T = R_T + jX_T$
$= 0.0216 + j0.0176$

$|Z_T| = \sqrt{0.0216^2 + 0.01760^2}$
$= \sqrt{0.000467 + 0.00031}$
$= \sqrt{0.000776} = 0.0279\ \Omega$

Prospective 3-phase symmetrical fault current at the Tap-off unit

$$I_{SC} = \frac{400/\sqrt{3}}{0.0279} = \frac{230}{0.0279} = 8.2kA$$

(ii) To calculate the phase to neutral short circuit current at the DB, the phase to line to neutral voltage behind an internal impedance from each DB to the utility infeed is applied. The equivalent circuit is shown as follows: -

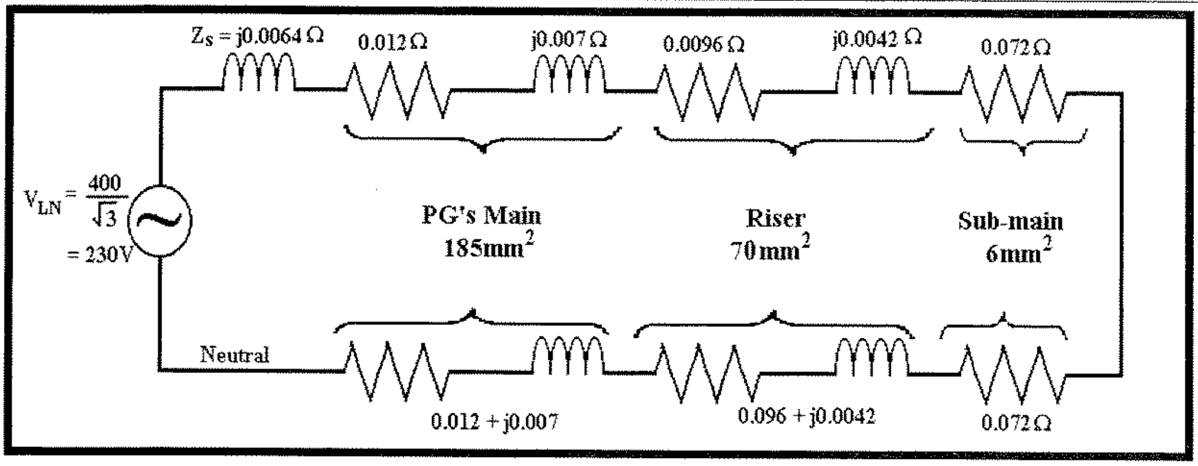


Figure 13. 19 Phase to Neutral Short Circuit

Where the per phase impedance of 6 mm^2 cable
$= 36 \times 10^{-3}$ Ω/m x 20m = 0.072 Ω

Since we are considering a phase-to-neutral short circuit, the total impedance is

$$Z_T = R_T + jX_T$$

where

$$
\begin{aligned}
R_T &= 0.012 \times 2 + 0.0096 \times 2 + 0.072 \times 2 \\
&= 0.024 + 0.0192 + 0.144 \\
&= 0.1872\ \Omega
\end{aligned}
$$

$$
\begin{aligned}
X_T &= 0.0064 + 2 \times (0.007 + 0.0042) \\
&= 0.0064 + 0.0224 \\
&= 0.0288\ \Omega
\end{aligned}
$$

$$\therefore Z_T = \sqrt{0.1872 + (0.0288)^2} = 0.189\ \Omega$$

$$I_{SC} = \frac{230V}{0.189\Omega} = 1216A = 1.216kA$$

Since the fault level at the single-phase DB is less than 6kA, a M6 or MCB with breaking capacity would be appropriate.

Ohmic Value of Cable Impedance

To calculate the fault current by ohmic value method, the ohmic value of cable resistance and reactance can be obtained from the voltage drop section of tables in Appendix 4 of Singapore Standard CP5: 1998 or Appendix 9 of IEE regulation 16th Edition.

An example of this drop table is shown in Table 13.2 for PVC insulated single core cable and Table13.3 for XLPE insulated single core cable. The phase conductor's resistance R and reactance x for each meter run of the phase conductor can be calculated from the tabulated mV/A/m values of the tables.

For example, actual resistance of conductor at maximum operating temperature (70°C for PVC insulation and 90°C for XLPE insulation) can be calculated by: -

$R_P = \frac{1}{2}\,(mV/A/m)_r$ & $X_P = \frac{1}{2}\,(mV/A/m)_x$
if the mV/A/m values are taken from the single phase columns

and

$R_P = (mV/A/m)_r/\sqrt{3}$ & $X_P = (mV/A/m)_x/\sqrt{3}$
if the value of mV/A/m and taken from the 3-phase columns

TABLE 4D1B

VOLTAGE DROP (per ampere per metre): Conductor operating temperature: 70°C

Conductor cross-sectional area	2 cables, d.c.	2 cables, single-phase a.c.									3 or 4 cables, three-phase a.c.											
		Reference Methods 3 & 4 (enclosed in conduit etc. in or on a wall)			Reference Methods 1 & 11 (clipped direct or on trays, touching)			Reference Method 12 (spaced*)			Reference Methods 3 & 4 (enclosed in conduit etc. in or on a wall)			Reference Methods 1, 11 & 12 (in trefoil)			Reference Methods 1 & 11 (flat and touching)			Reference Method 12 (flat spaced*)		
1	2	3			4			5			6			7			8			9		
(mm²)	(mV/A/m)	(mV/A/m)			(mV/A/m)			(mV/A/m)			(mV/A/m)			(mV/A/m)			(mV/A/m)			(mV/A/m)		
1	44	44			44			44			38			38			38			38		
1.5	29	29			29			29			25			25			25			25		
2.5	18	18			18			18			15			15			15			15		
4	11	11			11			11			9.5			9.5			9.5			9.5		
6	7.3	7.3			7.3			7.3			6.4			6.4			6.4			6.4		
10	4.4	4.4			4.4			4.4			3.8			3.8			3.8			3.8		
16	2.8	2.8			2.8			2.8			2.4			2.4			2.4			2.4		
		r	x	z	r	x	z	r	x	z	r	x	z	r	x	z	r	x	z	r	x	z
25	1.75	1.80	0.33	1.80	1.75	0.20	1.75	1.75	0.29	1.80	1.50	0.29	1.55	1.50	0.175	1.50	1.50	0.25	1.55	1.50	0.32	1.55
35	1.25	1.30	0.31	1.30	1.25	0.195	1.25	1.25	0.28	1.30	1.10	0.27	1.10	1.10	0.170	1.10	1.10	0.24	1.10	1.10	0.32	1.15
50	0.93	0.95	0.30	1.00	0.93	0.190	0.95	0.93	0.28	0.97	0.81	0.26	0.85	0.80	0.165	0.82	0.80	0.24	0.84	0.80	0.32	0.86
70	0.63	0.65	0.29	0.72	0.63	0.185	0.66	0.63	0.27	0.69	0.56	0.25	0.61	0.55	0.160	0.57	0.55	0.24	0.60	0.55	0.31	0.63
95	0.46	0.49	0.28	0.56	0.47	0.180	0.50	0.47	0.27	0.54	0.42	0.24	0.48	0.41	0.155	0.43	0.41	0.23	0.47	0.40	0.31	0.51
120	0.36	0.39	0.27	0.47	0.37	0.175	0.41	0.37	0.26	0.45	0.33	0.23	0.41	0.32	0.150	0.36	0.32	0.23	0.40	0.32	0.30	0.44
150	0.29	0.31	0.27	0.41	0.30	0.175	0.34	0.29	0.26	0.39	0.27	0.23	0.36	0.26	0.150	0.30	0.26	0.23	0.34	0.26	0.30	0.40
185	0.23	0.25	0.27	0.37	0.24	0.170	0.29	0.24	0.26	0.35	0.22	0.23	0.32	0.21	0.145	0.26	0.21	0.22	0.31	0.21	0.30	0.36
240	0.180	0.195	0.26	0.33	0.185	0.165	0.25	0.185	0.25	0.31	0.17	0.23	0.29	0.160	0.145	0.22	0.160	0.22	0.27	0.160	0.29	0.34
300	0.145	0.160	0.26	0.31	0.150	0.165	0.22	0.150	0.25	0.29	0.14	0.23	0.27	0.130	0.140	0.190	0.130	0.22	0.25	0.130	0.29	0.32
400	0.105	0.130	0.26	0.29	0.120	0.160	0.20	0.115	0.25	0.27	0.12	0.22	0.25	0.105	0.140	0.175	0.105	0.21	0.24	0.100	0.29	0.31
500	0.086	0.110	0.26	0.28	0.098	0.155	0.185	0.093	0.24	0.26	0.10	0.22	0.25	0.086	0.135	0.160	0.086	0.21	0.23	0.081	0.29	0.30
630	0.068	0.094	0.25	0.27	0.081	0.155	0.175	0.076	0.24	0.25	0.08	0.22	0.24	0.072	0.135	0.150	0.072	0.21	0.22	0.066	0.28	0.29
800	0.053		-		0.068	0.150	0.165	0.061	0.24	0.25		-		0.060	0.130	0.145	0.060	0.21	0.22	0.053	0.28	0.29
1000	0.042		-		0.059	0.150	0.160	0.050	0.24	0.24		-		0.052	0.130	0.140	0.052	0.20	0.21	0.044	0.28	0.28

NOTE: * Spacings larger than those specified in Method 12 (see table table 4A) will result in larger voltage drop.

Table 13.2 Voltage drop section of single core PVC cable which mV/A/m as phase to neutral voltage drop for single phase system and line to line voltage drop for 3-phases system

TABLE 4E1B

VOLTAGE DROP (per ampere per metre): Conductor operating temperature: 90°C

Conductor cross-sectional area	2 cables, d.c.	2 cables, single-phase a.c. Reference Methods 3 & 4 (enclosed in conduit etc. in or on a wall)			Reference Methods 1 & 11 (clipped direct or on trays, touching)			Reference Method 12 (spaced*)			3 or 4 cables, three-phase a.c. Reference Methods 3 & 4 (enclosed in conduit etc. in or on a wall)			Reference Methods 1, 11 & 12 (in trefoil)			Reference Methods 1 & 11 (flat and touching)			Reference Method 12 (flat spaced*)		
1	2	3			4			5			6			7			8			9		
(mm²)	(mV/A/m)	(mV/A/m)			(mV/A/m)			(mV/A/m)			(mV/A/m)			(mV/A/m)			(mV/A/m)			(mV/A/m)		
1	46	46			46			46			40			40			40			40		
1.5	31	31			31			31			27			27			27			27		
2.5	19	19			19			19			16			16			16			16		
4	12	12			12			12			10			10			10			10		
6	7.9	7.9			7.9			7.9			6.8			6.8			6.8			6.8		
10	4.7	4.7			4.7			4.7			4			4			4			4		
16	2.9	2.9			2.9			2.9			2.5			2.5			2.5			2.5		
		r	x	z	r	x	z	r	x	z	r	x	z	r	x	z	r	x	z	r	x	z
25	1.85	1.85	0.31	1.90	1.85	0.190	1.85	1.85	0.28	1.85	1.60	0.27	1.65	1.60	0.165	1.60	1.60	0.190	1.60	1.60	0.27	1.65
35	1.35	1.35	0.29	1.35	1.35	0.180	1.35	1.35	0.27	1.35	1.15	0.25	1.15	1.15	0.155	1.15	1.15	0.180	1.15	1.15	0.26	1.20
50	0.99	1.00	0.29	1.05	0.99	0.180	1.00	0.99	0.27	1.00	0.87	0.25	0.90	0.86	0.155	0.87	0.86	0.180	0.87	0.86	0.26	0.89
70	0.68	0.70	0.28	0.75	0.68	0.175	0.73	0.68	0.26	0.73	0.6	0.24	0.65	0.59	0.150	0.61	0.59	0.175	0.62	0.59	0.25	0.65
95	0.49	0.51	0.27	0.58	0.49	0.170	0.52	0.49	0.26	0.56	0.44	0.23	0.50	0.43	0.145	0.45	0.43	0.170	0.46	0.43	0.25	0.49
120	0.39	0.41	0.26	0.48	0.39	0.165	0.43	0.39	0.25	0.47	0.35	0.23	0.42	0.34	0.140	0.37	0.34	0.165	0.38	0.34	0.24	0.42
150	0.32	0.33	0.26	0.43	0.32	0.165	0.36	0.32	0.25	0.41	0.29	0.23	0.37	0.28	0.140	0.31	0.28	0.165	0.32	0.28	0.24	0.37
185	0.25	0.27	0.26	0.37	0.26	0.165	0.30	0.25	0.25	0.36	0.23	0.23	0.32	0.22	0.140	0.26	0.22	0.165	0.28	0.22	0.24	0.33
240	0.190	0.21	0.26	0.33	0.20	0.160	0.25	0.195	0.25	0.31	0.185	0.22	0.29	0.170	0.140	0.22	0.170	0.165	0.24	0.170	0.24	0.29
300	0.155	0.175	0.25	0.31	0.160	0.160	0.22	0.155	0.25	0.29	0.150	0.22	0.27	0.140	0.140	0.195	0.135	0.160	0.21	0.135	0.24	0.27
400	0.120	0.140	0.25	0.29	0.130	0.155	0.20	0.125	0.24	0.27	0.125	0.22	0.25	0.110	0.135	0.175	0.110	0.160	0.195	0.110	0.24	0.26
500	0.093	0.120	0.25	0.28	0.105	0.155	0.185	0.098	0.24	0.26	0.100	0.22	0.24	0.090	0.135	0.160	0.088	0.160	0.180	0.085	0.24	0.25
630	0.072	0.100	0.25	0.27	0.086	0.155	0.175	0.078	0.24	0.25	0.088	0.21	0.23	0.074	0.135	0.150	0.071	0.160	0.17	0.068	0.23	0.24
800	0.056		-		0.072	0.150	0.170	0.064	0.24	0.25		-		0.062	0.130	0.145	0.059	0.155	0.165	0.055	0.23	0.24
1000	0.045		-		0.063	0.150	0.165	0.054	0.24	0.24		-		0.055	0.130	0.140	0.050	0.155	0.165	0.047	0.23	0.24

NOTE: * Spacings larger than those specified in Method 12 (see table table 4A) will result in larger voltage drop.

Table 13.3 Voltage drop section of single core XLPE cable which mV/A/m as phase to neutral voltage drop for single phase system and line to line voltage drop for 3-phases system

Adjustment of Operating Temperature for Cable Resistance

As the $(mV/A/m)_r$ value of cables obtained from voltage section of appendix 4 of SS CP5: 1998 and appendix 9 of IEE 16th Edition are tabulated for maximum normal operating temperature for respective insulation type (i.e. 70°C for PVC and 90°C for XLPE), the actual resistive value of the phase conductor impedance must be adjusted by temperature because the temperature of the phase cable under short circuit condition may be higher and this will affect the resistive value as shown in Figure 13.20.

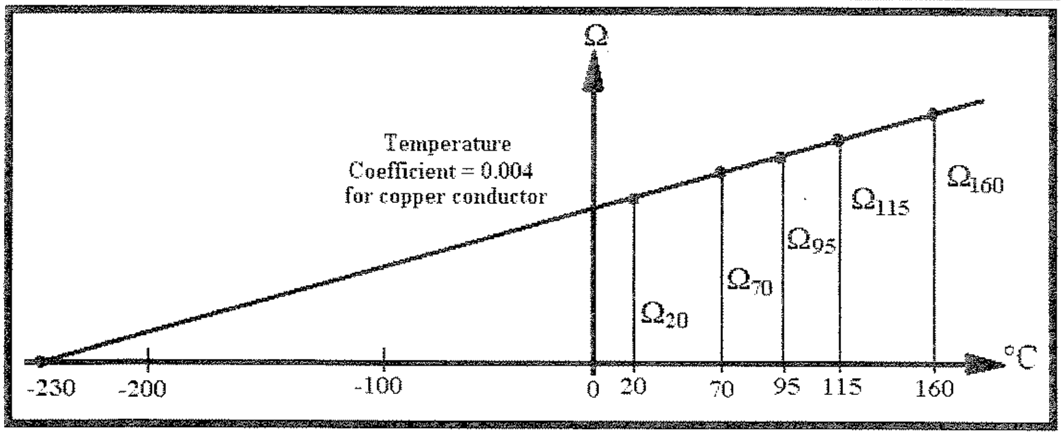


Figure 13. 20 Resistance Value at Various Temperatures

For assumed temperature t_g°C under short circuit condition, maximum normal operating temperature t_p°C, the resistive value of impedance at temperature t_g°C may be adjusted by the formula: -

$$R/\text{metre} = (\text{tabulated mV/A/m})_r \text{ at } t_p°C \times \left(\frac{230 + t_g}{230 + t_p}\right)$$

Example 13.5:

(a) For PVC insulated copper single core cable,

$t_p = 70°C$
t_{max} = critical temperature for PVC = 160°C

Average conductor temperature during fault condition is normally obtained by

$$t_g = \frac{(t_p + t_{max})}{2} = \frac{(70°C + 160°C)}{2} = 115°C$$

$$\therefore\ R_{115°C} = R_{70°C} \times \left(\frac{230 + 115}{230 + 70}\right)$$

(b) For XLPE insulated copper single core cable,

$t_p = 90°C$
t_{max} = critical temperature for XLPE = 250°C

Average conductor temperature during fault condition is obtained by

$$t_g = \frac{(t_p + t_{max})}{3} = \frac{(90°C + 250°C)}{2} = 170°C$$

$$\text{Therefore, } R_{170°C} = R_{90°C} \times \left(\frac{230 + 170}{230 + 70}\right)$$

1. The Low Voltage Supply System of an industrial plant is shown in Figure 13.21.

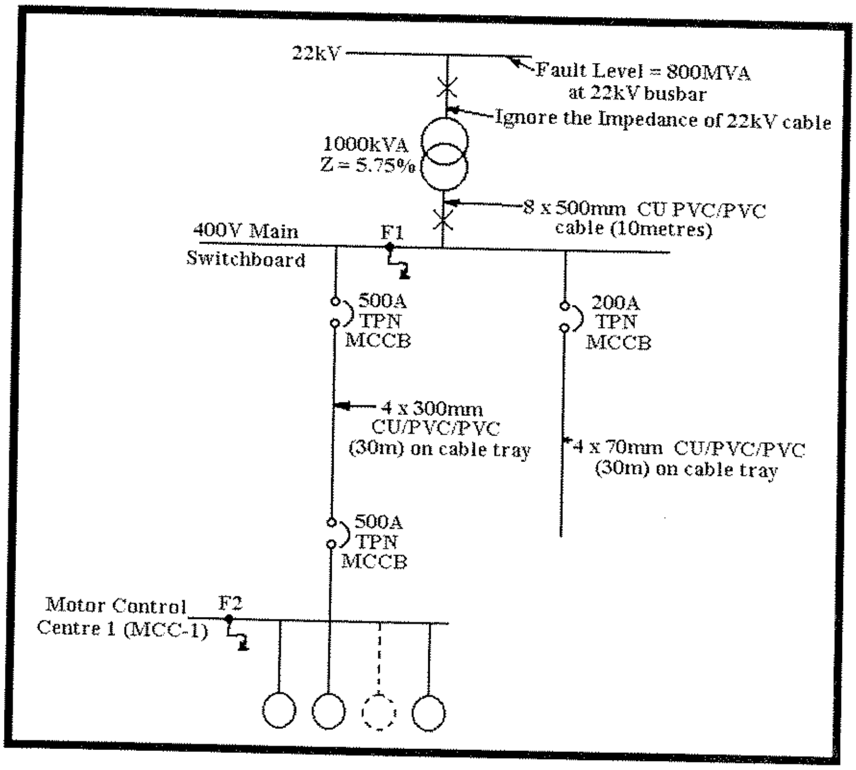


Figure 13. 21 Single-line Diagram of an Electrical Installation

The lengths of the 3-phase 400V sub-mains are as follows: -

	Length
8 x 500 mm² PVC/PVC single-core cables as transformer tail (2 Nos. per phase)	10m
4 x 300 mm² PVC/PVC single-core sub-main to Motor Control Centre 1	100m

Table 13.4

(a) Neglecting the impedance of the 22kV transformer cable, determine the prospective 3-phase short circuit current (in kA) at the 400V Main switchboard.

(b) Determine the required breaking capacity of the 500A MCCB at the Motor Control Centre 1 (MCC-1).

(c) Determine the required making capacity of the 500A MCCB at the MCC-1 if the reactance to resistance ratio of system impedance for the fault at point F2 is X/R = 5

The resistance and reactance values of the 500mm² and 300mm² single-core cable can be obtained from Table 4D1 of CP5: 1998.

2. The Low Voltage Supply to a 400V 3-phase main switchboard and sub-switchboard of a 2-storey shop is shown in Figure 13.22.

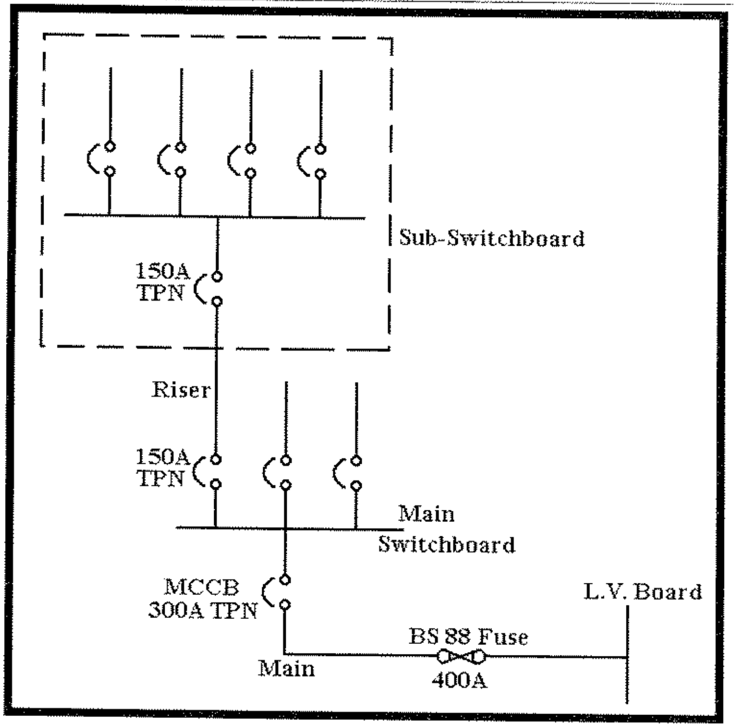


Figure 13. 22

The lengths and impedances per phase of the 3-phase main cable from the power supply company to the Main Switchboard at the first storey and the 3-phase sub-main to the sub-switchboard at the second storey are as follows: -

	Length
185 mm^2/4C PVC/SWA/PVC main from power supply company	100m
4 x 70 mm^2 PVC/PVC single core riser	20m

Table 13.5

If the declared fault level at the power supply company's L.V. Switchboard is 36kA, determine:

(a) the prospective 3-phase symmetrical short circuit current at the 400V Main Switchboard (MSB), and

(b) the prospective 3-phase symmetrical short circuit current at the 400V sub-switchboard (SSB).

The resistance and reactance values of the related cables can be obtained from appropriate tables in appendix 4 of CP5: 1998.

3. The electrical distribution of an industrial building receiving electricity supply at 22kV is shown in Figure 13.23.

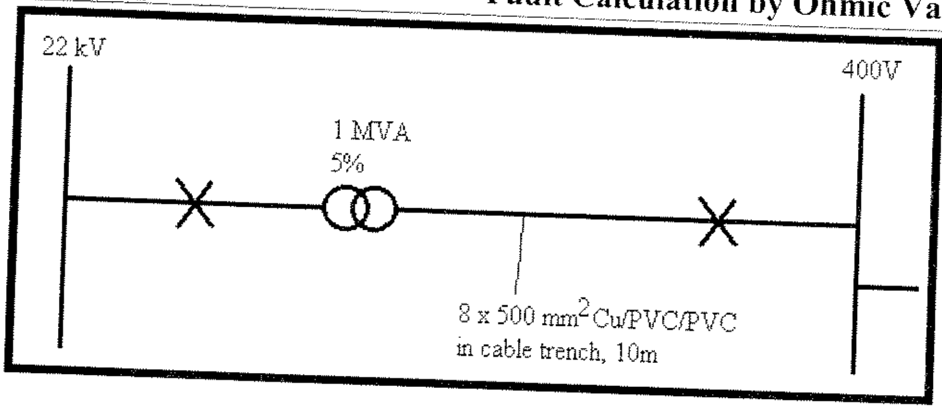


Figure 13. 23

The consumer transformer room and 400V Main switchroom are located adjacent to each other and a TNS-earthing system is adopted. The earthing system comprises the following earth cables and earth electrode system: -

Earthing cables from transformer star point to Main Earth Bar in Transformer Room	10 metres of 2 x 120mm^2/single core PVC insulated copper cable
Earthing cables from Earthing Bar 400V MSB to Main Earth Bar	10 metres of 2 x 120mm^2/single core PVC insulated copper cable
Earth electrode system with multiple electrodes sunk into the ground (Earth electrode system is connected to Main Earth Bar)	Overall electrode resistance value = 0.5 ohm

Table 13.6

(a) Draw a circuit diagram to show the earth fault loop path if a phase to earth fault has occurred at the 400V Main switchboard (MSB).

(b) Calculate the total Earth Fault Loop Impedance at the 400V Main Switchboard and determine the magnitude of the earth fault current.

The value of resistance and reactance of phase and earth cable can be obtained from appendix 4 of SS CP5: 1998

(c) Determine whether the 2 x 120mm^2/single-core PVC insulated earth cable can withstand the thermal energy produced by the earth fault current for one second.

Assuming that the thermal capacity constant of PVC copper earth cable is K =143.

CHAPTER 14
FAULT LEVEL CALCULATION USING PER UNIT SYSTEM

14.1 INTRODUCTION

Per Unit Quantities

When a power system involves several voltage levels, it is more convenient to make calculations by using per unit quantities (such as voltages and reactances).

The per unit system of calculation is used extensively in power network analysis and fault calculations.

14.2 DEFINITION OF PER UNIT VALUE

The per unit value system is a system of measurement in which various electrical quantities are normalized with respect to a specified base value.

Example 14.1:

A power system may have different voltages of 66kV, 230kV and 400kV at different points.

If we select 230kV as the base voltage, then

66kV will be $\frac{66}{230} = 0.29$ per unit

230kV will be $\frac{230}{230} = 1$ per unit

400kV will be $\frac{400}{230} = 1.73$ per unit

Similarly, the other electrical quantities (power in kVA, impedance, current) can also be expressed in per unit if a corresponding base value of the quantity is selected.

Notes:

(a) Some authorities express the per unit value as a percentage.

(b) Per unit values are numerically equal to per cent value divided by 100.

For example, 20% sub-transient reactance of a generator means the generator has a sub-transient reactance of 0.2 per unit.

Generally, in fault calculations, 2 base values are selected, viz. base kVA and base voltage – these 2 base values completely define the circuit because base current and base impedances may be calculated from base kVA and base voltage.

Notes:

(a) Base values of voltage, current and impedance are all real numbers.
(b) Per unit values (such as V_{pu}, I_{pu}, Z_{pu}) are complex numbers.
(c) Per unit values, being ratio of similar quantities, are dimensionless.

14.3 PER UNIT QUANTITIES IN SINGLE-PHASE AND THREE-PHASE SYSTEMS

We shall look at single-phase and 3-phase systems separately as follows:

Single-Phase Systems

Let Base power = kVA per phase
Base voltage = line-to-neutral voltage

Then,

$$\text{Base current in amps} = \frac{\text{Base power in kVA}}{\text{Base voltage in kV}} \quad \text{------------------- (1)}$$

$$\text{Base impedance in ohms} = \frac{\text{Base voltage in Volts}}{\text{Base current in amps}}$$

$$= \frac{\text{Base voltage in kV x 1000}}{\text{Base current in amps}}$$

$$= \frac{\text{Base voltage in kV}}{\text{Base voltage in kV}} + \frac{\text{Base voltage in kV x 1000}}{\text{Base current in amps}}$$

$$= \frac{(\text{Base voltage in kV})^2 \text{ x 1000}}{\text{Base power in kVA}} \quad \text{-------------------(2)}$$

$$\text{Per unit impedance} = \frac{\text{Actual impedance in } \Omega}{\text{Base impedance in } \Omega} \quad \text{-------------------(3)}$$

Three-Phase Systems

Let Voltage = line-to-line voltage
Power = total 3-phase kVA power

Then,

$$\text{Base current in amps} = \frac{\text{Base power in kVA}}{\sqrt{3} \text{ x Base voltage in kV}} \quad \text{------------------- (4)}$$

$$\text{Base impedance in ohms} = \frac{(\text{Base voltage in kV}/\sqrt{3})^2 \text{ x 1000}}{\text{Base power in kVA}/3}$$

$$= \frac{(\text{Base voltage in kV})^2 \text{ x 1000}}{\text{Base power in kVA}} \quad \text{-----------------------(5)}$$

Conclusion:

Since equation (2) and equation (5) for base impedance are identical, it follows that the same expression of per unit impedance is obtained for a single-phase and 3-phase systems.

Note:

In determining per unit values, it is NOT permitted to use single-phase values for the given system and 3-phase values for the base or vice versa. Both the given system and base values must be either in single-phase or 3-phase quantities.

We shall, from now on, use 3-phase power and line-to-line voltage for the given system and base quantities in calculating per unit values.

14.4 CONVERSION OF PER UNIT IMPEDANCE TO OTHER BASES

Impedances of electrical machines such as motors, generators and transformers are given in per unit or per-cent values by manufacturers. If the impedance is given in per unit, then the base is understood to be the rated kVA or rated kV of the machine.

However, in solving problems, it may be necessary to select some convenient values of base kVA and base kV which are different from the kVA and kV ratings of the machines in the system. In such cases, it will be necessary to convert the per unit impedances of the machines to the new bases selected. This must be done so that all per unit impedances of the system will be expressed on the same base impedances.

Conversion of Per Unit Impedance to Other Bases

Per Unit Impedance is given by

$$\text{Per Unit Impedance} = \frac{\text{Actual impedance in } \Omega}{\text{Base impedance in } \Omega}$$

From equation (5), we have,

$$\text{Base Impedance in } \Omega = \frac{(\text{Base kV})^2 \times 1000}{\text{Base kVA}}$$

$$\text{Therefore, Per Unit Impedance} = \frac{(\text{Actual Impedance in } \Omega) \times \text{base kVA}}{(\text{Base kV})^2 \times 1000}$$

$$\text{Therefore, Per Unit Impedance is proportional to } \frac{\text{Base kVA}}{(\text{Base kV})^2}$$

This shows that Per Unit Impedance is directly in proportion to base kVA and inversely in proportion to square of base voltage. Therefore, to change from Per Unit Impedance on a given base to Per Unit Impedance on a new base, the following formula applies:

$$puZ_{new} = puZ_{given} \frac{(\text{base kVA}_{new})}{(\text{base kVA}_{given})} \times \frac{(\text{base kV}_{given})^2}{(\text{base kV}_{new})} \quad \text{-----------(7)}$$

$$\text{or } puZ_{new} = puZ_{given} \frac{(\text{base kVA}_{new})}{(\text{base kVA}_{given})} \quad \text{-----------(8)}$$

if base kV_{given} = base kV_{new}

Example 14.2:

Figure 14.1 shows two generators, both of different ratings and percentage reactance. To enable calculations to be carried out a common base has to be chosen, this could be the size of the largest machine, i.e. 30MVA.

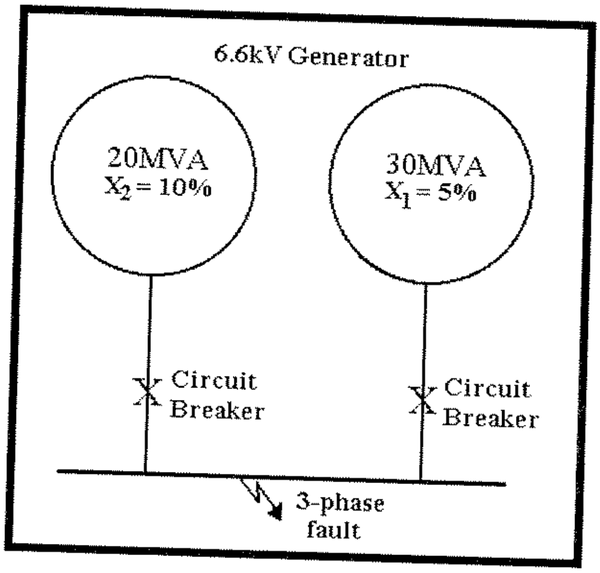


Figure 14. 1

Solution:

Changing the percentage reactance of the 20MVA machine to 30MVA base.

$$\text{New } \%X_1 = \frac{30\text{MVA}}{20\text{MVA}} \times 10\% = 15\%$$

The percentage reactance of the 30MVA machine remain unchanged

$$\%X_2 = 5\%$$

To calculate the percentage reactance at the fault, the percentage reactances worked out to a common base can now be treated as impedance in series or parallel. In the above example, the generators are in parallel, therefore,

$$\%\text{ reactance at the fault} = \frac{15 \times 5\%}{15 + 5} = 3.75\%$$

$$\text{Fault power} = \frac{\text{Base MVA x 100}}{\text{\% reactance}} = \frac{30 \text{ x } 100}{3.75} = 800\text{MVA}$$

$$\text{Fault current} = \frac{\text{MVA x 1000}}{\sqrt{3} \text{ x } V_L} = \frac{800 \text{ x } 1000}{1.732 \text{ x } 6.6\text{kV}} = 69984\text{A}$$

When the fault on the system is not symmetrical, the calculations become more involved and symmetrical components is then used to calculate the fault current.

14.5 SELECTION OF BASE FOR PER UNIT QUANTITIES

The selection of base values of kVA and kV is made to reduce the work required by calculations as much as possible.

The following points should be carefully noted:

(a) When the resistance and reactance of a network component are given by the manufacturer in per cent or per unit, the base is understood to be the rated kVA and rated kV of the device.

(b) If the ohmic values of resistance and leakage reactance of a transformer are expressed in per unit, the base kVA is understood to be the kVA rating of the transformer.

(c) If the ohmic values of resistance and leakage reactance are referred to the LT side of the transformer, the base voltage is understood to be the voltage rating of the LT winding.

(d) Similarly, if the ohmic values of resistance and leakage reactance are referred to the HT side of the transformer, the base voltage is understood to be the voltage rating of the HT winding.

(e) Per unit impedance referred to LT side of the transformer = Per unit impedance referred to HT side of the transformer

The following examples illustrate clearly the above points (a) to (e).

Example 14.3: (Involving one transformer only)

Transformer Data:

Rating = 10,000kVA single-phase
Voltage ratio = 13.8 / 138kV (that is, step-up transformer)
Z_1 = Impedance of LT winding = 1.75Ω
Z_2 = Impedance of HT winding = 15.44Ω

Determine the per unit impedance of the transformer referred to HT and LT sides.

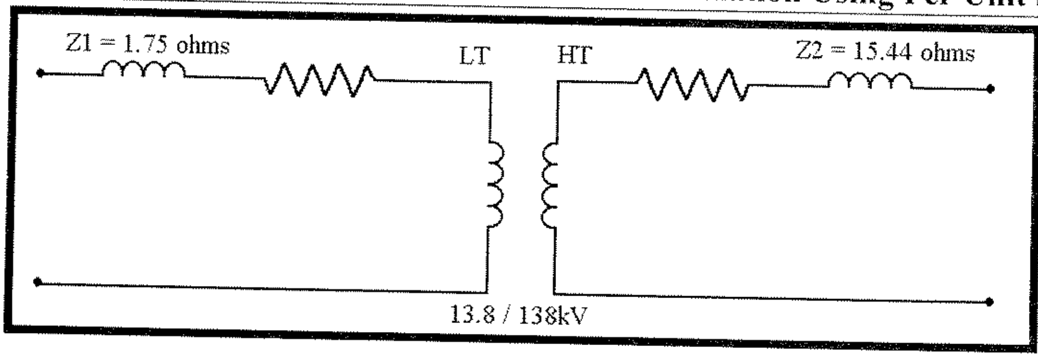


Figure 14. 2

Solution:

Step 1:Select the following bases

Base power = 10,000kVA
Base voltage on LT side = 13.8kV
Base voltage on HT side = 138kV

Step 2: Calculate the base impedance on LT Side and HT Side

Base impedance on LT side

$$= \frac{(\text{Base kV})^2 \times 1000}{\text{Base kVA}}$$

$$= \frac{(13.8)^2 \times 1000}{10,000} = 19.04\Omega$$

Base impedance on HT side

$$= \frac{(138)^2 \times 1000}{10,000} = 1904.40\Omega$$

Step 3: Calculate the Per Unit Impedance

Using basic transformer theory $Z_1 = Z_2 [(V_1)^2 / (V_2)^2]$

Total impedance referred to LT side
$= 1.75 + 15.44 (13.8)^2 / (138)^2$
$= 1.9044\Omega$

Total impedance referred to HT side
$= 15.44 + 1.75 (138)^2 / (13.8)^2$
$= 190.44\Omega$

Therefore, Per Unit impedance referred to LT side
$= 1.9044 / 19.04 = 0.1$

and Per Unit impedance referred to HT side
$= 190.44 / 1904.40 = 0.1$

$\therefore$ Per Unit impedance referred to LT side = Per Unit impedance referred to HT side

From Example 14.3, it can be seen that the base voltage on the LT side is the rated voltage of the LT winding and that the base voltage on the HT side is the rated voltage of the HT winding. The base power is the same for both sides of the transformer.

Example 14.4: (Involving 2 transformers)

Three parts of a single-phase system are designated A, B and C and are connected to each other through transformers as shown in Figure 14.3.

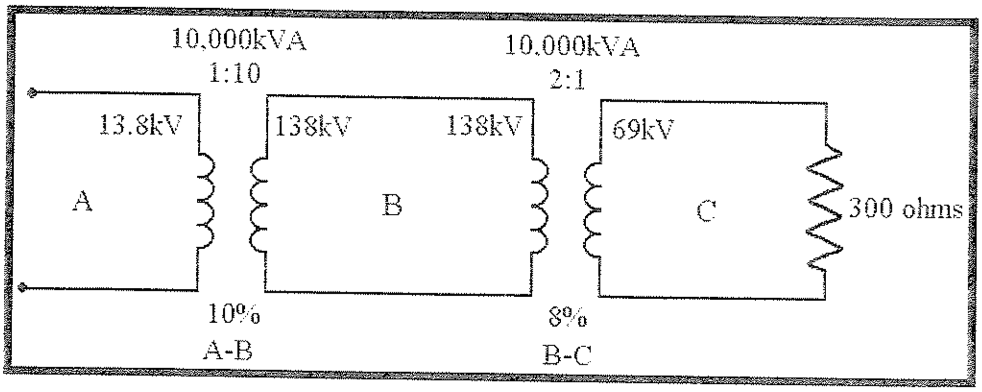


Figure 14. 3

The transformers are rated as follows:

Transformer A-B: 10,000kVA, 13.8 / 138kV, leakage reactance 10%.
Transformer B-C: 10,000kVA, 138 / 69kV, leakage reactance 8%.

If the base in Circuit B is chosen as 10,000kVA and 138kVA,

(a) Find the per unit impedance of the 300Ω resistive load in Circuit C referred to Circuits C, B and A

(b) Draw the impedance diagram neglecting magnetising current, transformer resistance and line impedance.

Solution:

Step 1: Select base power and base voltage

Base power for the system = 10,000kVA
Base voltage for Circuit B = 138kV

Step 2: Calculate other base quantities

Using basic transformer theory $\frac{V_1}{V_2} = \frac{N_1}{N_2}$, we have

Base voltage for Circuit A = 138 x (1/10)
= 13.8kV

Base voltage for Circuit C = 138 x (½) = 69kV

Base impedance of Circuit C = $\dfrac{(\text{base kV})^2 \times 1000}{\text{base kVA}}$

$= \dfrac{(69)^2 \times 1000}{10000} = 476\Omega$

Step 3: Calculate Per Unit Impedance

Therefore, Per Unit impedance of load in Circuit C = $\dfrac{300}{476} = 0.63$

Impedance of load referred to Circuit B = $300 \times \dfrac{(138)^2}{(69)^2} = 1200\Omega$

Base impedance of Circuit B = $(138)^2 \times \dfrac{1000}{10{,}000} = 1900\Omega$

Therefore, Per Unit impedance of load referred to Circuit B = $\dfrac{1200}{1900} = 0.63$

Impedance of load referred to Circuit A = $1200 \times \dfrac{(13.8)^2}{(138)^2} = 12\Omega$

Base impedance of Circuit A = $13.8^2 \times \dfrac{1000}{10{,}000} = 19\Omega$

Therefore, Per Unit of load referred to Circuit A = $\dfrac{12}{19} = 0.63$

Hence, reactance diagram is

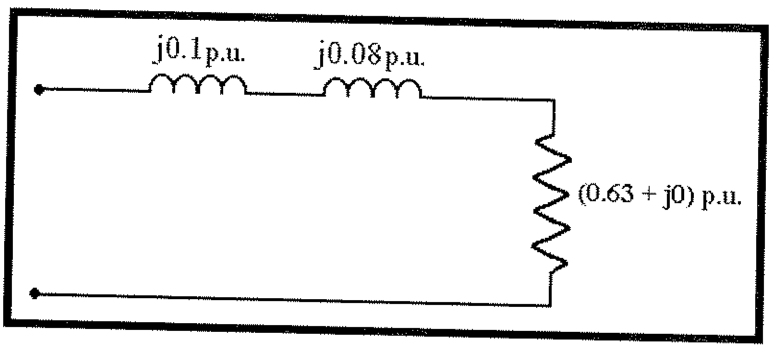


Figure 14. 4

From Example 14.4, it is seen that the Per Unit impedance of the loads and circuit elements (such as transformers and machines) referred to any part of the system will remain the same.

Important Points to Note in Selecting Base kVA and Base kV

(a) The selection of base kVA and base kV should be made to simplify the calculation work required.

(b) The bases selected should be such that the per unit values of rated voltages and currents are nearly unity.

(c) The bases should, as far as possible, be selected in such a way that the per unit quantities already known need not be converted to new base.

(d) The base kVA selected must be the same for the entire system.

(e) The selection of base kV in one part of the system determines the base kV to be assigned to the other parts of the system according to the turns ratio (or voltage ratio) of the transformers.

(f) Following the above principle of assigning base kVA and base kV allows us to combine, in one impedance diagram, the per unit impedances determined in different parts of the system.

14.6 CALCULATION OF FAULT CURRENT AND FAULT POWER USING PER UNIT SYSTEM

Basic Steps in Fault Calculations

(a) Draw single-line diagram (if not given) of the system with the network component and machines represented by their symbols.

(b) Draw reactance diagram for the given system and mark all the reactances in per unit.

All impedances must be converted to a common base at this point.

(c) Determine the pre-fault voltage in per unit at the fault point.

(d) Reduce the impedance by calculation to a single impedance between the source(s) and the fault point in per unit.

Thevenin's Theorem and other network reduction methods are used here.

(e) The fault current and fault power can then be calculated by the equations given below:

$$I_f(pu) = \frac{V_f(pu)}{Z_f(pu)} \quad \text{------------} \quad (9)$$

$$I_f(A) = I_f(pu) \times \text{Base I}(A) \quad \text{------------} \quad (10)$$

$$\text{Fault power (pu)} = V_f(pu) \times I_f(pu) \quad \text{------------} \quad (11)$$

$$\text{Fault power (kVA)} = \text{Fault power (pu)} \times \text{Base kVA} \quad \text{------------} \quad (12)$$

where

$I_f(pu)$	is per unit fault current
$V_f(pu)$	is per unit pre-fault voltage
$Z_f(pu)$	is per unit resultant impedance between the source and the fault point
$I_f(A)$	is fault current in amps
Fault power (pu)	is per unit fault power
Fault power (kVA)	is fault power in kVA
Base kVA	is base power in kVA

Notes:

(a) The "fault MVA" = $\frac{\text{fault power in kVA}}{1000}$ is often termed "fault level".

(b) Utility system reactance is often given in terms of short-circuit kVA (or MVA fault level) available at the consumer's service entrance, and may be calculated by the formula:

$$X_{pu} = \frac{\text{Base kVA}}{\text{S/C kVA of Utility}} \quad \text{------------------------------} \quad (13)$$

where X_{pu} = per unit reactance of the utility system

(c) Base current = $\frac{\text{Base kVA}}{\sqrt{3} \text{ x Base kV}}$

Useful Formulae:

(a) Combining Series Reactances

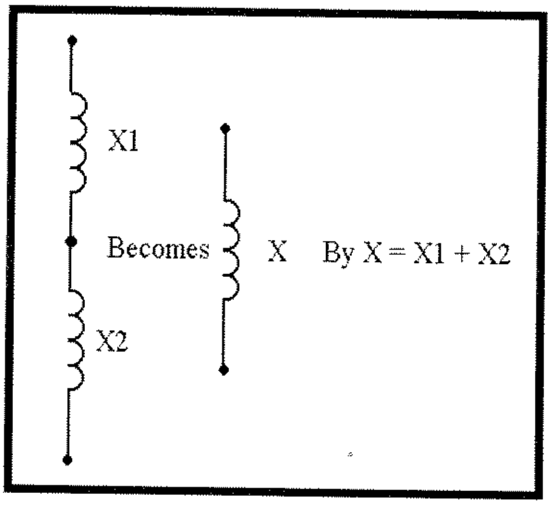


Figure 14. 5

(b) Combining Parallel Reactances

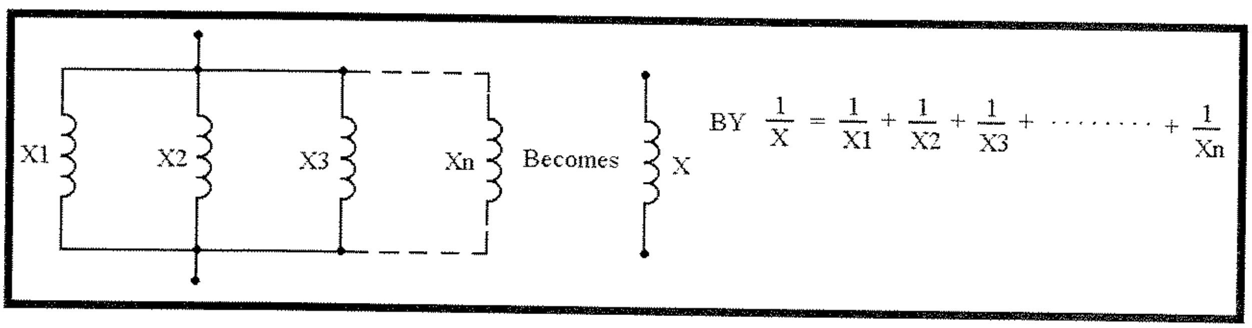
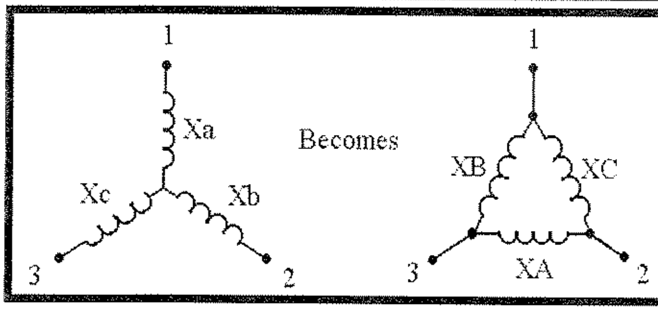


Figure 14. 6

(c) Wye to Delta



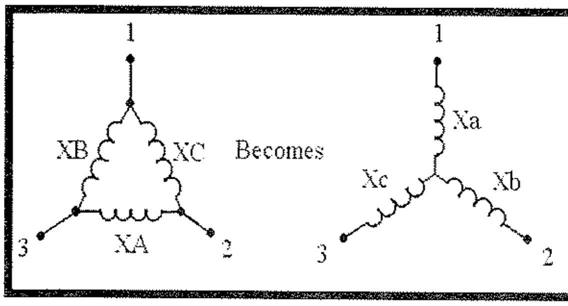
$$BY \quad XA = \frac{Xb\,Xc}{Xa} + Xb + Xc$$

$$XB = \frac{Xa\,Xc}{Xb} + Xa + Xc$$

$$XC = \frac{Xa\,Xb}{Xc} + Xa + Xb$$

Figure 14. 7

(d) Delta to Wye



$$BY \quad Xa = \frac{XB\ XC}{XA + XB + XC}$$

$$Xb = \frac{XA\ XC}{XA + XB + XC}$$

$$Xc = \frac{XA\ XB}{XA + XB + XC}$$

Figure 14. 8

Example 14.5:
Fault Level Calculations

An alternator and a synchronous motor are both rated 30000kVA, 13.2kV and both have a sub-transient reactance of 20%. The line connecting them has a reactance of 10% on the base of the machine ratings. The motor is drawing 20,000kW at 0.8 pf leading and at a terminal voltage of 12.8kV when a symmetrical three-phase fault occurs at the motor terminals. Find the sub-transient current in the fault.

The single-line diagram is shown in Figure 14.9.

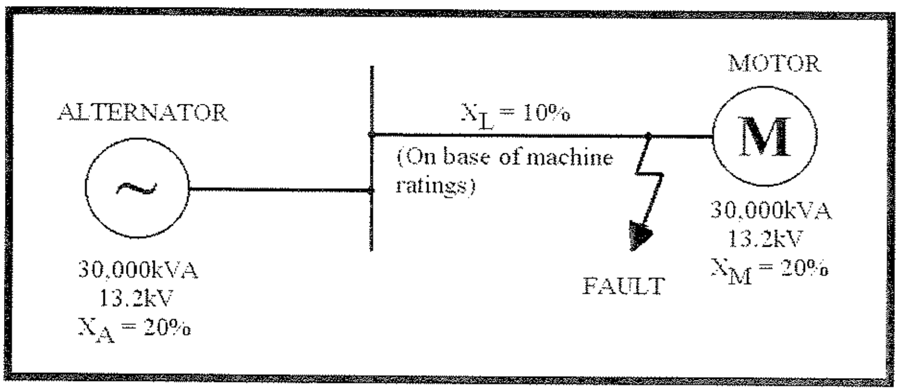


Figure 14. 9

Solution:

Step1: Select base power and base voltage

Base power = 30,000kVA
Base voltage = 13.2kV

Step 2: Draw reactance diagram

Since the machine and line reactances are all given on same kVA and kV bases, no correction to new bases are necessary. Reactance diagram for the system before the fault is shown as follows:

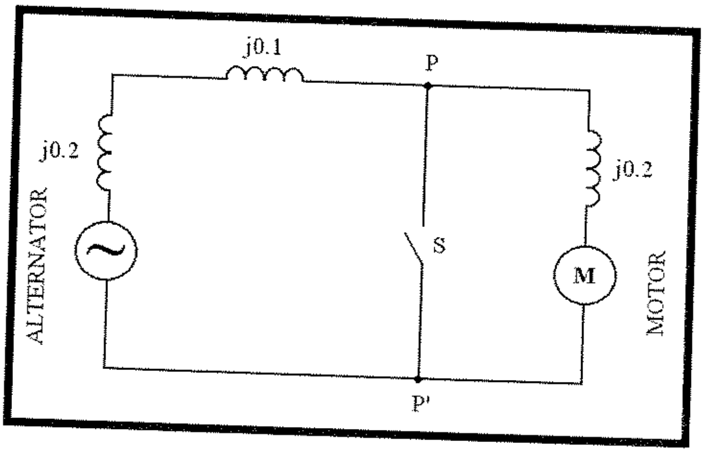


Figure 14. 10

Step 3: Simplify the reactance diagram

The impedance viewed at terminals PP' is the parallel combination of j0.2 (X'' of motor) with the series combination of j0.2 (X'' of alternator) and j0.10 (X_L of line).

Therefore, Resultant reactance

$= \frac{(j0.3 \times j0.2)}{(j0.3 + j0.2)} = \frac{j0.06}{0.5}$

$= j0.12$

The pre-fault voltage is the voltage that appears between terminals PP' just before closing the switch S,

that is, pre-fault voltage = 12.8kV (given)

Therefore, V_f(pu) = per unit pre-fault voltage at motor terminals PP'

$= 12.8 / 13.2 = 0.97\angle 0°$

The fault at the motor terminals is initiated by closing the switch S.

The reactance diagram for the system during the fault is therefore as shown in Figure 14.11.

Step 4: Calculate the fault current.

Z_f(pu) = per unit fault impedance

= resultant impedance = j0.12

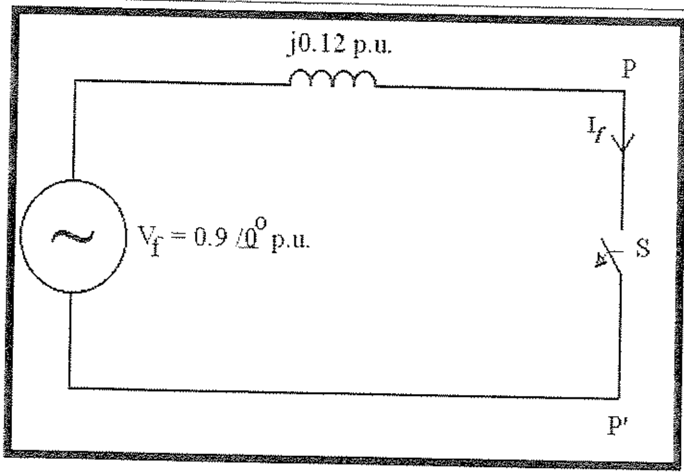


Figure 14. 11

Therefore, $I_f(pu)$
= per unit fault current

$$= \frac{V_f(pu)}{Z_f(pu)} = \frac{0.97\angle 0°}{j0.12} = -j8.08$$

$$\text{Now, Base current} = \frac{\text{Base kVA}}{\sqrt{3} \text{ x Base kV}} = \frac{30000}{\sqrt{3} \text{ x } 13.2} = 1312\text{A}$$

Therefore, Fault current
= $I_f(pu)$ x Base current
= -j8.08 x 1312 = -j10,600A
(-j indicates that current lags the voltage by 90°).

Also, per unit fault power = $V_f(pu)$ x $I_f(pu)$
= 0.97 x 8.08
= 7.84 per unit

Therefore, Fault power in kVA
= Per unit fault power x base kVA
= 7.84 x 30,000
= 235,200kVA
= 235.2MVA (the fault level)

14.7 ADVANTAGES OF PER UNIT COMPUTATIONS

Some advantages of the per unit method are summarised below:

(a) Calculations are made simple.

(b) Manufacturers usually specify the impedance of a machine in per unit (or per cent) on the base of the nameplate rating.

(c) For circuits connected by transformers, per unit system is particularly useful. By choosing suitable base kV's for the circuits, the per unit impedance remains the same, referred to either the HT or the LT side of the transformer. This also allows the various circuits of the network to be connected in the impedance diagram.

(d) The way in which transformers are connected in 3-phase circuits do not affect the per unit impedances of the equivalent circuit (although the transformer connection does determine the relation between the voltage bases on the two sides of the transformer).

(e) The use of $\sqrt{3}$ in 3-phase calculations is reduced.

14.8 REACTOR CONTROL OF FAULT CURRENTS

Use of Reactors

When a fault occurs at a point in a large generation and transmission network, the resulting short-circuit current is very large. In order to limit the short-circuit current to a value which the circuit breaker can safely handle, current limiting reactors are used. In fact, switchgear equipment of lower interrupting capacity can be used if reactors are fitted.

Construction of Reactors

Reactors consist of large coils wound for high self-inductance and very low resistance. As their resistance is kept small, no appreciable amount of energy is wasted in the reactors.

Reactors are normally air-cored so that with high currents, the reactance is not reduced by magnetic saturation. Saturation of a magnetic iron core would lead to a reduction in its inductance at high currents.

The 2 types of air-core reactors are:

(a) Oil-immersed Reactors

These reactors can be used in a circuit having any voltage. The windings are similar to those of a transformer and are housed in tanks similar to transformer tanks.

(b) Dry-type Reactors

These reactors are used in circuits having voltages up to 33kV. For the satisfactory transfer of heat, forced circulation of air must be maintained. Dry-type reactors are built with Class B insulation (130°C).

Methods of Locating Reactors

A reactor may be located in such a way that while there is no large voltage drop across it under normal conditions of operation, it will prevent a large short-circuit current being fed by the generators into the fault.

Reactors may be located in the following positions:

(a) Generator Reactors

When the reactors are connected in series with each generator as shown in Figure 14.12, they are called generator reactors.

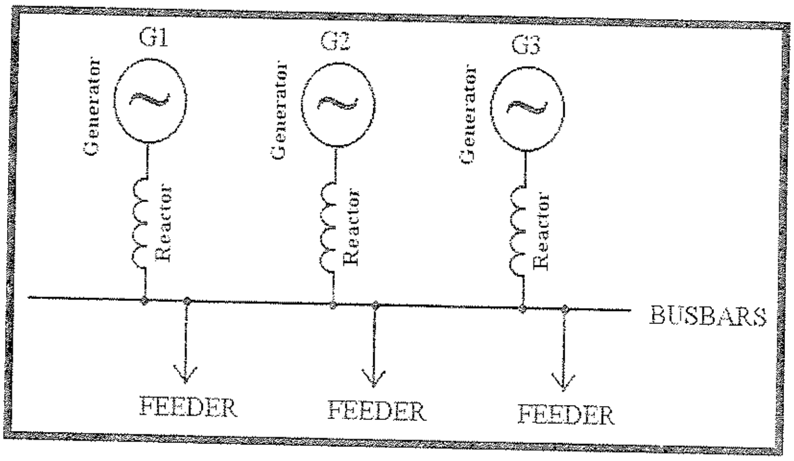


Figure 14. 12 Generator Reactors

With this arrangement, the reactor may be considered as a part of the reactance of the generator and the effect is to protect the generator for any short-circuit beyond the reactors.

Disadvantages of generator reactors:

(i) There is a constant voltage drop and power loss in the reactors during normal operation when only the load current is flowing.

(ii) In the event of a fault occurring on a feeder, the voltage on the common busbar drops to a low value with the result that the remaining feeders (which are healthy) may also fall out of step. The whole system is therefore interrupted and will need re-synchronising after isolating the faulty feeder.

(b) Feeder Reactors

When the reactors are connected in series with each feeder as shown in Figure 14.13, they are called feeder reactors.

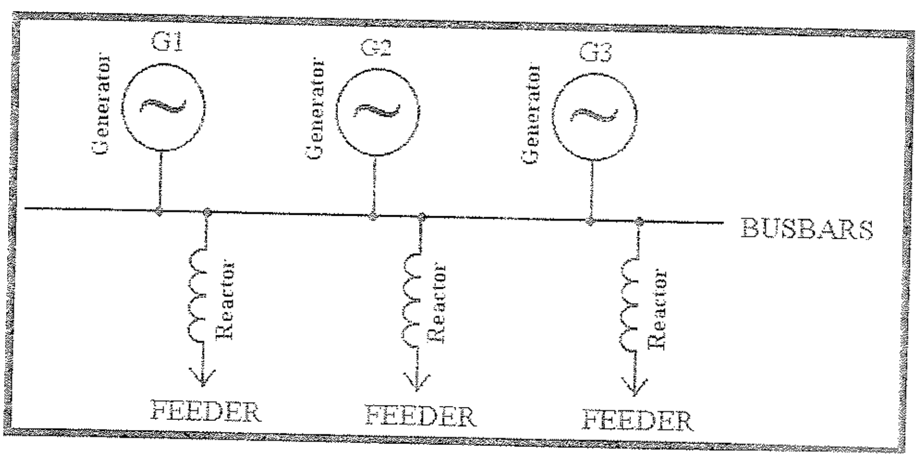


Figure 14. 13 Feeder Reactors

Advantage of Feeder Reactors:

In the event of a fault on any one feeder, the main voltage drop is in its reactor only so that the busbar voltage is not much affected and there is only small tendency for the generators to lose synchronism.

Disadvantages of Feeder Reactors:

(i) There is a constant power loss and voltage drop in the reactors even during normal operation.

(ii) If a short-circuit occurs at the busbars, no protection is provided to the generators. However, such faults are rare and modern generators have considerable reactance to limit the short-circuit current within safe margins.

(iii) Since most of the faults occur on feeders, a large number of reactors are used.

(iv) If the number of generators is increased, the size of feeder reactors will have to be increased to keep the short-circuit currents within the breaking capacities of the feeder circuit breakers.

(c) Busbar Reactors

Both generator and feeder reactors suffer from the disadvantage that they carry the full-load current of the circuits, thus causing constant voltage drop and copper loss in the reactors. This advantage can be overcome by locating the reactors in the busbars. There are 2 methods for this purpose, viz. ring system and tie-bar system.

(i) Ring System

In this system, the busbar is divided into sections and these sections are connected through reactors as shown in figure 14.14.

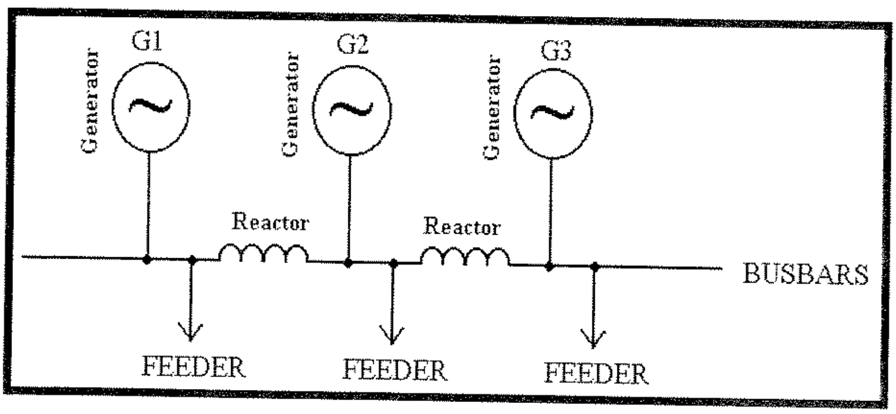


Figure 14. 14 Busbar Reactors (Ring System)

Generally, one feeder is fed from one generator only. Under normal operating conditions, each generator will supply its own section of the load and very little power will flow across the reactors. This results in low power loss and low voltage drop in the reactors.

Advantage of the Busbar Reactors (Ring System)

If a fault occurs on any feeder, only one generator (to which the faulty feeder is connected) mainly feeds the fault while the current fed from other generators is small because of the presence of reactors.

(ii) Tie-Bar System

This method as shown in figure 14.15 is particularly suited to a system where large extensions are likely to be made.

Advantages of the Busbar Reactors (Tie-Bar System)

- In the tie-bar system, there are effectively 2 reactors in series between sections so that reactors must have approximately half the reactance of those used in a comparable ring system.
- The tie-bar arrangement allows additional generators to be connected to the system without requiring changes to the existing reactors.
- With the increase of the number of sections in the system, the current that flows into the fault will not exceed the value fixed by the size of the individual reactor.

Disadvantage of the Tie-Bar System

The system requires an additional busbar (that is, the tie-bar).

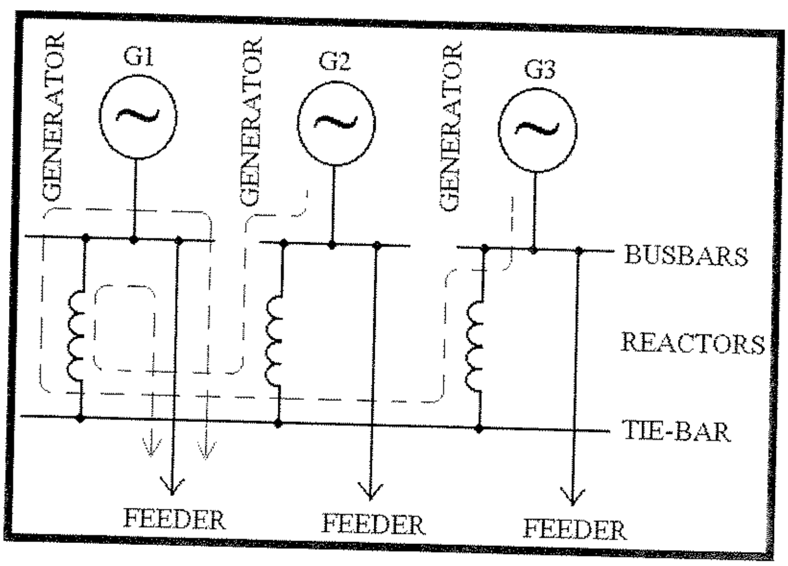


Figure 14. 15 Busbar Reactors (Tie-Bar System)

Note for the Installation of Reactors:

Generally, it is NOT economical to use reactors and hence the installation of reactors in power systems should be avoided as far as possible.

14.9 EXAMPLES

Example 14.6:

Figure 14.16 shows a transmission network with the following ratings:

Generator G1: 20MVA, 132kV, $X_{G1} = 20\%$
Generator G2: 10MVA, 132kV, $X_{G2} = 15\%$
Transformer T: 10MVA, 132/33kV, $X_T = 12\%$
Transmission Line L: $R_L = 20\Omega$, $X_L = 40\Omega$

Calculate:

(a) the fault level at circuit breaker A and the fault current through breaker A for a short-circuit fault at F1.

(b) the fault level at circuit breaker B and the fault current through breaker B for a short-circuit fault at F2.

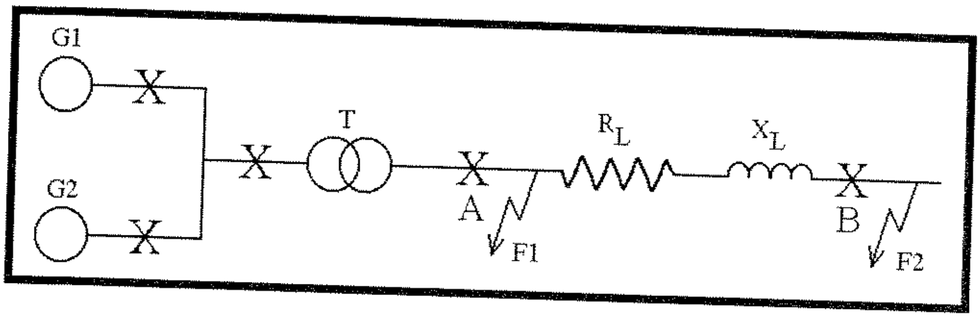


Figure 14. 16

Solution:

Select Base kVA = 10,000kVA
Base kV = 33kV (on 33kV side)
Base kV = 132kV (on 132kV side)

Convert all reactances to the same bases:
$X_{G1} = 0.2 \times 10{,}000/20{,}000 = 0.1$ pu
$X_{G2} = 0.15$ pu
$X_T = 0.12$ pu

$$\text{Base impedance on 33kV side} = \frac{(\text{Base kV})^2 \times 1000}{\text{Base kVA}} = \frac{33^2 \times 1000}{10{,}000} = 108.9\Omega$$

$$Z_L\,(\text{pu}) = \frac{(20 + j40)}{108.9} = 0.1837 + j0.3673$$

The impedance diagram is as shown

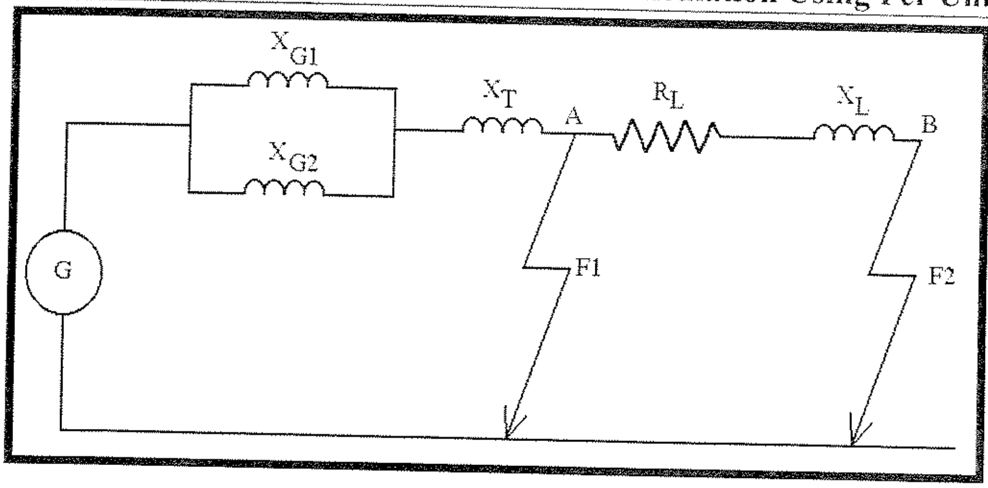


Figure 14. 17

(a) Total reactance up to F1 is

$$Z_{F1} = \frac{0.1 \times 0.15}{0.1 + 0.15} + 0.12 = 0.18$$

Since pre-fault voltage at F1 = Base voltage at F1, $V_{F1} = 1.0$ pu

Fault current I_{F1} (pu) = V_{F1} / Z_{F1}
= 1.0 / 0.18 = 5.56

Fault power (pu) = $V_{F1} \times I_{F1}$
= 1.0 x 5.56 = 5.56

Fault level (kVA) = Fault power (pu) x Base kVA
= 5.56 x 10,000
= 55,600kVA

Base current (A) (on 33kV side)

$$= \frac{\text{Base power (kVA)}}{\sqrt{3} \times \text{Base Voltage (kV)}}$$

$$= \frac{10000}{\sqrt{3} \times 33} = 175\text{A}$$

Fault current I_{F1} (A) = I_{F1} (pu) x Base current (A)
= 5.56 x 175 = 973A

(b) Total reactance up to fault point F2
X_{F2} (pu) = 0.18 + 0.3673 = 0.5473

Total resistance up to fault point F2,
R_{F2} (pu) = 0.1837

Total impedance up to fault point F2,
Z_{F2} (pu) = $\sqrt{(0.1837^2 + 0.5473^2)} = 0.5773$

Since pre-fault voltage at F2 = Base voltage at F2,
$V_{F2} = 1.0$ pu

Fault current I_{F2} (pu) = V_{F2} / Z_{F2} = 1.0 / 0.5773 = 1.732

Fault power (pu) = V_{F2} x I_{F2}
= 1.0 x 1.732 = 1.732

Fault level (kVA) = Fault power (pu) x Base kVA
= 1.732 x 10,000
= 17,320kVA

Fault current I_{F2} (A) = I_{F2} (pu) x Base current (A)
= 1.732 x 175 = 303A

Example 14.7:

Figure 14.18 shows an 11kV network comprising of three generators and three identical transformers.

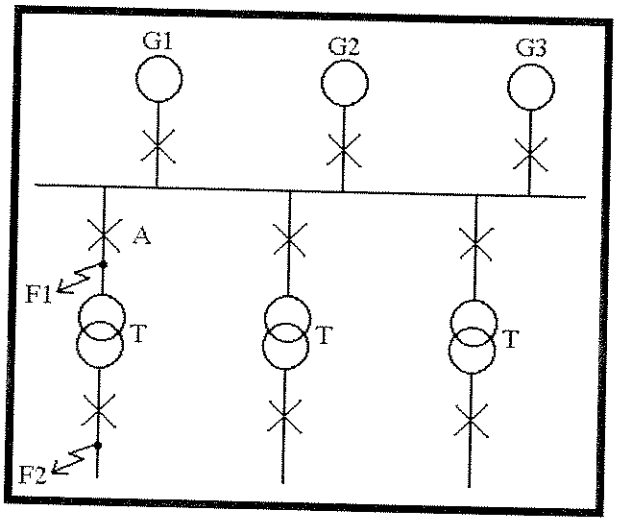


Figure 14. 18

The ratings are:

Generators G1, G2:	8MVA, 11kV, 14.5%
Generator G3:	4MVA, 11kV, 9.5%
Transformers T:	3MVA, 11/33kV, 4.0%

Determine:

(a) the minimum short-circuit kVA rating of breaker A
(b) the symmetrical fault current at F1
(c) the minimum short-circuit kVA rating of breaker B

Solution:

Select Base kVA = 8,000kVA
Base kV = 11kV (on generator side)

Convert all reactances to the same bases:
$X_{G1} = X_{G2} = 0.145$ pu
$X_{G3} = 0.095 \times 8 / 4 = 0.19$ pu
$X_T = 0.04 \times 8 / 3 = 0.107$ pu

Since the other two transformers do not contribute to the fault level at points A and B, their reactances are not included in the impedance diagram. The impedance diagram is shown as below in Figure 14.19 and 14.20.

(a) Total pu impedance up to the fault point F1 is

$$\frac{1}{Z_{F1}} = \frac{1}{X_{G1}} + \frac{1}{X_{G2}} + \frac{1}{X_{G3}}$$
$$= \frac{1}{0.145} + \frac{1}{0.145} + \frac{1}{0.19}$$
$$Z_{F1} = 0.0525$$

Since pre-fault voltage at F1 = Base voltage, $V_{F1} = 1.0$ pu

Fault current I_{F1} (pu)
$= V_{F1} / Z_{F1} = 1.0 / 0.0525 = 19.048$

Fault power (pu) $= V_{F1} \times I_{F1}$
$= 1.0 \times 19.048 = 19.048$

Fault power (kVA) (or fault level) = Fault power (pu) x Base kVA
= 19.048 x 8000 = 152,384 kVA

The impedance diagram can be simplified as shown in Figure 14.20.

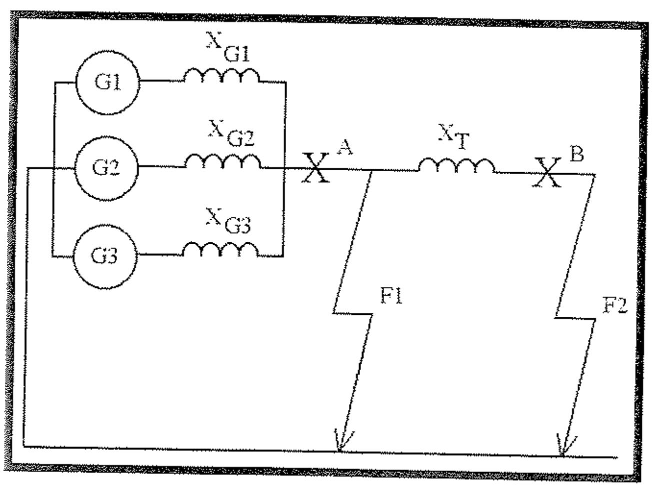


Figure 14. 19

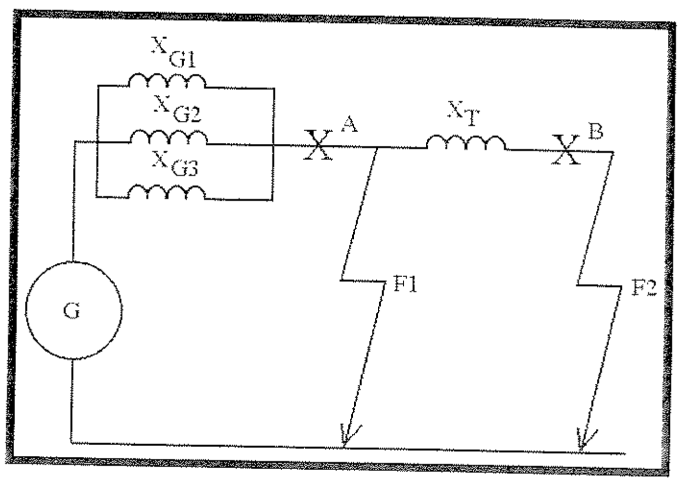


Figure 14. 20

(b) Base current $= \dfrac{\text{Base power (kVA)}}{\sqrt{3} \times \text{Base Voltage (kV)}}$
$= \dfrac{8000}{\quad} = 419.9$A

Fault current I_{F1} (A) = I_{F1}(pu) x Base current (A)
= 19.048 x 419.9A = 7998A

(c) Total impedance up to fault point F2,
Z_{F2} (pu) = 0.0525 + 0.107 = 0.1595

Since pre-fault voltage at F2 = Base voltage,
V_{F2} = 1.0 pu

Fault current I_{F2} (pu) = V_{F2} / Z_{F2} = 1.0 / 0.1595 = 6.27

Fault power (pu) = V_{F2} x I_{F2} = 1.0 x 6.27 = 6.27

Fault power (kVA) (or fault level)
= Fault power (pu) x Base kVA
= 6.27 x 8000 = 50,160 kVA

Example 14.8:

The single line diagram in figure 14.21 shows the electrical network of a commercial building taking electricity from the supply authority at 22kV. The authority has advised that the fault level at the intake point is 1000MVA.

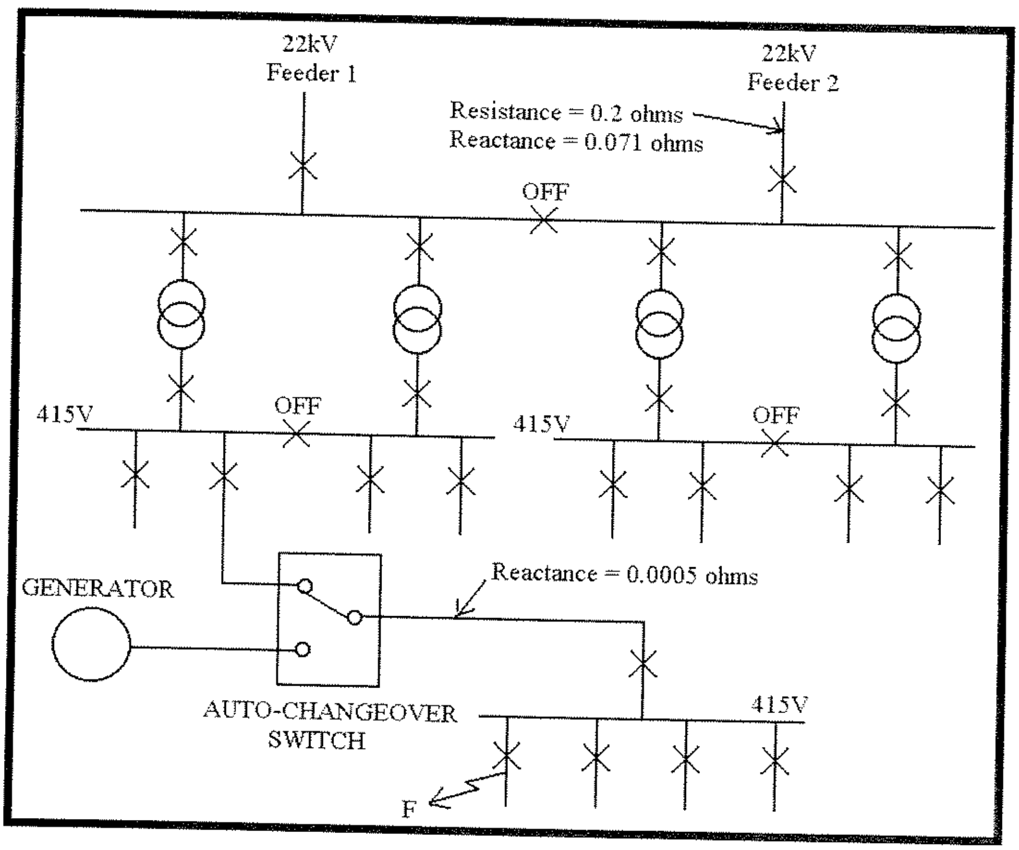


Figure 14. 21

Calculate the fault current and the fault level in kVA at location marked 'F' in the event of a three phase short-circuit and when the LT switchboard is receiving power from

(a) supply authority
(b) the standby generator during a power supply

The reactance of the four identical 2MVA, 22kV/415V transformers is 8.0%.
The sub-transient reactance of the 1MVA, 415V generator is 10.0%.
(Use of a value of 2,000kVA as the Base kVA)

Notes:

1. All breakers are closed unless otherwise stated.
2. Impedance of cables and busbars are assumed to be negligible unless otherwise stated.

Solution:

Select Base kV (on HT side) = 22kV
Base kV (on LT side) = 0.415kV

$$\text{Utility reactance, } X_s = \frac{\text{Base kVA}}{\text{Short-circuit kVA of utility}} = \frac{2000}{(1000 \times 1000)} = 0.002 \text{ pu}$$

$$\text{Base impedance (22kV side)} = \frac{22^2 \times 1000}{2000} = 242\Omega$$

$$\text{pu impedance of 22kV cable, } R_1 + jX_1 = \frac{(0.2 + j0.071)}{242} = 0.0008264 + j0.0002933$$

pu reactance of transformer, $X_T = 0.08$

$$\text{Base impedance (415V side)} = \frac{0.415^2 \times 1000}{2000} = 0.08611\Omega$$

$$\text{pu impedance of 415V cable, } X_2 = j\,\frac{0.0005}{0.08611} = j0.005807$$

pu reactance of generator, X_G
$= j0.1 \times 2000 / 1000 = j0.2$

(a) The impedance diagram is as shown in Figure 14.22.

Total impedance up to fault point, $Z_F = 0.0008264 + j0.0881$

Since pre-fault voltage at F = Base Voltage,
$V_F = 1.0$ pu

$$\text{Fault current } I_F \text{ (pu)} = V_F / Z_F = \frac{1.0}{0.0881} = 11.35$$

Base current (A) (on LT side) = $2000 / (\sqrt{3} \times 0.415) = 2782$A

Fault current $I_F = 11.35 \times 2{,}782 = 31{,}580A$

Fault level (kVA) $= \sqrt{3} \times V_F \times I_F$
$= \sqrt{3} \times 0.415 \times 31580 = 22{,}700kVA$

(b) The impedance diagram is as shown in Figure 14.23.

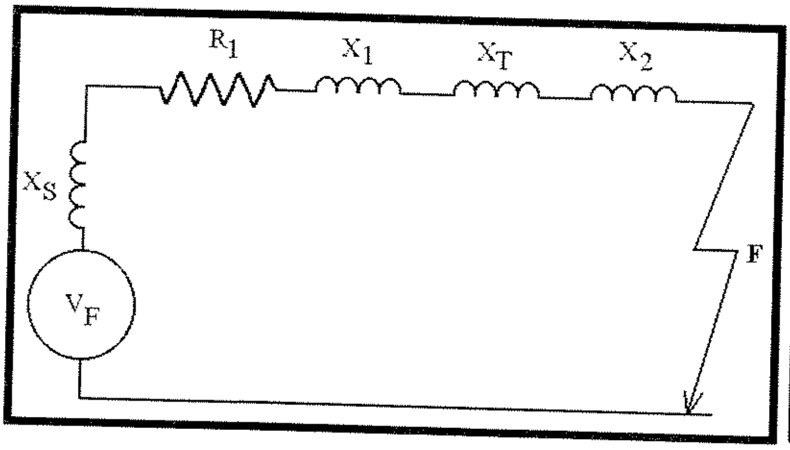


Figure 14. 22

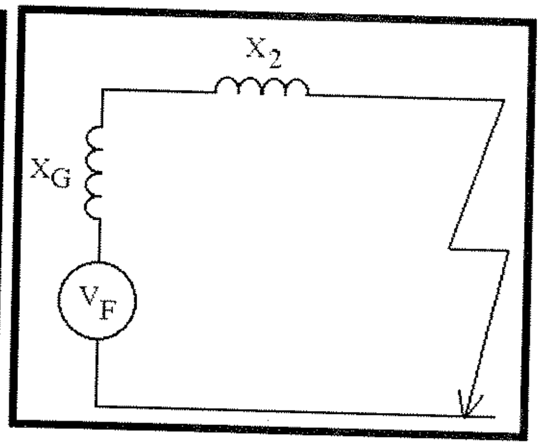


Figure 14. 23

Z_F (pu) $= j0.2 + j0.005807 = j0.205807$

Since pre-fault voltage at F = base voltage
$V_F = 1.0$ pu

Fault current I_F (pu) $= \dfrac{1.0}{0.205807} = 4.859$

$I_F = 4.859 \times 2782 = 13518A$

Fault level (kVA) $= \sqrt{3} \times V_L \times I_F$
$= \sqrt{3} \times 415 \times 13518 = 9717kVA$

Example 14.9:

A transformer rated 25,000kVA, 22/132 kV with leakage reactance of 5% is connected to the 22kV busbars of a substation by a short length of cable of negligible resistance and reactance as shown in figure 14.24.

The substation receives supply from two generators via two 22kV feeder cables, each 20km long and having an impedance of (0.05 + j0.1) ohms/km. One of the feeders is connected to a generator rated 50,000kVA, 22kV with a sub-transient reactance of 15%. The other feeder is connected to a generator rated 75,000kVA, 22kV with a sub-transient reactance of 10%.

When the generated voltage of both generators is 23.7kV and the system is unloaded, a three-phase short circuit takes place on the 132 kV side of the transformer.

Determine:

(a) the value of the phase angle of the fault current at the fault point
(b) the fault level (MVA)

(Select a Base kVA of 25,000kVA)

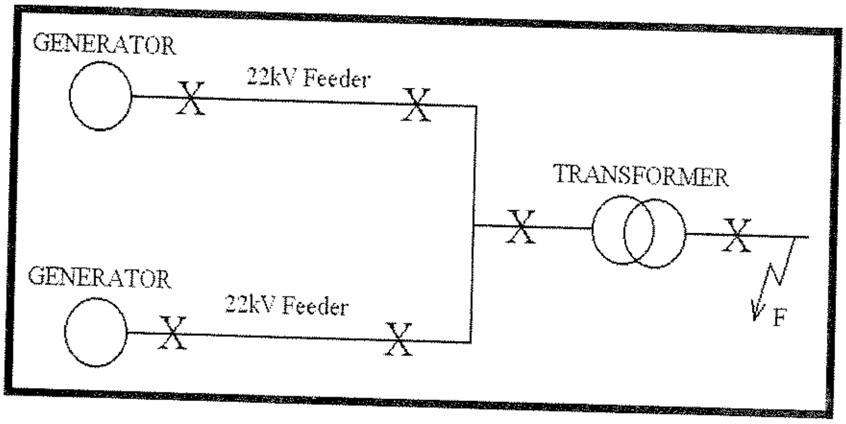


Figure 14. 24

Solution:

Select Base kV (on generator side) = 22kV
Base kV (on HT side of transformer) = 132kV

Convert all reactances to the same bases:

$$X_{G1} = 0.15 \times \frac{25{,}000}{50{,}000} = 0.075 \text{ pu}$$

$$X_{G2} = 0.10 \times \frac{25{,}000}{75{,}000} = 0.033 \text{ pu}$$

$X_T = 0.05$ pu

$$\text{Base impedance (on 22kV side)} = \frac{22^2 \times 1000}{25{,}000} = 19.36\Omega$$

$$\text{p.u. impedance of feeder} = \frac{(0.05 + j0.1) \times 20}{19.36} = 0.0517 + j0.1033$$

The impedance diagram is as shown in figure 14.25.

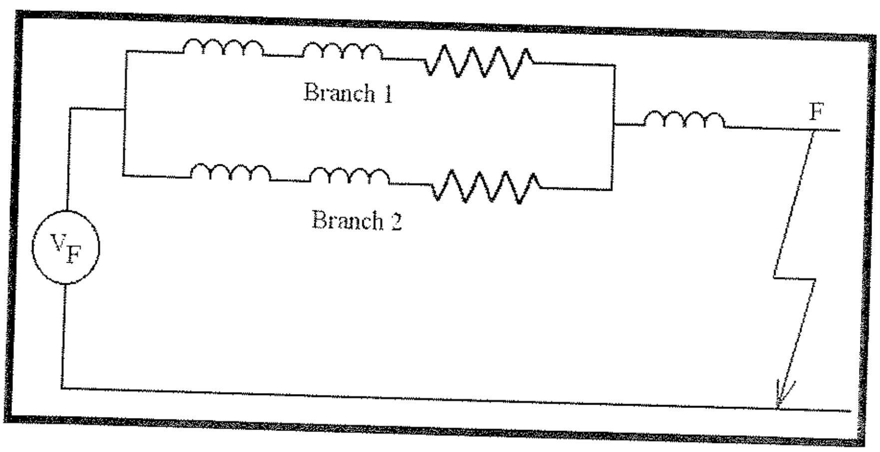


Figure 14. 25

pu impedance of branch 1, $Z_1 = 0.0517 + j(0.075 + 0.1033)$
$= 0.0517 + j0.1783 = 0.1856 \angle 73.8°$

pu impedance of branch 2, $Z_2 = 0.0517 + j(0.0333 + 0.1033)$
$= 0.0517 + j0.1366 = 0.1461 \angle 69.3°$

Equivalent impedance of Z_1 and Z_2,

$$\frac{1}{Z} = \frac{1}{Z_1} + \frac{1}{Z_2}$$

$Z = 0.0263 + j0.0775$

Total impedance up to fault point, Z_F
$= 0.0263 + j0.0775 + j0.05$
$= 0.0263 + j0.1275 = 0.1302 \angle 78.4°$

Since pre-fault voltage = 23.7kV, $V_F = 27 / 22 = 1.0773$ pu

(a) Taking V_F as reference,

Fault current I_F (pu)

$$= \frac{V_F}{Z_F} = \frac{1.0773 \angle 0°}{0.1302 \angle 78.4°} = 8.2742 \angle -78.4°$$

Base current on 132kV circuit $= \frac{25{,}000}{\sqrt{3} \text{ X } 132} = 109.4\text{A}$

Fault current $I_F = 8.2742 \angle -78.4° \text{ x } 109.4$
$= 905.2\text{A} \angle -78.4°$

(b) Fault level $= \sqrt{3} \text{ x } V_L \text{ x } I_F$
$= \sqrt{3} \text{ x } 142.2 \text{ x } 905.2$
$= 222{,}949$kVA
$= 223$MVA

1. Two 3-phase, 22kV/400V transformers are connected in parallel at the 400V Main switchboard. The power ratings of the transformers are as follows:

	Capacity	Reactance
Transformer No.1	1MVA	5%
Transformer No.2	2MVA	6.25%

   Determine the prospective symmetrical short-circuit current at the 400V busbar.

2. Two 3-phase, 22kV/11kV transformers are connected in parallel to a 11kV busbar. The power ratings of the transformers are as follows:

	Capacity	Reactance
Transformer No.1	7.5MVA	10%
Transformer No.2	10MVA	9%

   Determine the prospective symmetrical short circuit current at the 11kV busbar.

3. A 1.5MVA 11kV, star-connected generator with a reactance of 15% is connected to a 1MVA 11kV/400V transformer with a reactance of 5%. Neglecting the impedances of the connecting cables, determine the prospective symmetrical 3-phase short-circuit current at the 400V side of the transformer.

4. The single line diagram in Figure14.26 shows the electrical network of a commercial building taking electricity supply from the power supply company at 22kV. The power supply company has advised that the fault level at the intake point is 800MVA.

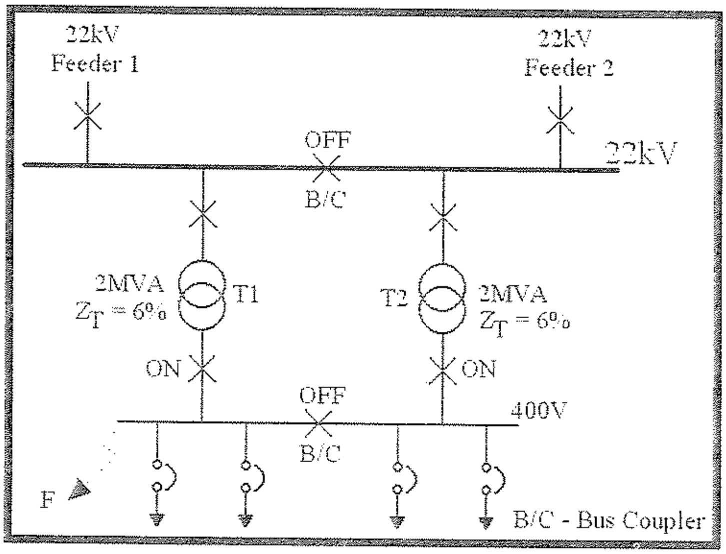


Figure 14. 26

Both transformers are identical. The rating of each transformer is 2,500kVA 22kV/400V with a reactance of 6.25%.

The resistance and reactance of each of the 22kV cable and the 400V cable are as follows:

22kV cable, Resistance = 0.014Ω
Resistance = 0.017Ω

400V cable, Resistance = 0.002Ω
Resistance = 0.001Ω

If the bus coupler at the 22kV MSB and 400V MSB are maintained at 'OFF' position, use per unit value method to determine the fault level in MVA and fault current in kA at location marked 'F' in the event of a three-phase short-circuit.

5. The single line diagram in Figure 14.27 shows the electrical network of a commercial building taking electricity from the power supply company at 22kV. Both transformers are identical and the rating of each transformer is 2,000kVA 22kV/400V with a reactance of 6%.

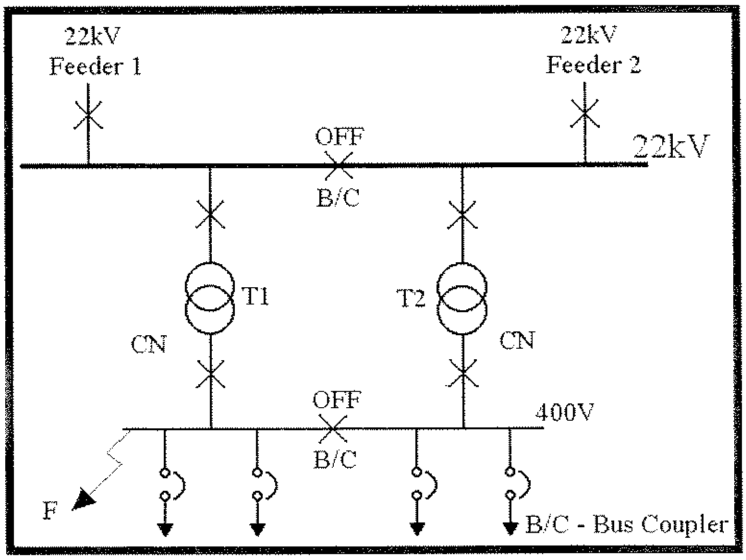


Figure 14. 27

The resistance and reactance of each of the 22kV cable and the 400V cable between the 22kV and 400V switchboard are as follows:

22kV cable, Resistance = 0.14Ω
Resistance = 0.06Ω
400V cable, Resistance = 0.00337Ω
Resistance = 0.00260Ω

The power supply company has advised that the fault level at the intake point is 1000MVA.

If the bus coupler at the 22kV MSB is maintained at 'OFF' position, and by mistake the bus-coupler and the two main breakers at 400V MSB are as maintained at 'ON' position, calculate the fault level in MVA and fault current in kA at location marked 'F' in the event of a three-phase short-circuit.

CHAPTER 15
CASE STUDIES IN DESIGN OF ELECTRICAL INSTALLATION

15.1 INTRODUCTION

Two cases selected to illustrate how electrical installations are designed to receive electricity supply at H.V. (22 kV) and L.V. (400V / 230V) respectively and to show how electrical installations are designed to meet:

(a) fundamental requirements for safety;

(b) requirements for protection against overcurrent

(c) requirements for protection against electric shock by proper design of earthing system and equipotential bonding system.

15.2 CASE STUDY 1

- High Voltage Electricity Supply at 22 kV
(Total Load: 3.2 MVA with 2 Nos. of 1.6 MVA Transformers and Earthing System is TN-S)

<u>**Assessment of General Characteristics**</u>

(a) Assessment of Maximum Demand

Chapter 31, Clause 311-01-01 requires that the maximum demand should be determined by calculations, measurements, enquiry or inspection.

Diversity may be taken but must be carefully determined by design engineer.

(b) Arrangement of 'Live' Conductors

Clause 312-02-01 requires that the number and type of 'live' conductors (e.g. single-phase 2-wires a.c., three-phase 3-wires, 3-phase 4-wires) shall be determined both for the source of energy and for each circuit.

(c) Type of Earthing Arrangement

Clause 312-03-01 requires that the type of earthing system be determined.

As the H.V./L.V. distribution transformer is provided by the consumer in the same premises together with the 400V MSB, TN-S earthing system is adopted, i.e. Neutral earthing and protective earthing share the same electrode system.

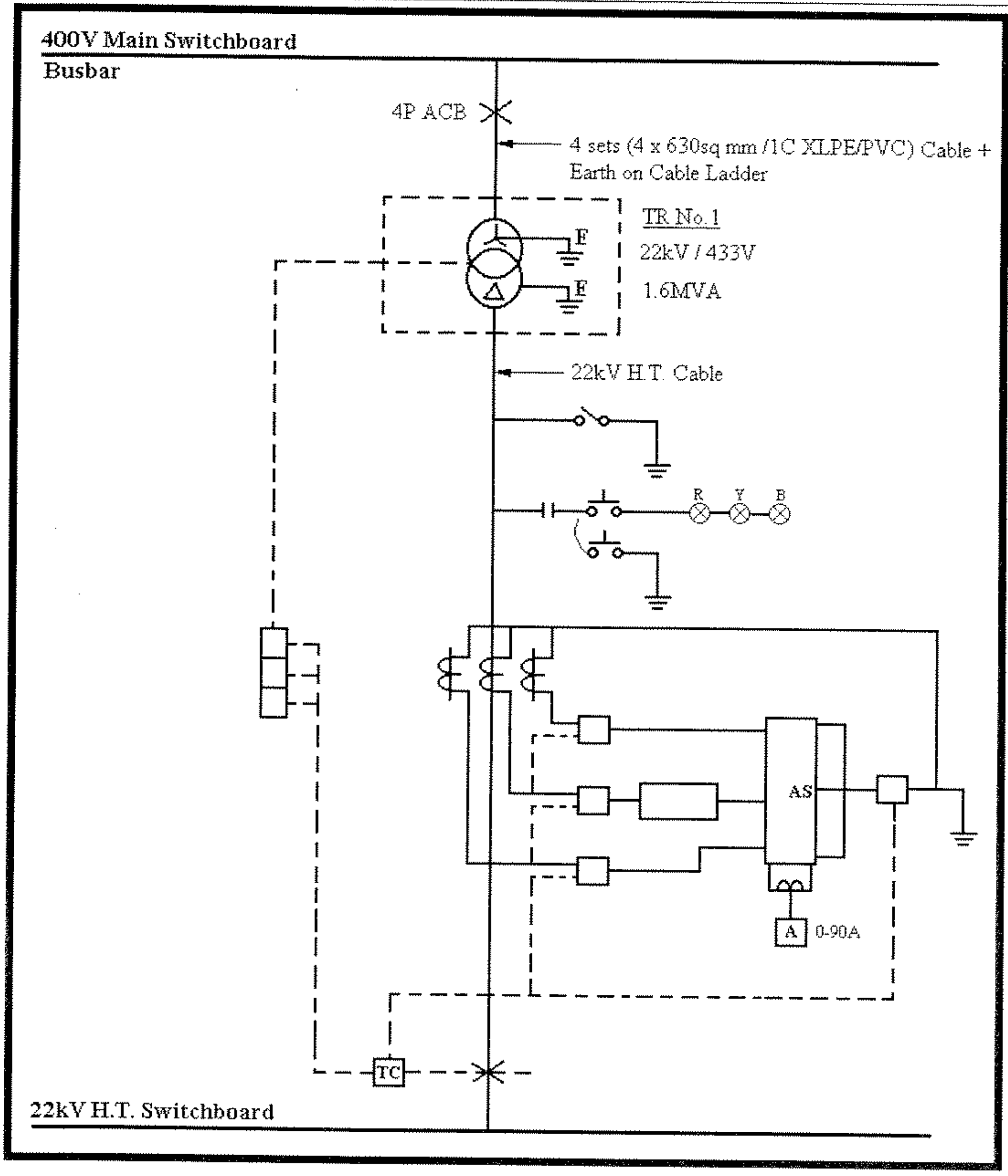


Figure 15. 1 22kV Supply System

(d) Nature of Supply

Among other things, the Clause 313-01-01 requires the following to be determined by calculation, measurement, enquiry or inspection:-

(i) The nominal voltage and frequency - 22 kV, 50 Hz

(ii) The prospective 3-phase short circuit level at PowerGrid intake at 22 kV is 25 kA or 1000 MVA.

This value can be converted to a per unit Value Impedance of the Source Impedance based on a selected Base MVA by the following formula:-

$$\text{Per Unit Value of Source Impedance} = \frac{\text{Base MVA}}{\text{Utility fault level in MVA}}$$

(iii) The earth fault loop impedance (Z_e) of that part of the system external to the installation – This can be calculated as shown in later part of this exercise.

(e) Installation Circuit Arrangement

Clause 314-01-01 requires that:

314-01-01 Every installation shall be divided into circuits as necessary to:

(i) avoid danger and minimize inconvenience in the event of a fault, and

(ii) facilitate safe operation, inspection, testing, and maintenance.

314-01-02 A separate circuit shall be provided for each part of the installation which needs to be separately controlled for compliance with this Code or otherwise to prevent danger so that such circuits remain energised in the event of failure of any other circuit of the installation, and due account shall be taken of the consequences of the operation of any single protective device.

314-01-03 The number of final circuits required and the number of points supplied by any final circuit shall be such as to facilitate compliance with the requirements of Chapter 43 for overcurrent protection. Chapter 46 for isolation and switching and Chapter 52 as regards current-carrying capacities of conductors.

314-01-04 Where an installation comprises more than one final circuit, each final circuit shall be connected to a separate way in a distribution board. The wiring of each final circuit shall be electrically separate from that of every other final circuit so as to prevent indirect energising of a final circuit intended to be isolated.

<u>Clause 130-03 – Overcurrent Protective Device</u>

130-03-01 Where necessary to prevent danger, every installation and every circuit thereof shall be protected against overcurrent by devices which:

(i) will operate automatically at values of current which are suitably related to the safe current rating of the circuit, and

(ii) are of adequate breaking capacity and, where appropriate, making capacity, and

(iii) are suitably located and are constructed so as to prevent danger from overheating, arcing or the scattering of hot particles when they come into operation and to permit ready restoration of the supply without danger.

<u>Clause 130-04 – Precautions Against Earth Leakage and Earth Fault Currents</u>

130-04-01 Where metalwork of electrical equipment, other than current-carrying conductors, may become charged with electricity in such a manner as to cause danger:

(i) the metalwork shall be connected with earth in such a manner as will cause discharge of electrical energy without danger, or

(ii) other equally effective precautions shall be taken to prevent danger.

130-04-02 Every circuit shall be arranged so as to prevent the persistence of dangerous earth leakage currents.

130-04-03 Where metalwork is connected with earth in accordance with Clause 130-04-01 (i) the circuits concerned shall be protected against the persistence of an earth fault current by:

(i) the overcurrent protective devices required by Clause 130-03-01, or

(ii) a residual current device or equally effective device.

The method described in item (ii) above shall be used whenever the prospective earth fault current is insufficient to cause prompt operation of the overcurrent protective devices.

130-04-04 Where metalwork of electrical equipment is connected with earth in accordance with Clause 130-04-01 (i) and is accessible simultaneously with substantial exposed metal parts of other services, the latter shall be effectively connected to the main earthing terminal of the installation.

<u>Protective Devices and Switches</u>

130-05 Protective Devices and Switches

130-05-01 A single-pole fuse, switch or circuit breaker shall be inserted in the phase conductor only.

130-05-02 No switch or circuit breaker, excepting where linked, or fuse, shall be inserted in an earthed neutral conductor and any linked switch or linked circuit-breaker inserted in an earthed neutral conductor shall be arranged to break all the related phase conductors.

130-06 Isolation And Switching

130-06-01 Effective means, suitably placed for ready operation, shall be provided so that all voltage may be cut off from every installation, from every circuit thereof and from all equipment, as may be necessary to prevent or remove danger.

<u>Sizing of the 400V Transformer Tails of the 22 kV/L.V. Transformer</u>

(a) The full load current of the 16 MVA transformer on the 400V side

$$= \frac{1600 \text{ kVA}}{\sqrt{3} \times 0.4 \text{ kV}} = 2309\text{A}$$

(b) Assuming 630 mm^2 single-core XLPE/PVC cables are to be used, the value of current I_t tabulated in Table 4E1A is <u>1115</u> (Method 11, flat touching, Column 9).

(From Table 4B1, correction factor for group)
With group correction factor 0.85 for 3 circuits of 12 single core cable (i.e. each phase has 3 conductors), therefore the 630 mm^2 cable is de-rated to 0.85 x 1115 = 948A

For 3 circuits in parallel connection (12 Nos. of 630 mm^2), the total current carrying capacity = 3 x 948A = 2309A, which is sufficient.

Alternatively, Bus-duct of equivalent current carrying capacity can be considered.

<u>Calculation of Prospective 3-Phase Short Circuit Current Amount at the 400V MSB</u>

Assuming 10 metres of 22 kV 300 mm^2 / 3C XLPE/SWA/PVC cable
& 20 metres of 12 Nos. 400V 630 mm^2 / SC XLPE/PVC cable
& Transformer Impedance = Z_T = 6% (IEC 76)
& Fault Level at PG's 22 kV intake = 1000 MVA

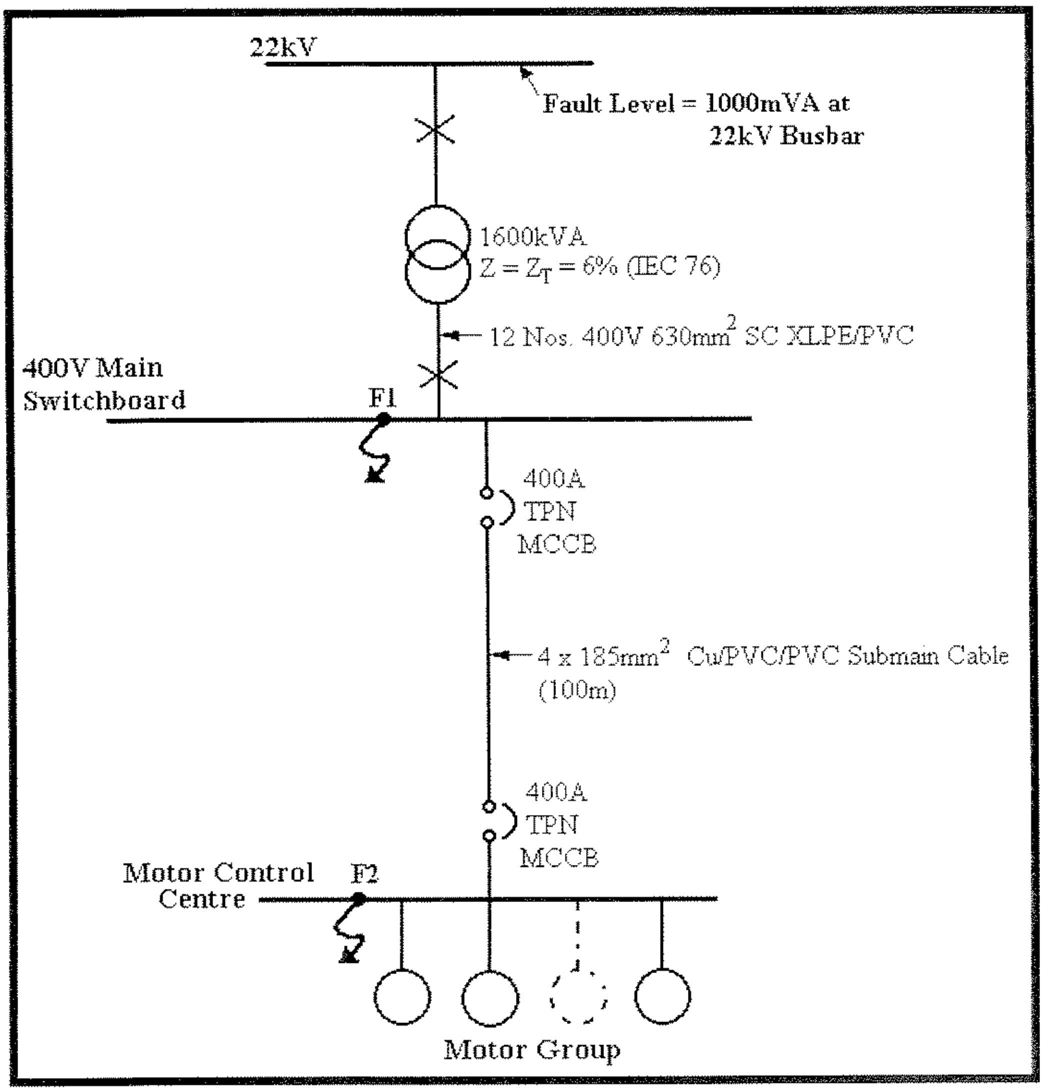


Figure 15.2

(a) Select Base MVA = 1.6 MVA
Base Voltage (H.V.) = 22 kV
Base Voltage (L.V.) = 0.4 kV

(b) Calculate:

$$\text{Base Impedance (22kV)} = \frac{(\text{Base V in kV})^2 \times 1000}{\text{Base Power in kVA}}$$

$$= \frac{(22)^2 \times 1000}{1600} = 302.5\Omega$$

$$\text{Base Impedance (0.4 kV)} = \frac{0.4^2 \times 1000}{1600} = 0.1\Omega$$

(c) Covert Utility Fault Level to p.u. value

$$Z_{\text{Source}} = \frac{\text{Base MVA}}{\text{Utility Fault Level}}$$

$$= \frac{1.6\ \text{MVA}}{1000\ \text{MVA}} = j0.0016\ \text{p.u.}$$

(d) Convert Cable Impedance to p.u. value

Ignore 22 kV cable
From Table

$$Z_{630\ \text{mm}^2} = 1/3\ [0.071/\sqrt{3} + j0.16/\sqrt{3}] \times 10^{-3} \times 20\text{m}$$
$$= (0.000273 + j0.000616)\ \Omega$$

$$Z_{630\ \text{mm}^2}\ (\text{p.u.}) = \frac{0.000273 + j0.000616}{0.1}$$
$$= (0.00273 + j0.00616)\ \text{p.u.}$$

(e) Total Impedance up to 400V MSB

$$= Z_S + Z_{22\text{kV}} + Z_T + Z_{630\ \text{mm}^2}$$
$$= j0.0016 + j0.06 + (0.002732 + j0.00616)$$
$$= 0.002732 + j0.06776$$
$$= 0.0678\ \angle\phi$$

$$\therefore \text{Fault Level at 400V MSB} = \frac{\text{Base MVA}}{Z_{\text{Total}}}$$

$$= \frac{1.6\ \text{MVA}}{0.0678\text{p.u.}} = 25\text{MVA}$$

∴ Prospective Symmetrical 3-phase Short Circuit Current (r.m.s.)

$$= \frac{25 \times 10^6}{\sqrt{3} \times 400} = 36.0\ \text{kA}$$

∴ A 2500A ACB with 43 kA or 50kA Breaking Capacity is recommended.

Calculation of Earth Fault Loop Impedance & Sizing of Earth Cable (TN-S Earthing System)

Assuming T/F Neutral Earthing Cable = 15 metres
Protective Main Earth Cable = 20 metres

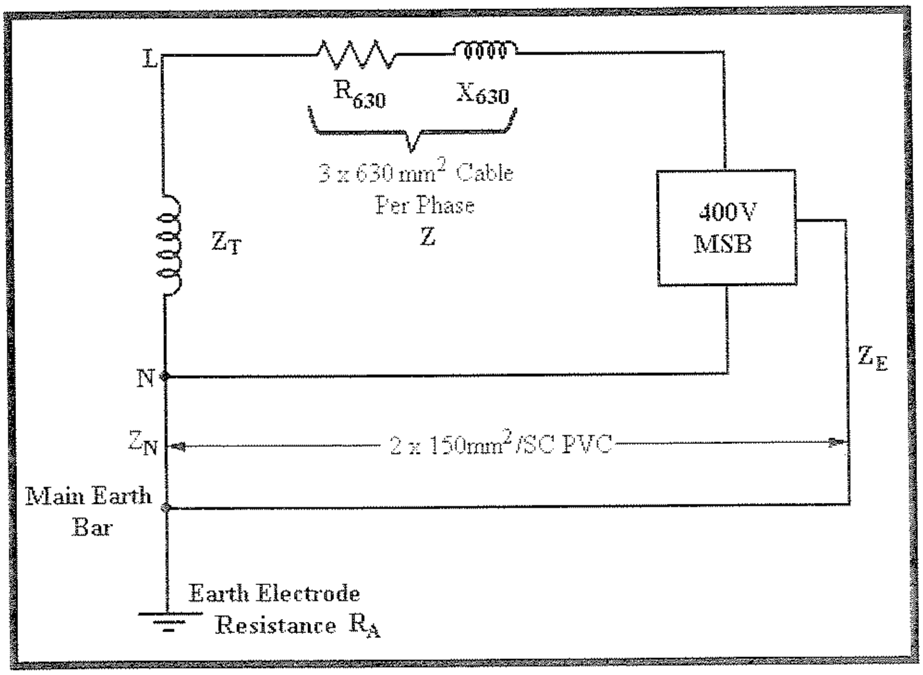


Figure 15. 3

(a) Assuming 2 x 150 mm²/SC PVC Main Earth Cable is used Total Earth Fault Loop Impedance, $Z_{EFLI} = Z_T + Z_{630} + Z_E + Z_{N/E}$

Earth Electrode Resistance is not included as it is not in the earth fault loop path in TN-S earthing system.

(b) 3-ϕ Short Circuit Level at the secondary terminal of

$$T/F = \frac{1.6\ MVA}{0.06} = 26.67\ MVA$$

$$I_{SC} = \frac{26.67 \times 10^6}{\sqrt{3} \times 400} = 38.50\ kA$$

$$\therefore Z_T = \frac{400/\sqrt{3}}{38.50 \times 10^3} = 0.00597\Omega$$

Assuming X/R ratio of 5 for transformer

$$R_T = \frac{Z_T}{\sqrt{1^2 + 5^2}} = Z_T \times 0.196 = 0.00117\Omega$$

$$X_T = 5 \times R_T = 5 \times 0.00117 = 0.00585\Omega$$

(c) 630 mm² XLPE Cable, from Table 4E1B of SS CP5 : 1998

$r = 0.071/\sqrt{3}\ m\Omega/m$, $X = 0.160/\sqrt{3}\ m\Omega/m$,
$= 0.04099\ m\Omega/m$ $= 0.0924\ m\Omega/m$

(d) Adjusted by Average Conductor Temp. for XLPE Cable

$= \frac{\text{Max. Normal Operating Temp.} + \text{Max. Final Temp.}}{2}$

$= \frac{90°C + 250°C}{2} = 170°C$

$r = (0.071 / \sqrt{3}) \times \frac{230 + 170}{230 + 90}$

$= 0.04099 \times 1.219$

$= 0.04996\ m\Omega/m$

$\therefore Z_{630} = {}^1/_3\ [0.0499 + 0.0924] \times 10^{-3} \times 20$

$= 0.000333 + j0.000616\ \Omega$

(e) 150 mm² PVC Earth Cable, From Table 4D1B of SS CP5: 1998

$r = 0.29/2\ m\Omega/m$, (At temp. = 70°C) $X = 0.26/2\ m\Omega/m$, $= 0.13\ m\Omega/m$

Adjusted by Average Conductor temp. for PVC Cable

$= \frac{\text{Max. Normal Operating Temp.} + \text{Max. Final Temp.}}{2}$

$= \frac{30°C + 160°C}{2} = 95°C$ (where 30°C is the ambient temp.)

$r = (0.29 / 2) \times \frac{230 + 95°C}{230 + 70}$

$= 0.145 \times 1.083$

$= 0.157\ m\Omega/m$

$\therefore Z_{150} = 1/2\ [0.157 + j0.13] \times 10^{-3} \times [20m + 15m]$

$= (0.00275 + j0.00228)$ ohm

Total Earth Fault Loop Impedance

$Z_{EFLI} = Z_T + Z_{630} + Z_E + Z_{N/E}$

$= (0.00117 + j0.00585) + (0.000333 + j0.000616) + (0.00275 + j0.00228)$

$= 0.004253 + j0.008746$

$= 0.0097\angle\phi$

$\therefore I_{E/F} = \frac{230V}{0.0097\Omega} = 23711A$

(f) Sizing Of Earth Cable as per Clause 543-01-03

$K^2S^2 \geq I_{EF}^2 t$ or $S = \frac{I\sqrt{t}}{K}$

From Table, K = 143 for PVC Earth Cable

No bunch with phase cable

Assuming t = 3 sec, $\therefore S = \frac{23711\sqrt{3}}{143}$

$= 287\ mm^2$ approx. 2 x 150 mm^2

Assuming t = 1sec, $\therefore S = \frac{23711\sqrt{1}}{143}$

$= 170\ mm^2$ approx. 2 x 95 mm^2

(g) Main Equipotential Bonding at the Main Switchroom

At $I_{E/F}$ = 23711A, the touch voltage at the metal body of the MSB
= $I_{E/F}$ x $[Z_E]$
= 23711 x [0.00275 + j0.00228] x (20m / 35m)
= 23711 x [0.00157 + j0.0013]ohm
= 23711 [0.00245]
= 59V >50V (Safe Touch Voltage Limit)

Conclusion:

From this exercise, it can be seen that substantial touch voltage can exist during fault conditions and these will be present not only between equipment and the Main Earth Terminal (MET) but also between it and other exposed – conductive parts and extraneous – conductive parts. It is therefore necessary:-

(a) To provide main equipotential bonding for all extraneous conductive part of non-electrical services at the entrance of services.

(b) To establish proper protective device co-ordination so that the duration for these touch voltages does not give rise to danger.

(c) To provide supplementary equipotential bonding to reduce such touch voltage.

Regulation 413-02-01 acknowledges that this protective measure is for general application and refers to the particular regulations applicable when using the option with regard to the system type and Earthing arrangement.

Regulation 471-08-01 goes on to make clear that for some installations and locations of increased shock rise (include some of those special installations or locations addressed in Part 6 of CP5:1998), protection against indirect contact will be by means of an RCD and the maximum permissible fault clearance times reduced. Additionally, where appropriate, supplementary equipotential bonding is required.

Protection against short circuit current as required by Clause 434-03-03

(a) The 12 Nos. 630 mm^2 (3 x 630 mm^2 per phase) XLPE cable connected to the 400V MSB is protected against I_{SC} = 36 kA short circuit current by the direct acting trip

(Magnetic trip) of ACB which operates within 0.04 sec.

Since Critical time $t_c = \frac{K^2S^2}{I_{SC}^2} = \frac{143^2 \times [3 \times 630]^2}{(36000)^2}$
For the cable

The cable is protected = 56.306 sec > 0.04 sec

(b) To check whether the 4 x 185 mm^2 Cu/PVC/PVC Submain Cable (100m) to MCC is protected against short circuit current.

(i) At the origin of the 400A MCCB for 185 mm^2 submain near MSB, I_{SC} (max.) = 36 kA (r.m.s.) as calculated earlier.

Check from MCCB characteristic for 400A MCCB, it should operate in 0.02sec on magnetic trip.

$$\text{Critical time for the Cable, } t_c = \frac{K^2S^2}{I_{SC}^2} = \frac{115^2 \times [185]^2}{(36000)^2}$$
$$= 0.348 \text{ sec} > 0.02 \text{ sec.}$$

(ii) At the remote end of the 185 mm^2 submain
I_{SC} (max.) = Phase to Neutral Short Circuit Current at the remote end.

For the 4 x 185 mm^2 PVC/SC submain cable (100m)

From Table 4D1B of SS CP5:1998

$r = 0.21/\sqrt{3}$, mΩ/m, $x = 0.22/\sqrt{3}$ mΩ/m,
(at temp. = 70°C)

$$\text{r to be adjusted to average temperature} = \frac{70°C + 160°C}{2} = 115°C$$

$$\therefore r = (0.21/\sqrt{3}) \times \frac{230 + 115°}{230 + 70°}$$
$$= 0.1213 \times 1.15 \text{ m}\Omega/\text{m}$$
$$= 0.140 \text{ m}\Omega/\text{m}$$

$$\therefore Z_{185} = (0.140 + j0.127) \times 10^{-3} \times 100$$
$$= (0.014 + j0.0127)\ \Omega$$

$$\therefore Z = Z_S + Z_T + 2 \times Z_{630} + 2 \times Z_{300}$$
$$= (0.00117 + j0.00585) + 2 \times [0.000333 + j0.000616] + 2 \times [0.014 + j0.0127]$$
$$= 0.0298 + j0.03248$$
$$= 0.044\underline{/\phi}$$

$$\therefore I_{SC}(\text{Min}) = \frac{230V}{0.044} = 5227A$$

& Check from MCCB characteristic

$I_{SC} = \frac{5227A}{400A} = 13 \times I_n = 13 \times$ thermal trip rating of MCCB

The MCCB operate in 0.03 sec

Critical time for 185 mm^2 cable, $t_c = \frac{K^2S^2}{I_{SC}^2}$

$$= \frac{115^2 \times [185]^2}{5227^2} = 4.07 \text{ sec} > 0.03 \text{ sec}$$

∴ The cable is protected.

Protection Against Indirect Contact – TN-S system

Protection by Automatic Disconnection of Supply

(a) CP5 : 1998 Requirements

(i) **Clause 413-02-07L**

413-02-06L Each exposed-conductive-part of the installation shall be connected by a protective conductor to the main earthing terminal of the installation and that terminal shall be connected to the earthed point of the supply source in accordance with Clause 542-01-02.

413-02-07L One or more of the following types of protective device shall be used:

- an overcurrent protective device
- a residual current device.

(ii) **Clause 413-02-08**

413-02-08 Clause 413-02-04 is considered to be satisfied if the characteristic of each protective device and the earth fault loop impedance of each circuit protected by it are such that automatic disconnection of the supply will occur within a specified time when a fault of negligible impedance occurs between a phase conductor and a protective conductor or an exposed-conductive-part anywhere in the installation. This requirement is met where the following condition is fulfilled:

$$Z_s \leq \frac{U_0}{I_a}$$

where:

Z_S is the earth fault loop impedance.

I_a is the current causing the automatic operation of the disconnecting protective device within the time stated in Table 41A as a function of the nominal voltage U_0 or under the conditions stated in Clauses 413-02-12 and 413-02-13 within a time not exceeding 5s.

U_o is the nominal voltage to Earth.

(iii) Clause 413-02-09

413-02-09 The maximum disconnection times of Table 41A shall apply to a circuit supplying socket-outlets and to other final circuits which supply portable equipment intended for manual movement during use or hand-held Class I equipment.

This requirement does not apply to a final circuit supplying an item of stationary equipment connected by means of a plug and socket-outlet where precautions are taken to prevent the use of the socket-outlet for supplying hand-held equipment nor to the reduced low-voltage circuits described in Clause 471-15.

(b) For this case study, the following design features were incorporated to comply with the above

(i) RCCB with 30mA sensitivity provided at DB for lighting and small power final circuits for supplementary protection against Direct Contact (Comply with Clause 412-06-01 & 412-06-02L) and protection against indirect contact by means of automatic disconnection (operate in 0.04 sec for current exceeding $5I_{\Delta n}$ = 5 x 30 mA)

This arrangement is particularly applicable to DB for lighting and SSO in Domestic premises, DB for SSO in Non-Domestic premises, DB for temporary supply, market/food stall.

(ii) RCCB with 100 mA, 300 mA sensitivity (operate in 0.04 sec at 5 x $I_{\Delta n}$) or ELR (set to operate within 0 to 0.5 sec) to provide protection against indirect contact for stationary equipment or DB with final circuits which do not require protection by 30 mA sensitivity RCCB

(iii) ELR (may be set to operate within 0 to 0.5 sec) or EFR (may be set to operate within 0 to 1 sec) to provide protection against indirect contact by means of automatic disconnection for Submain or distribution circuit

Additional Equipotential Bonding at the DB and MCC – Calculation of Earth Fault Loop Impedance at Sub-Board, DB or Motor Control Centre

Total Earth Fault Loop Impedance = $Z_T + Z_{630} + Z_{185} + Z_{95} + Z_E + Z_{N/E}$

As calculated before

$Z_T = 0.00117 + j0.00585\Omega$
$Z_{630} = 0.000333 + j0.000616\Omega$
$Z_{185} = 0.014 + j0.0127\Omega$
$Z_E + Z_{N/E} = 0.00275 + j0.00228\Omega$
& $Z_{95} = R_{95} + jX_{95}$

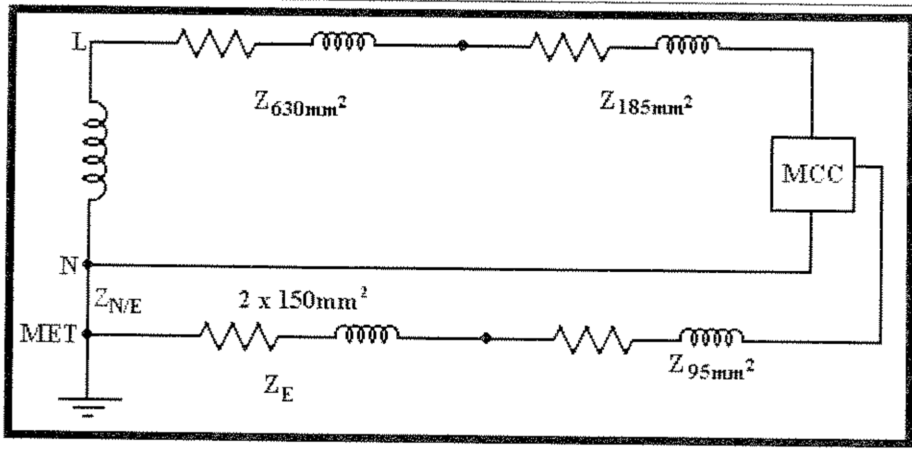


Figure 15. 4

From Table 4D1B of SS CP5 : 1998

$$R_{95} = \frac{0.47}{2} \times 10^{-3} \times 100m \times \frac{230 + 95}{230 + 70}$$

$$= 0.0235 \times 1.083$$

$$= 0.0255 \text{ ohm}$$

$$\text{At Average Conductor Temp.} = \frac{30°C + 160°C}{2} = 95°C$$

$$X = \frac{0.27}{2} \times 10^{-3} \times 100 = 0.0135 \text{ ohm}$$

Total Earth Fault Loop Impedance at the MCC

$$\therefore Z = Z_T + Z_{630} + Z_{185} + Z_{95} + Z_E + Z_{N/E}$$

$$= (0.04375 + j0.0350)\Omega$$

$$= 0.056 \text{ ohm}$$

$$I_{E/F} \text{ at the MCC} = \frac{230}{0.056} = 4107A$$

This current will cause the touch voltage at the metal body of the MCC on the motor to rise by 4107A x $[Z_{150} + Z_{95}]$

$$= 4107 \times (0.00275 + j0.00228) \times \frac{20}{35} + (0.0255 + j0.0135)$$

$$= 4107 \times (0.00157 + j0.0013 + 0.0255 + j0.0135)$$

$$= 4107 \times [0.02707 + j0.0148]$$

$$= 4107 \times [0.03\angle\phi]$$

$$= 123V > 50V \text{ (safe touch voltage limit)}$$

Conclusion

Substantial touch voltage can exist during fault conditions.

Solution

Additional Local Equipotential Bonding of extraneous conductive part (e.g. water pipe) at each of the Motor Control Centre, DB, Sub-board and each of the sub-electrical system.

15.3 CASE STUDY 2

- Low Voltage Electricity Supply at 400V/230V
(Earthing system is TT)

Assessment of General Characteristics

(a) Assessment of Max. Demand

(b) Arrangement of 'Live' Conductor

(c) Type of Earthing Arrangement

As the electricity supply is received from L.V. network of the PowerGrid, Neutral Earthing is implemented at the Power Supply Co. side, while protective earthing is implemented at the consumer side, and each has its own earth electrode system.

(d) Nature of Supply

(i) The nominal voltage and frequency – 400V/230V 50 Hz

(ii) The prospective 3-phase short circuit level at the PowerGrid intake (400V/230V) depend on where the electricity supply is tapped.

This value can be converted to an ohmic value of utility Source Impedance by the following formula:-

$$\text{Ohmic value of Source Impedance} = \frac{400V/\sqrt{3}}{\text{Prospective 3-}\phi\text{ Short Circuit Current}}$$

(iii) The earth fault loop impedance value (Z_c) is dominated by the earth electrode resistance R_A of the Neutral earthing system at the distribution transformer and the earth electrode resistance R_B of the protective earthing system at the consumer's Main Switchroom.

This value can be calculated as shown in later part of this case study.

Fundamental Requirements for Safety

(a) Overcurrent protective device
(b) Precautions against Earth leakage and Earth fault currents
(c) Protective Devices and Switches

Case Study

The Low Voltage Supply System to the 1st floor of a multi-storey building is shown in Figure 15.5.

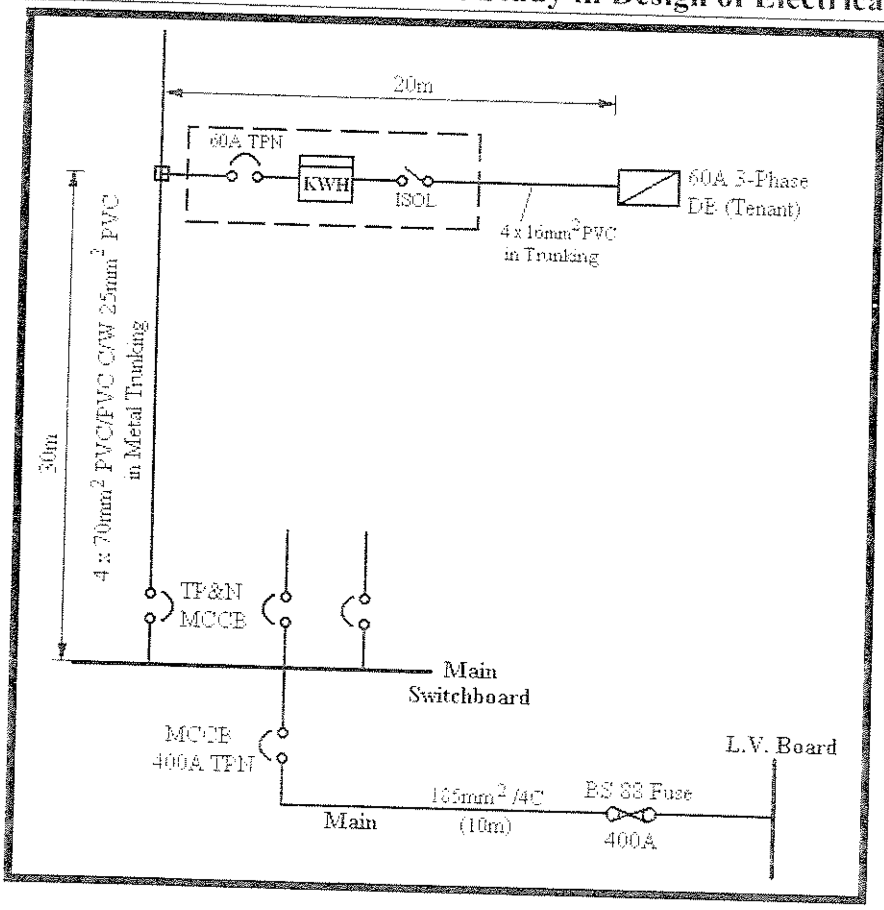


Figure 15. 5

The length and impedances of the cables are as follows:-

	Impedance Per Phase Per Metre	Length
185 mm²/4C XLPE/SWA/PVC main from PowerGrid (Table 4E4B)	$\left[\frac{0.22}{\sqrt{3}} + j\frac{0.125}{\sqrt{3}}\right] \times 10^{-3}$	10m
4 x 70 mm² PVC/PVC single core riser (Table 4D1B)	$\left[\frac{0.56}{\sqrt{3}} + j\frac{0.25}{\sqrt{3}}\right] \times 10^{-3}$	30m
4 x 16 mm² PVC single core service to tenant (Table 4D1B)	$\frac{2.4}{\sqrt{3}} + j0 \times 10^{-3}$	20m

Fault Level Calculation

(a) Calculate of Fault Level at the 400V 3-phase MSB

The declared fault level at the PowerGrid intake is 36 kA, this prospective short circuit current can be converted to an equivalent source impedance.

$$Z_{source} = \frac{400V/\sqrt{3}}{36 \times 10^3} = j0.00639 \text{ ohms (Reactive)}$$

$\therefore$ Total Impedance up to the MSB

$$\begin{aligned} Z_{total} &= Z_{source} + Z_{185} \\ &= j0.00639 + (0.127 + j0.0722) \times 10^{-3} \times 10 \\ &= j0.00639 + 0.00127 + j0.000722 \\ &= 0.00127 + j0.00711 \\ &= 0.00722\underline{/\phi} \end{aligned}$$

$\therefore$ Prospective 3--ϕ short circuit current at the MSB is $= \frac{400V/\sqrt{3}}{0.00722} = 33.24$ kA

$\therefore$ A 400A MCCB with breaking capacity 36 kA is recommended.

(b) At the Tap-off unit

$$Z_{total} = Z_s + Z_{185} + Z_{70}$$

$$Z_{70} = \left(\frac{0.56}{\sqrt{3}} + \frac{j0.25}{\sqrt{3}}\right) \times 10^{-3} \times 30m$$

$$= 0.0097 + j0.00433 \text{ ohm}$$

$$\begin{aligned} \therefore Z_{total} &= j0.0039 + (0.00127 + j0.000722) + (0.0097 + j0.00433) \\ &= 0.01097 + j0.0114 = 0.0158\underline{/\phi} \end{aligned}$$

$$I_{SC} = \frac{400V/\sqrt{3}}{0.0158} = 14.56kA$$

Prospective 3-phase short circuit level at tap-off unit is 14.56 kA. A 16 kA MCCB is required.

(c) At the tenant DB

$$Z_{16} = \frac{2.4}{\sqrt{3}} \times 10^{-3} \times 20m$$

$$\begin{aligned} \therefore Z_{total} &= Z_S + Z_{185} + Z_{70} \\ &= (0.01097 + j0.00114) + 0.0278 \\ &= 0.0388 + j0.0114 \\ &= 0.04\underline{/\phi} \end{aligned}$$

$$\therefore I_{sc} = \frac{400V/\sqrt{3}}{0.04} = 5.75 \text{ kA}$$

$\therefore$ 6 kA MCB is required at the DB.

Calculation of Earth Fault Loop Impedance

(a) At the Main Switchboard

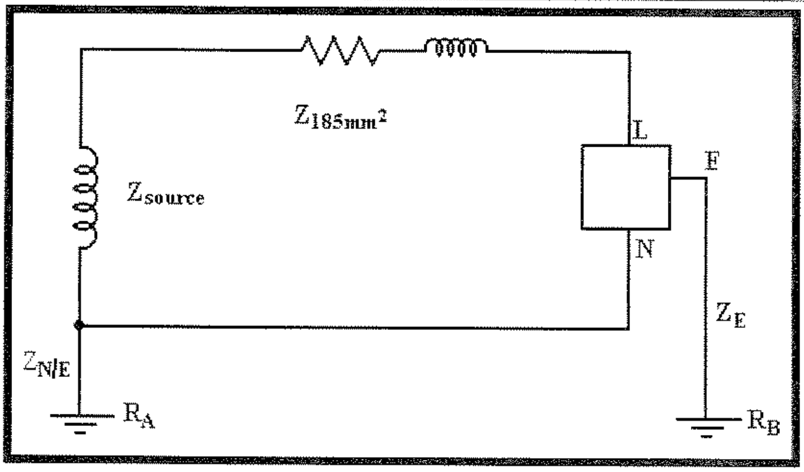


Figure 15.6

Earth Fault Loop Impedance = $Z_{source} + Z_{185} + Z_E + R_B + R_A + Z_{N/E}$

where $Z_{source} = 0.00639\Omega$

$Z_{185} = 0.00127 + j0.000722$

$$Z_E = Z_{70} = \left(\frac{0.56}{\sqrt{3}} + \frac{j0.25}{\sqrt{3}}\right) \text{x } 10^{-3} \text{ x } 10\text{m}$$

$$= 0.00323 + j0.00144$$

Therefore, Z_{source} approx. $R_A + R_B$

If $R_A = R_B = 1\Omega$, $Z_{EFLI} = 1 + 1 = 2\Omega$

$$I_{EFLI} = \frac{400V / \sqrt{3}}{2\Omega} \text{ approx. } 120A$$

If $R_A = R_B = 0.1\Omega$, $Z_{EFLI} = 0.1 + 0.1 = 0.2\Omega$

$$I_{EFLI} = \frac{400V / \sqrt{3}}{0.2\Omega} \text{ approx. } 1200A$$

(b) Protection against Indirect Contact by Automatic Disconnection of Supply

As $I_{E/F}$ may be as low as 120A to 1200A, it may not be sufficient to cause the overcurrent protection device (i.e. MCB, MCCB or overcurrent relay) to operate.

Therefore for TT earthing system, Clause 413-02-19 recommended that Residual Current Device is preferred for protection against indirect contact.

CHAPTER 16
TESTING ON MAIN SWITCHBOARD

16.1 TESTING BEFORE TURN-ON ELECTRICITY SUPPLY

Before the turn-on of electricity supply to a new main switchboard (MSB), the following tests must be satisfactorily carried out to ensure that the switchboard is safe for turn on:

(a) Primary current injection test (PI Test) on all protection current transformers, overcurrent relays and earth fault relays.

(b) Earthing system test (Earth Resistance Test).

(c) Insulation resistance test on all busbars.

(d) Insulation resistance test on all incoming feeders and outgoing submains and risers.

(e) Inspection and checking to ensure that all joints between busbars and all termination of cables are electrically and mechanically sound.

(f) Checking to ensure that the mechanical interlocks of the incoming breakers and outgoing breakers are designed and installed correctly.

Primary Current Injection Test on L.V. Circuit Breaker

Purposes of PI Test

The purposes of PI Test are:

(a) to ensure that wiring connection of protection system is in order;

(b) to check C.T.'s ratios and polarities;

(c) to check that O/C relays and E/F relays are set to correct settings (both tripping current and tripping time must be set correctly).

Test Method

(a) Primary Current Injection (PI) Test

(i) Connect the PI set (a current source) between a phase and neutral conductor as shown in Fig. 16.1 and send a current at 100% of the switchboard rated current (primary current).

Measure the ammeter reading at the secondary side of the Current Transformer (C.T.) which should read 5A (the rated secondary current of the C.T.). This is to ensure that C.T. ratio is correct.

O/C & E/F System

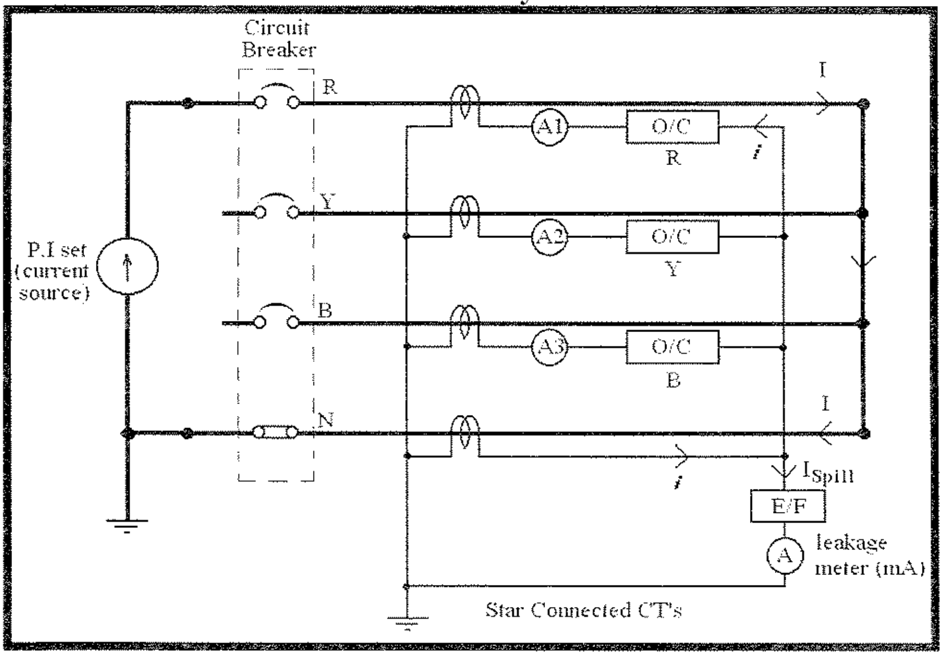


Fig. 16.1 Primary Injection Test for Overcurrent Relay

Measure the leakage current or spill current flowing through the Earth Fault Relay (E/F) which should be negligible (in mA range), this is to ensure that polarities (S_1 and S_2 terminals) and connections of all current transformers are correct. If the mA leakage meter reads 10A in this test, polarity of one of the C.T. must be wrong.

Repeat the test on the same phase at 50% of the switchboard rated current.

(ii) Repeat the test at the other 2 phases and tabulate the result as shown in Fig. 16.2.

(iii) Testing on Direct Acting element

Disable the tripping circuit (shunt trip circuit) of the circuit breaker. Send PI current at value of direct acting trip (in the form of magnetic trip) between a phase and neutral conductor to trip the breaker and check the tripping time, tabulate and check the tripping time, tabulate the result as shown in Fig. 16.2.

Repeat the test for 2 other phases.

(b) <u>Overcurrent and Earth Fault Operation Test</u>

<u>DTL O/C and E/F Relays</u>

(i) Set the O/C relay to 100% of the approved load. Inject a current between phase and neutral as shown in Fig. 16.1 until the circuit breaker trips to check the tripping time.

(ii) Set the E/F relay to the approved setting. Inject a current into a phase until the circuit breaker trips. Repeat the test as shown in Fig. 16.3 to check the tripping time.

(iii) Tabulate the results as shown in Fig. 16.3.

PRIMARY CURRENT INJECTION TEST ON CIRCUIT BREAKER

NAME OF CONSUMER ____________________ REF NO: __________

INSTALLATION ADDRESS ____________________

DATE OF TEST __________ MAKE OF SWITCHGEAR __________ PANEL NO. __________

APPROVED LOAD: ________ kW at ________ Volts SERVICE TYPE *Direct from: PowerGrid / Landlord

PARTICULARS OF CIRCUIT BREAKER: *ACB

Make: _____ Type: ________ Short Circuit Capacity: ________ kA for ______ sec(s)

Serial No. ______ Rated Voltage: _____ V Rated Current: ______ A Shunt Trip Coil Rated Voltage: ______ V

PARTICULARS OF PROTECTION EQUIPMENT:

	Make	Type	CT Ratio	Class	Burden
O/C Relay:					
E/F Relay:					

TEST RESULTS:

Phase Injected	Secondary Current Setting (A)	Primary Trip Current (A)	Tripping Time (s)	Spill Current (mA)	
R – N Y – N B – N (set for o/c)	(sealed)		(sealed)	(50%)	(100%)
* R/Y/B - E (set for E/F)	(sealed)		(sealed)		

* Back-up Fuse Rating / Direct Acting Setting (A): R ________ Y ________ B ________

Direct Acting Tripping Time (sec) : R ________ Y ________ B ________

Hand Trip: * Satisfactory / Unsatisfactory

DECLARATION BY HIGH HIGH VOLTAGE TESTING ENGINEER: (HVTE)

I, ____________________, a duly appointed HVTE under regulation 20 of the Electrical Workers and Contractors Licensing Regulations 1997, declare that the above tests are carried out in accordance with SS/BS/ equivalent standards and to the best of my knowledge, the results comply with the relevant standards and/or engineering practice.

____________________ ____________________ ____________________

Signature of HVTE Licence No. Date

ENDORSEMENT BY LICENSED ELECTRICAL WORKER (LEW):

The above test results are satisfactory and acceptable to me.

____________________ ____________________ ____________________

Name and Signature of LEW-in-charge of above-mentioned installation Licence No. Date

(* Delete whichever is not applicable)

Fig. 16.2 Test Result of Operation of DTL O/C and E/F Relays

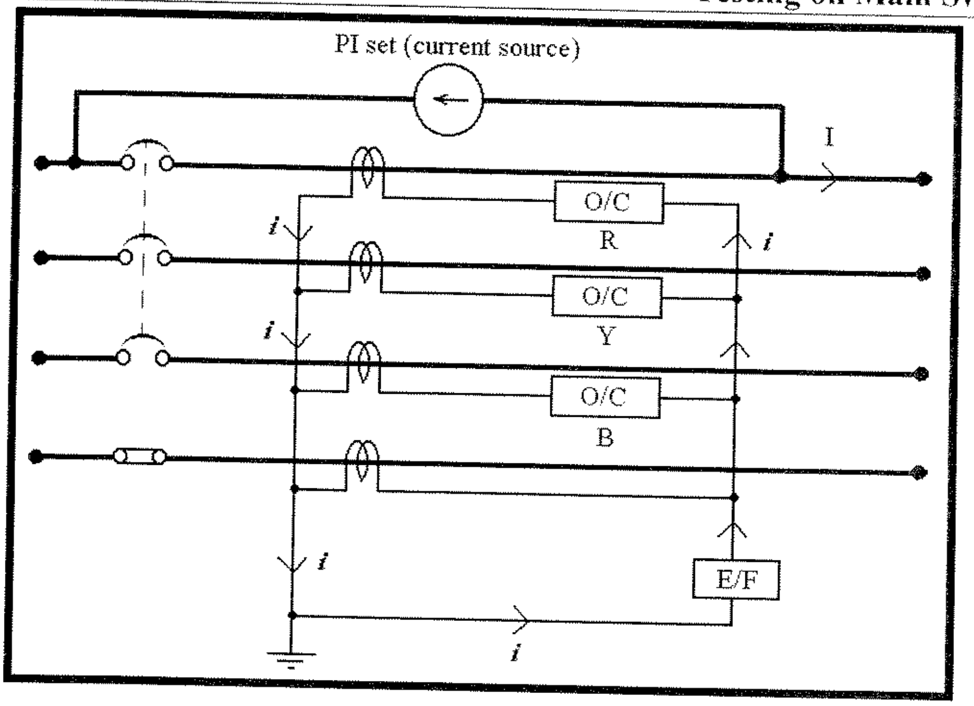


Fig. 16.3 Earth Fault Relay Operation Test

IDMTL Relays

If the protection relays are of the IDMTL type, secondary injections at the relays shall be carried out as follows:

(i) O/C Relay (IDMTL)

At plug setting (P.S.) set at 100% (or at 5A rated current) and time multiplier (TM) set at the required TM setting, injection current at secondary current equals to 5 times, 3 times, 2 times of the plug setting (P.S.) shall be injected to the relay and the operating time of the relay are recorded as shown in Fig. 16.4.

The results are to be compared with the standard operating time of IDMTL relay.

Repeat the test for the actual setting of plug setting and TM setting.

Repeat the test for all other phases and seal the relays for the final setting.

(ii) E/F Relay (IDMTL)

At plug setting (P.S.) set at the required setting (normally 10 to 20% of rated current) and the time multiplier (TM) set at required value. Injection current at secondary current equal to 5 times, 3 times, 2 times of the plug setting (P.S. %) shall be injected to the relay and the operating time of the relay recorded. The test result shall be compared with the standard operating time of IDMTL relay.

Repeat the test for the actual setting of plug setting and TM setting and seal the relay for the final setting.

OVERCURRENT AND EARTH FAULT RELAY OPERATION TEST

NAME OF CONSUMER ______________________________ REF NO: __________

INSTALLATION ADDRESS ______________________________

DATE OF TEST __________ MAKE OF SWITCHGEAR __________

SERVICE TYPE *Direct from: PowerGrid / Landlord

PARTICULARS OF RELAYS

	Make	Type	Tripping Charac	Rating	S/No.
O/C Relay:					
E/F Relay:					

TEST RESULTS of LT Installation: Panel No/Circuit Name __________

O/C RELAY					E/F RELAY				
Plug Setting	Sec. Current (A)	Operating Time (s)			Plug Setting	Sec. Current (A)	Operating Time (s)	TM Setting	Std Time
		R	Y	B					
Seal at					Seal at			Seal at	

Plug Setting	Starting Current			Plug Setting	Starting Current
	R	Y	B		
High Set	Operating Current			High Set	Operating Current
	R	Y	B		
Secondary Wiring Insulation Resistance:		Mohm			

DECLARATION BY HIGH HIGH VOLTAGE TESTING ENGINEER: (HVTE)

I, ______________________, a duly appointed HVTE under regulation 20 of the Electrical Workers and Contractors Licensing Regulations 1997, declare that the above tests are carried out in accordance with SS/BS/ equivalent standards and to the best of my knowledge, the results comply with the relevant standards and/or engineering practice.

______________________ Signature of HVTE

______________________ Licence No.

______________________ Date

ENDORSEMENT BY LICENSED ELECTRICAL WORKER (LEW):

The above test results are satisfactory and acceptable to me.

______________________ Name and Signature of LEW-in-charge of above-mentioned installation

______________________ Licence No.

______________________ Date

(* Delete whichever is not applicable)

Fig. 16.4 Test result of Relay Operation of IDMTL O/C Relays – SI Test

Earth Electrode Resistance Test

The earth electrode, where used, is the means of making contact with the general mass of earth. Thus it must be tested to ensure that good contact is made.

Method – Using a Dedicated Earth Resistance Tester

(a) Testing the electrode resistance of individual electrode

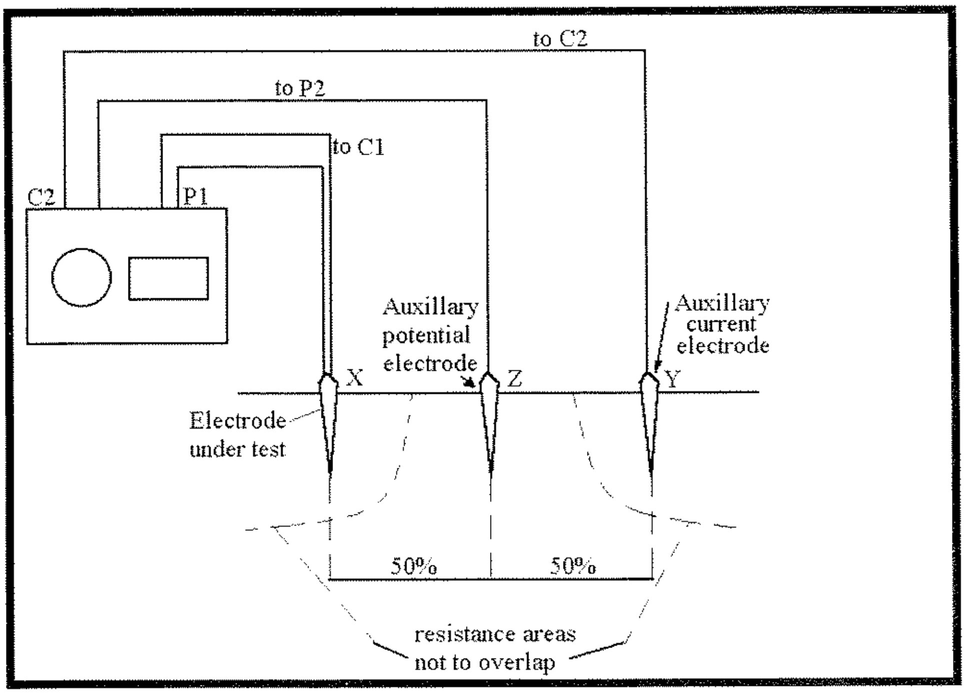


Fig. 16.5 Earth Electrode Resistance Test for Individual Point Electrode

(i) Remove all connection to copper tape at every point electrode and test the earth electrode resistance of each point electrode individually.

(ii) The instrument is connected as shown with terminal C_1 and P_1 being connected to the electrode under test (X).

(iii) Terminals C_2 and P_2 are connected to temporary spikes which are driven into the ground, making a straight line with the electrode under test. It is important that the test spikes are far enough from each other and from the electrode under test. Usually the distance from X and Y will be about 25m to 100m.

(iv) A current is passed through the electrode under test (X) to the general mass of earth and hence to the test electrode. The voltage between X to Z is measured and the earth resistance is indicated by the tester directly as:

$$Z = \frac{\text{Voltage between XZ}}{\text{Current Injected}}$$

(b) Testing the total electrode resistance of electrode resistance

(i) Divide the point electrodes into 2 groups, i.e. group 1 for electrode point 1 to point 5 and graph 2 for electrode point 6 to point 10.

(ii) Remove all connection to copper tape at every electrode and link the first group of electrodes together by a 2.5mm^2 PVC or 4mm^2 PVC wire. Test the total electrode resistance of the first group as shown in Fig. 16.6.

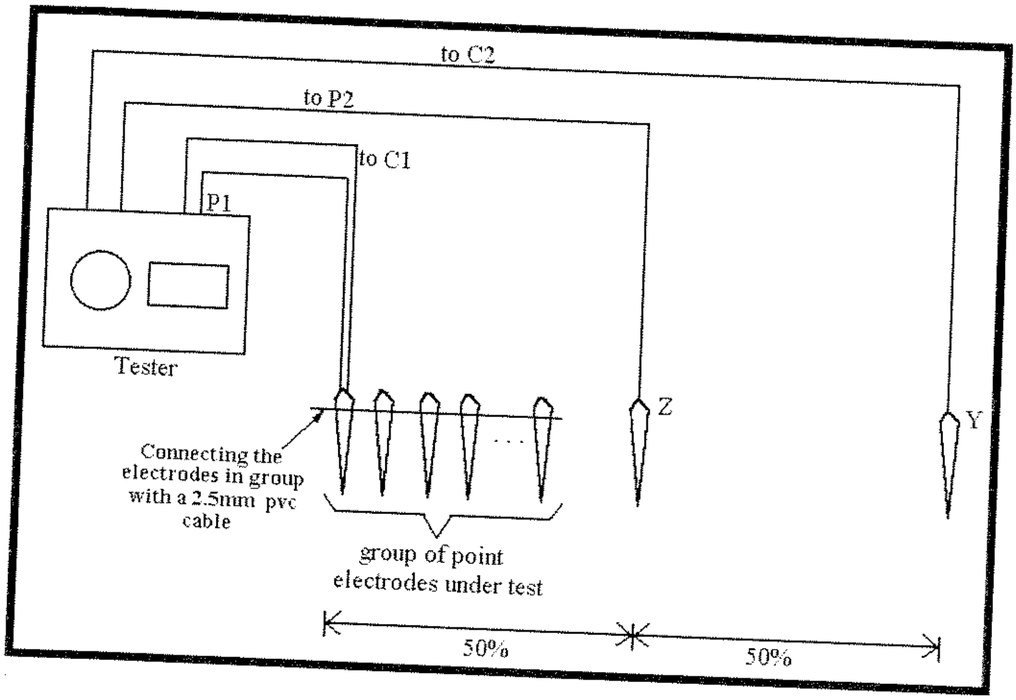


Fig. 16.6 Earth Electrode Resistance Test for a Group of Electrode

(iii) Repeat the test for the other group.

(iv) Link all the point electrodes in the whole earthing system together and test for the total electrode resistance and tabulate the value in Fig. 16.7.

Insulation Resistance Test on L.V. Busbars

(a) All fuses to indicator lights, all connections to voltage coil of kWh meter and all submains and risers connected to load shall be isolated.

(b) An insulation test (Megger) of D.C. voltage 500V is used to test the insulation resistance:

(i) Between Phases
R & Y
Y & B
B & R

(ii) Between Phase and Neutral
R & N
Y & N
B & N

EARTHING SYSTEM TEST

NAME OF CONSUMER ______________________________

INSTALLATION ADDRESS ______________________________

DATE OF TEST ____________________ APC NO.: ____________________

PARTICULARS OF EARTHING MATERIAL:

Earth-Electrode : Rod (Make) Plate (Make)

Earthing Clamp : Make

Electrode Coupler : Make

TEST RESULTS:

1. Overall Resistance Value : ohms (without Cu tape)
2. No. of Earthing Points :

Earthing Point	Number of Rods	Resistance Value (ohms)	Earthing Point	Number of Rods	Resistance Value (ohms)
No. 1			No. 6		
No. 2			No. 7		
No. 3			No. 8		
No. 4			No. 9		
No. 5			No. 10		

DECLARATION BY TESTING ENGINEER:

I declare that the above tests are carried out in accordance with SS, BS or equivalent Standards and to the best of my knowledge, the results comply with the relevant Standards and/or engineering practice.

Name and Signature of Testing Engineer ____________ Licence No. ____________ Date ____________

ENDORSEMENT BY LEW:

The above test results are satisfactory and acceptable to me.

Name and Signature of LEW ____________ Licence No. ____________ Date ____________

Fig. 16.7 Test Results for Earth Electrode Resistance Test for a Group of 10 Point Electrodes

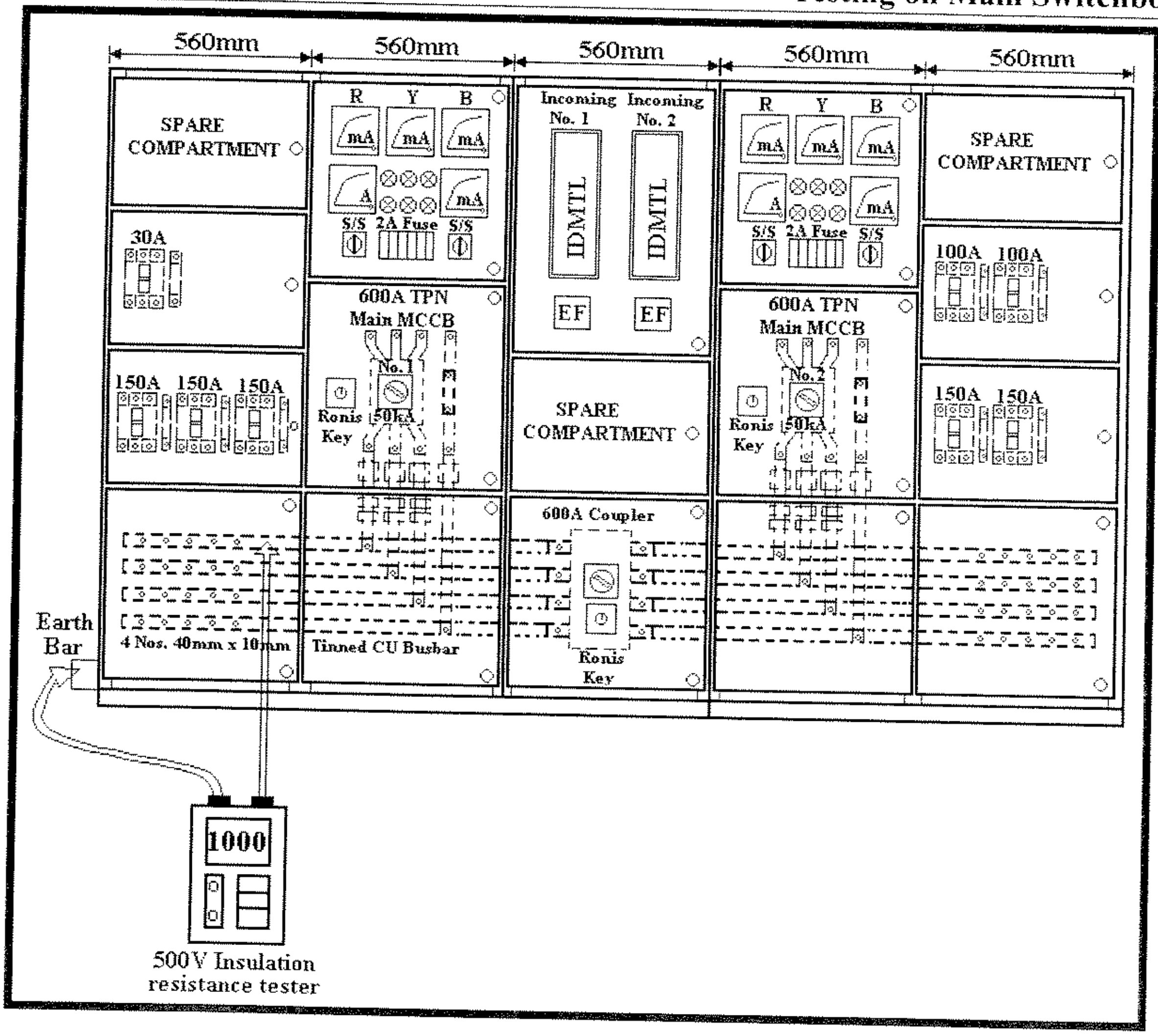


Fig. 16.8 Insulation Resistance Test

(iii) Between Phase and Earth
R & Earth
Y & Earth
B & Earth

As shown in Fig. 16.8.

(c) All readings of insulation resistance measured must be more than 500 k-ohm. If the insulation resistance of any phase is lower than 500 k-ohm, the busbar must be thoroughly checked for any contamination, ingress of moisture or any defective part which has resulted in a low resistance path.

Insulation Resistance Test on L.V. Incoming and Outgoing Circuits (Submains, Risers, Etc.)

(a) All incoming and outgoing circuits shall be isolated at both ends, so that all loads and equipment (such as transformers, etc.) are disconnected from the circuits.

(b) An insulation tester (Megger) of D.C. voltage 500V is used to test the insulation resistance:

(i) Between Phases
R & Y
Y & B
B & R

(ii) Between Phase and Neutral
R & N
Y & N
B & N

(iii) Between Phase and Earth
R & Earth
Y & Earth
B & Earth

(c) All readings of insulation resistance measured must be more than 500k-ohm. If the insulation resistance of any phase is lower than 500k-ohm, the circuit, riser or submain must be thoroughly checked for any contamination, ingress of moisture, or any defective part which has resulted in a lower resistance path.

Inspection and Checking on All Joints and Cable Terminations

(a) Inspection and tightening of the electrical connections at all joints and cable terminations at the switchboards, the risers and submain circuits are essential in preventing high resistance and overheating at the loose joint.

(b) Proper selection of cable lug and use of proper crimping tools for the cable termination are also essential to ensure proper electrical connection of cables, wires and conductors.

Use of defective cable crimping tools and wrong size of cable lug are often the causes of poor electrical connection at the terminations and these have often resulted in burning at the neutral and phase connections.

(c) Common errors found in the preparation of joints and terminations of cables are as follows:

(i) Strands of conductor removed/broken at the termination.

(ii) Wrong size of cable lug used for termination of cable – inadequate contact surface between conductor and cable lug to ensure electrically sound connection.

(iii) Improper tool used for compression joint or crimping joint.

Checking on Mechanical Interlocks

Mechanical key interlocks must be checked to ensure that:

(a) when both incoming breakers are closed, bus-coupler cannot be closed;

(b) when any one incoming breaker and the bus-coupler are closed, the other incoming cannot be closed.

This is to prevent the flow of circulating current if the 2 incoming cables are from different sources.

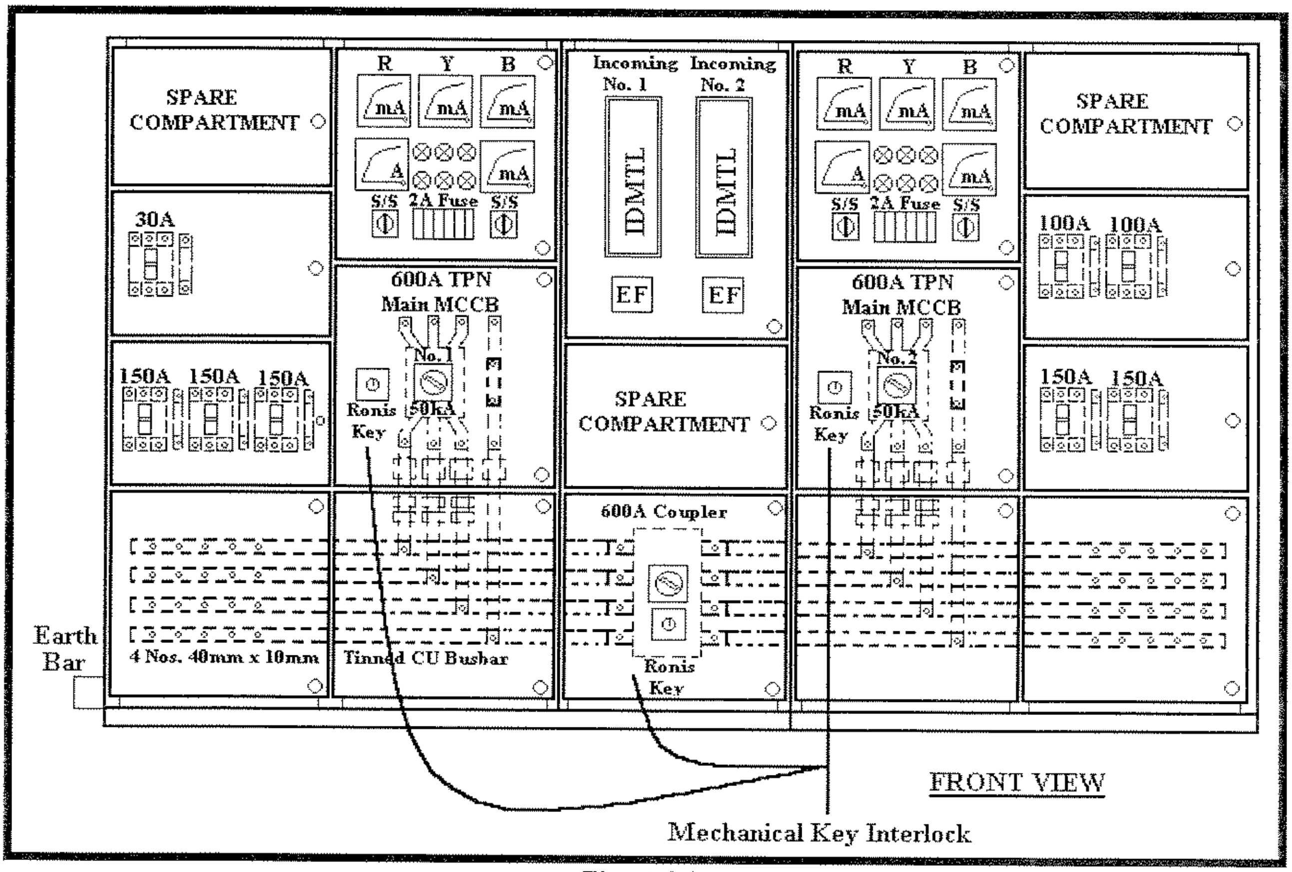


Fig. 16.9

16.2 TESTING AFTER ELECTRICITY SUPPLY TO MAIN SWITCHBOARD HAS BEEN TURNED ON

After the electricity supply to the main switchboard has been turned on, tests have to be carried out to ensure that:

(a) all components on the switchboards are correctly installed;

(b) the phasing and polarity of the 3-∅ supply is correct;

(c) the earth loop impedance value of the system is satisfactory.

These tests include:

(a) Tests to check that indicator lights and selector switches for voltmeters are connected correctly.

(b) Phase rotation test on busbars.

(c) Phasing-out test for switchboard with two incoming cables.

(d) Earth fault loop impedance test.

(e) Trip test on tripping circuit of the circuit breakers.

(f) Test to check that the kWh meters rotate in the correct direction.

Test to Check the Indicator Lights and Voltmeters are Connected Correctly

After the supply is turned on at the incoming cable, the indicators connected at the source side of the incoming circuit breaker must be lighted up.

After the incoming breaker is closed on, the indicators at the load side must be lighted up.

The voltmeter must be checked to ensure that it reads 400V when the selector switch is switched to read phase to phase voltage and 230V when the selector switch is switched to read phase to neutral voltage.

Phase Sequence Test

A phase sequence meter is connected to the R,Y and B phase of the busbar to check that the phase sequence (sequence of R, Y and B phases) of the incoming electricity supply is correct.

If there are two incoming cables, phase sequence test must be carried out on both sections of the busbar.

Tong Tester

The tong tester or clip-on ammeter is a variation of the bar-primary current transformer as shown in Figure 16.10. It consists of an insulated iron core in two parts that can be separated (like tongs), on one end of which is the secondary winding and an ammeter.

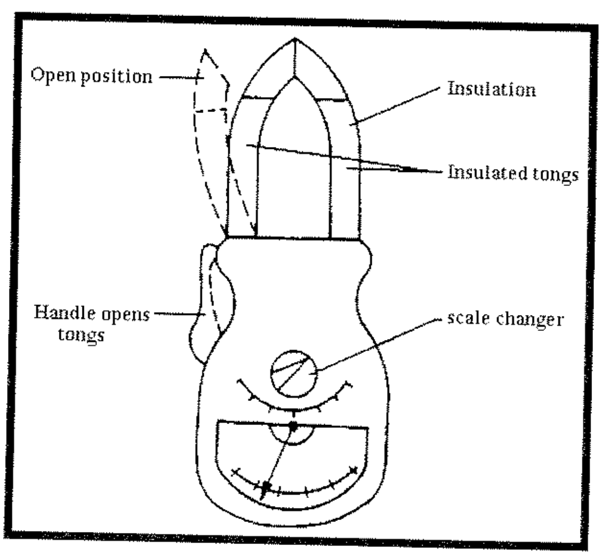


Fig. 16.10 Clip-on Ammeter

The core is clipped around a bus-bar or single-core cable and the current is registered on the ammeter.

Phase-rotation Indicator

The phase-rotation indicator is a simple 3-phase induction motor as shown in Figure 16.11. When connected to a 3-phase supply, a disc, connected to the motor, rotates in the direction of the supply sequence. It is used when two 3-phase systems are paralled together.

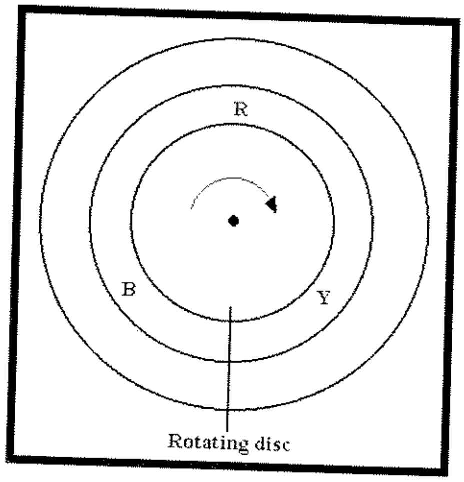


Fig. 16.11 Phase Rotation Indicator

Phasing-out Test on Two Incoming Cables

If there are two incoming cables terminated on the left and right sides of the switchboard, phase-out test must be carried out to check that the red, yellow, blue phase and neutral of each cable are demarcated and connected to the corresponding red, yellow, blue phases and neutral of the busbars when both incoming circuit breakers are closed. This can be done by:

(a) Test lamp method
(b) Voltmeter method

The test lamp can be used where voltage of the busbars is suitable for the use of lamps; the lamp when it is connected in corresponding same phase on two sections of the busbars, will remain practically dark.

If the lamp is connected to 2 different phases of the two sections of busbars, it will give out extreme brightness (400V). If it is connected to any phase to neutral, it will only give out moderate brightness (230V).

Before phasing out with the lamps, it should be ensured that the filament of the lamp is not broken.

With a voltmeter, the readings between the correspondingly same phase on the 2 sections of the busbars will be zero. It should read 400V between phases and 230V between any phase to neutral.

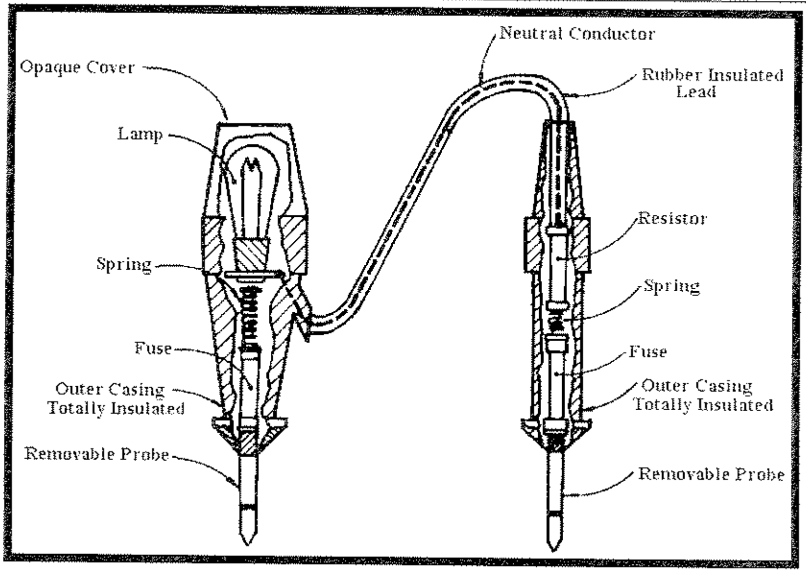


Fig. 16.12 Approved Test Lamp

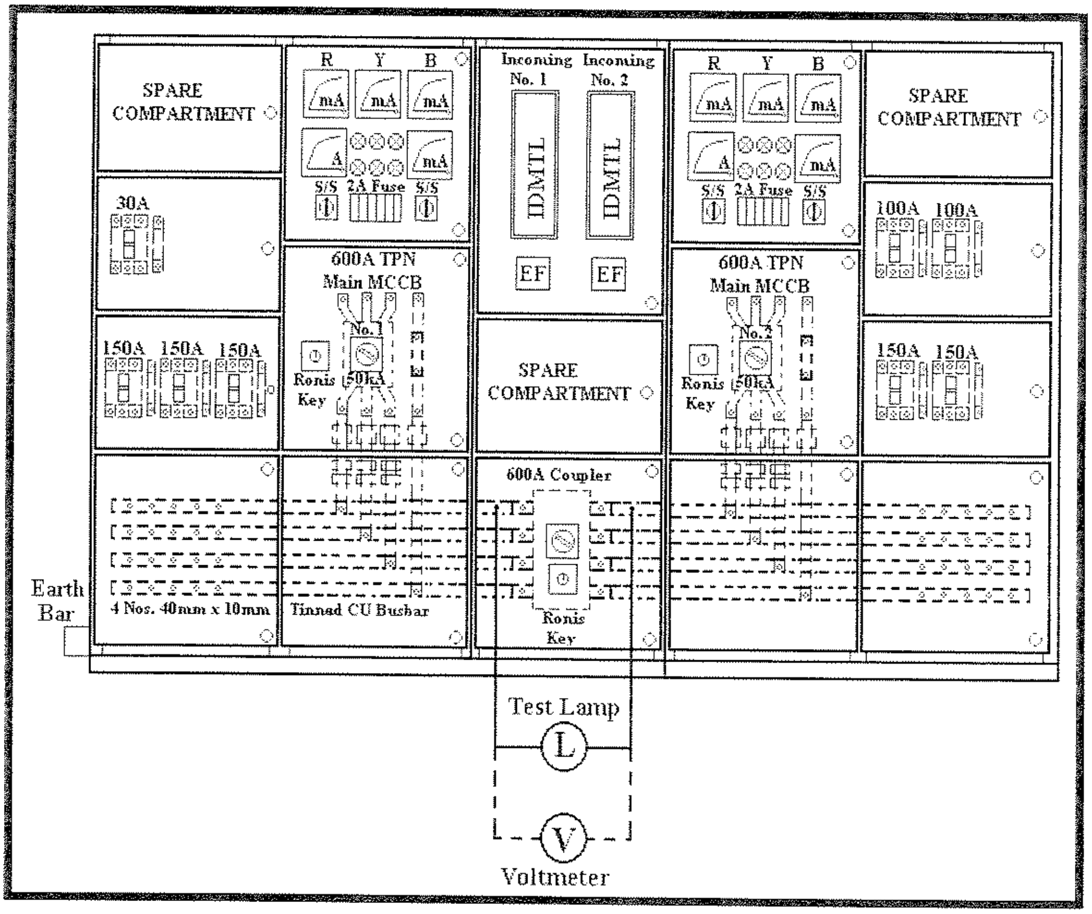


Fig. 16.13 Phasing-Out

Earth Fault Loop Impedance Test

(a) Earth Fault Loop Impedance

Earth Fault Loop is the path the current takes when an earth fault occurs. The following diagram shows the earth fault loop of a faulted system.

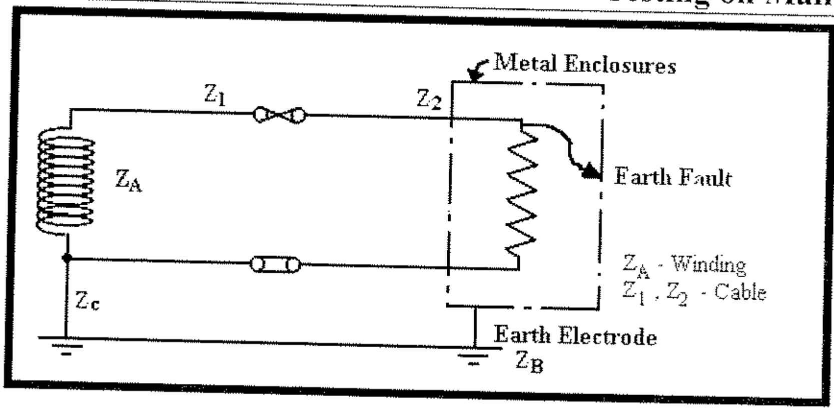


Fig. 16.14

At the instance of the fault, current will flow through the phase winding of the transformer, along the phase conductor up to the fault, and then through the earth electrode back to the transformer. The total impedance of the path:

$$Z_F = Z_A + Z_1 + Z_2 + Z_B + Z_C$$

is known as the Earth Fault Loop Impedance.

(b) Earth Fault Loop Impedance Test

The purpose of the test is to ensure that:

(i) In the event of a phase to earth fault, sufficient residual operating current will be developed to cause disconnection by earth leakage protection devices.

(ii) When there is no earth fault, the presence of earth leakage currents from electrical equipment will not cause excessive voltage to occur on exposed metal enclosure of equipment.

(c) Test Method

The most common method of testing the earth fault loop impedance is by using a phase earth fault loop impedance tester.

A fault current of small amount is circulated through the earth fault loop; the value of the impedance is:

$$Z_S = \frac{\text{the supply voltage}}{\text{fault current}}$$

(d) Limit of Earth Fault Loop Impedance

When a residual current device (e.g. earth fault relay, earth leakage relay, etc.) is used in an installation, the product of its rated operating current and the earth fault loop impedance must not exceed 50V.

$Z_S\, I_{\Delta N} \leq 50 \qquad \text{Or} \qquad Z_S \leq \frac{50}{I_{\Delta n}}$

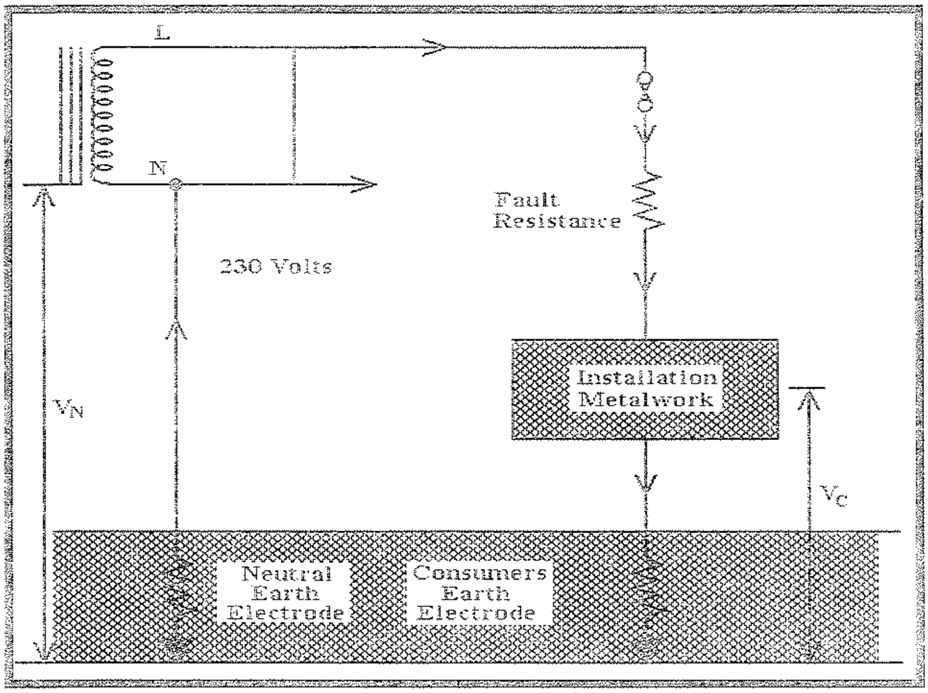


Fig. 16.15 (a)

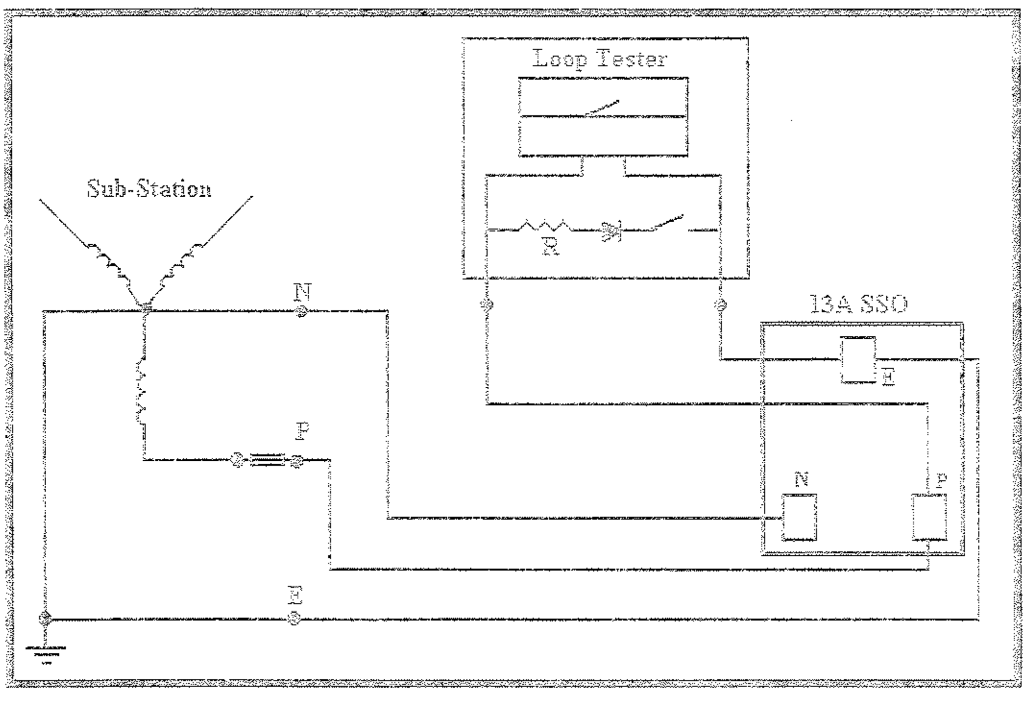


Fig. 16.15 (b)

Trip Test

Trip test of incoming circuit breakers must be carried out manually, causing the O/C relays of E/F relays to operate.

The test is to ensure that the tripping circuits are properly connected to the contact of the relays and the power supply is functioning properly.

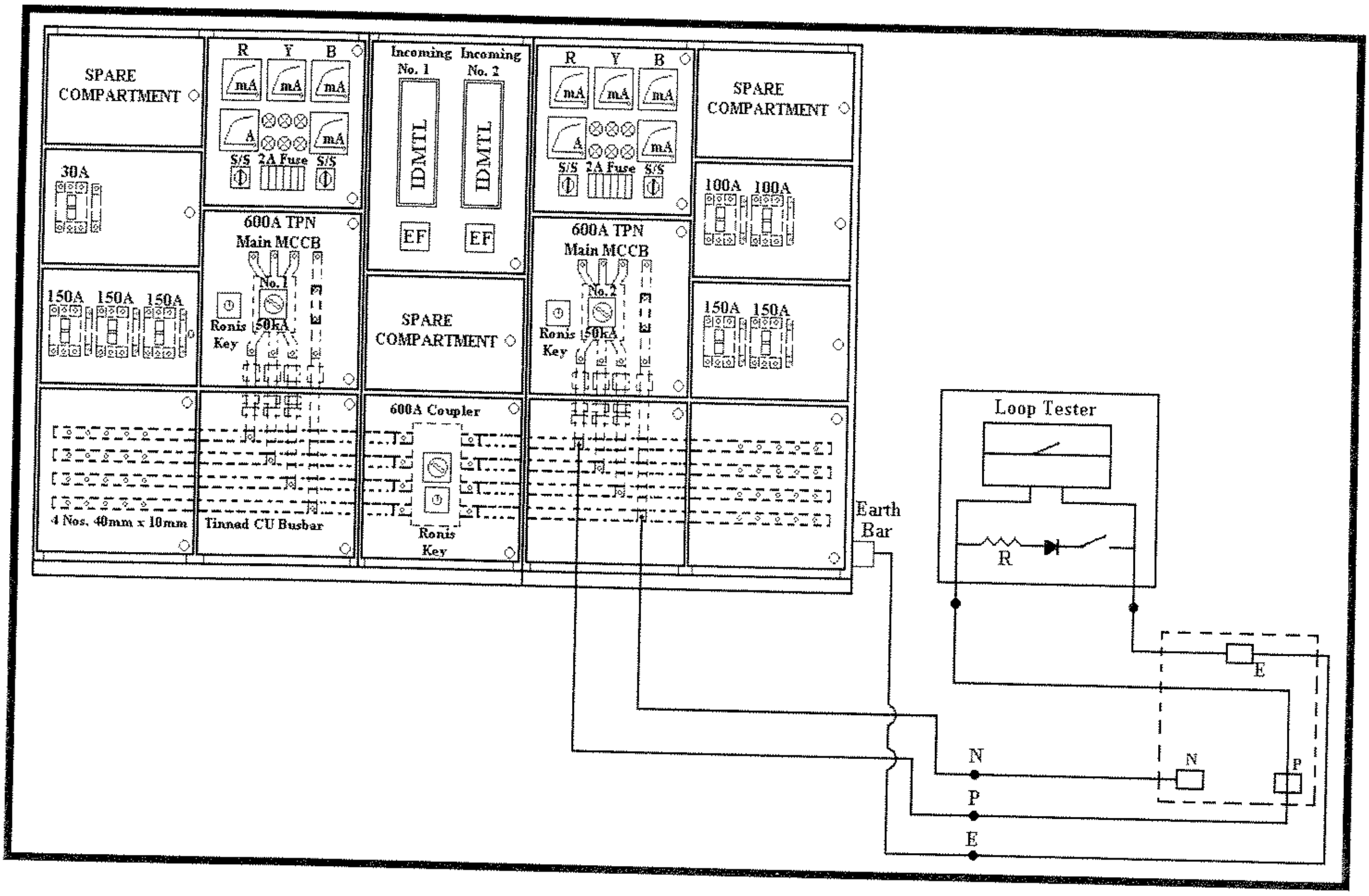


Fig. 16.15 (c) Earth Fault Loop Impedance Test

kWh Meters

kWh meters must be caused to rotate by connecting a high wattage test lamp to confirm its direction of rotation.

1. Briefly describe and explain the tests needed to be carried out before turn-on of electricity supply to a switchboard.

2. Briefly describe and explain the tests needed to be carried out after turn-on of electricity supply to a switchboard.

3. Explain briefly:

   (a) The important reasons to carry out the Earth Fault Loop Impedance tests after turn-on of electricity supply to a switchboard and distribution board.

   (b) How does the value of Earth Fault Loop Impedance indicate the condition of the earthing system?

4. Explain briefly, how does:

   (a) the value of Earth Fault Loop Impedance in the TN-S earthing system

   (b) the value of earth electrode resistance in the TT earthing system.

   affect the maximum setting of the operating current of Residual Current Device (RCD) at the MSB.

5. For a 3-phase 400V 4-wire electrical installation, briefly explain

   (a) how phase to earth leakage current can be measured.

   (b) what are the reasons for the existence of this leakage current in an electrical installation?

CHAPTER 17
MAINTENANCE OF ELECTRICAL INSTALLATION

17.1 INTRODUCTION

No electrical installation, no matter how carefully designed and erected, can be expected to last forever. Deterioration will take place due to age as well as due to normal wear and tear.

With this in mind, the Regulations require regular inspection and testing to take place so that the installation can be maintained in a good and safe condition.

The time interval concerned will, of course, depend on the type of installation and on the way in which it is used.

17.2 INSPECTION AND MAINTENANCE OF CABLES AND CONDUCTORS

Cables

(a) Cables, if they are installed to suit their specified operation conditions need little attention, in that their protection and method of installation tend to ensure a long life free from potential faults.

(b) However, there are changes in installation conditions which affect cables and conductors; heat, dampness, corrosion and mechanical damage, changes in circuit items' characteristics (e.g. increase in reactance causing voltage surges and often failure of lamps) and circuit conditions (e.g. increase in loading).

(c) The maintenance of cables and conductors involves an investigation into the causes of cable faults and then evolving a scheme based on the frequency of fault occurrences.

Joints

(a) Main conductor failures include the overheating of joints, contacts and the overheating of the conductor body (caused by short-circuits and mechanical distortion). Ageing, and the progressive deterioration of insulation, will eventually cause faults due to voltage surges and the like.

(b) In underground cables, the faults include mechanical damage (human agency), sheath fracture/corrosion, insulation failure, joint failure, and termination failure.

Maintenance

(a) The maintenance of circuitry includes the periodic testing of insulation resistance and the inspection of all points at which cables, wires and conductors are terminated or jointed. The frequency of inspection varies with the installation conditions. The maintenance also involves the earthing conductors. A useful sequence of testing is:

(i) Measure the insulation resistance between conductors and between each conductor and earth (first proving the earth connection).

(ii) Inspect the protective devices such as fuses and circuit-breaker.

(iii) Measure the earth-loop impedance.

(iv) Visually inspect connections and wiring.

(b) The use of log-books is an essential part of any maintenance scheme for an electrical installation. Results logged faithfully, together with observations made on periodic visits, will indicate the gradual or rapid deterioration of circuit wiring and accessories, and allow the appropriate action to be taken at a suitable time.

17.3 MAINTENANCE OF SWITCHBOARDS

A typical planned maintenance program for switchboard includes repetitive inspection, servicing and overhaulings. Repetitive inspection and servicing activities are especially important for switchboards with heavy load currents.

Periodic inspection on switchboard should include checking on:

(a) Condition of Switchroom

Any sign of flooding, roof water leakage, etc. Any danger signs, rubber mat, etc.

(b) Ammeter Reading

Recording of current loadings of incoming circuits and outgoing circuits indicated by Ammeters and maximum demand current meters and note down any readings which may indicate overloading in any circuit.

(c) Voltage Meter Reading

Recording of phase to phase voltage and phase to neutral voltage and note down readings which indicate overvoltage.

(d) Condition of Busbars

Any burn marks, abnormal temperature rise, any discoloration and cracks due to overheating.

(e) Condition of Circuit Breakers

Any signs of abnormal temperature rise, any sign of overloading, etc.

(f) Cable Terminations

Check for any sign of improper termination, any sign of overheating or burning at termination of incoming circuits, outgoing circuits, submains and risers.

Periodic maintenance of switchboard should include:

(a) Servicing and overhauling of circuit breakers which include:

(i) cleaning of circuit breaker contacts;

(ii) lubricating and checking the closing and tripping mechanism;

(iii) trip test on shunt trip coil and tripping circuit.

(b) Primary Current Injection Test (PI) and Secondary Current Injection Test (SI) on protection circuits.

(c) Insulation resistance test on the circuit breakers and insulation resistance test on all outgoing circuits. (The insulation resistance must be at least 1 M-ohm).

(d) Checking and tightening of busbars and cable terminations for all incoming and outgoing circuits.

(e) Inspection and test on earthing system (wherever necessary Earth electrode resistance and Earth fault loop impedance tests are to be carried out).

1. Explain briefly why tightening of electrical connections on the electrical switchboards, distribution boards, tap-off units and the whole electrical wirings and installations are important.

2. In a test to obtain the earth fault loop impedance at a 3-phase 400V main switchboard (MSB), the reading of the meter shows infinity reading and the phase to neutral voltage of one of the phase shows 320V A.C. Explain briefly the possible reason and what would be the consequence.

3. In a test to measure the phase to earth leakage current of a 1000A Main Switchboard, the reading of the earth leakage meter show a 60A reading at half load condition and 120A at full load condition, explain briefly the possible reason and suggest the steps to be taken to trace the cause of the problem.

4. Draw a schematic diagram to explain the importance of ensuring 'neutral conductor' connection solidly to earth in a 3-phase 400V/230V 4-wire system and the consequence of losing this connection to earth.

5. In a 3-phase 400V main switchboard, explain briefly the possible reason of the frequent tripping of

   (a) DTL overcurrent relays
   (b) DTL earth fault relays

   and the possible method of remedy.

6. Explain briefly the essential steps to be taken in the maintenance of

   (a) low voltage switchboards, distribution boards, etc.
   (b) low voltage electrical risers, tap-off units, busbar systems, etc.

7. Explain what is meant by "Thermography' and how it is used in the maintenance and troubleshooting in Low Voltage electrical systems.

CHAPTER 18
STANDBY GENERATORS

18.1 INTRODUCTION

It is an authority requirement that all public buildings (such as office buildings, shopping complexes, hotels, hospitals, etc.) must be provided with automatic mains failure diesel engine driven generators (standby generators).

The purpose of installing standby generators in public buildings is to provide a back-up power source to supply to all the essential and emergency equipment during the time of power failure. The reason for such requirement is primarily the safety of the occupants of the buildings.

18.2 RANGE OF SIZES

Diesel generating assets are rated according to their electrical output expressed in kW at a load power factor usually assumed to be 0.8 lagging. The smallest units, up to say to 10 kW, are often arranged for L.V. single-phase output but the great majority between say, 10 and 1000 kW have a three-phase output, some of the larger sizes generating at 3.3-11kV.

The most popular sizes for general industrial standby use lies in the 150 to 500 kW range and where greater standby capacity is required, two or more sets may be operated in parallel. Multiple set schemes frequently involve less capital outlay than a single larger unit and also provide greater flexibility, easier maintenance schedules and better system reliability.

To minimise initial cost, diesel sets are generally run at relatively high speeds and four-pole generators are very common running at 1500 rev/min for 50 Hz output.

18.3 CONTINUOUS AND STANDBY RATINGS

The electrical output is decided by the power available at the engine flywheel. Engines are usually rated on a continuous basis against Standard Reference Conditions, defined in BS 5514: Part 1 (ISO 5046) as 1000 kN / m^2 Barometric pressure, and 27°C air temperature and 60% relative humidity.

Industrial diesel engines built to standard specifications will handle 10% overload for 1 Hour in any 12 hours of operation at the continuous rated load. This overload rating is frequently used as a continuous standby rating on the assumption that normal industrial loads are of a fluctuating nature and standby duty is relatively infrequent.

Some engines are assigned a special standby rating by the manufacturer which may be higher than the 10% overload rating but in such cases a restriction on total engine service life may be imposed.

18.4 FUNCTIONS OF STANDBY GENERATORS

The functions of standby generators in public buildings are as follows:

(a) To provide power supply for essential equipment and systems installed in the buildings during the time of normal mains failure. These equipment include emergency lighting and exit lighting.

(b) To provide power supply to critical equipment such as fireman's lifts and fire fighting systems during emergency situations like a fire in the building.

Emergency & Exit Lighting

Emergency illumination includes all required exit lights and all other lights necessary to provide sufficient illumination along escape routes (such as exit points, corridors and staircases) for evacuation purposes.

Emergency lighting systems are powered by essential services circuits under standby generator supply and must be so designed that the failure of any lighting fitting cannot leave any space in total darkness.

Fireman's Lifts

It is an authority's requirement that, among other essential services, the capacity of the standby generator must be sized to operate the fire lifts at all times during mains failure and fire conditions. The fire lifts are used by firemen to fight the fire and to rescue people.

It should be noted here that in order to ensure the integrity of the generator supply, cabling for all emergency supply circuits are required to be carried out in fire resistant cables or MICC cables.

Fire Fighting Equipment and Systems

In the event of fire, the standby generator will be required

(a) to operate the pressurization fans for protected areas in order to prevent the spread of smoke:

(b) to operate the sprinkler pumps and wet riser pumps for fire-fighting purposes.

18.5 COMPONENTS OF MAINS FAILURE GENERATING SETS

Mains failure generating sets comprise a diesel engine, coupled to a generator with appropriate control gear for operation, protection and instrumentation. Usually the sets are electrically started from 12 V to 24 V batteries and arranged to run up automatically to speed upon mains failure, take over the load and shut down again when the normal mains supply returns.

The Engine

The most common generating sets used in public buildings are driven by internal combustion engine as the prime mover. The majority of diesel engines used are of the 4-cycle type, although 2-cycle engines are also being used. In general terms, the number of cylinders increases while the power output of the set, and while the twin-cylinder engines are often used for small sets, 12 & 16 cylinder engines are common of the larger outputs and 6 & 8 cylinder engines predominate for the most popular middle part of the output range.

The mechanical system associates with the engine includes:

(a) the engine and the speed governor
(b) the fuel tank system
(c) the cooling system and radiator
(d) the smoke exhaust system

The Alternator

The standby sets, the usual alternator has 4 poles and rotates at 1500 rpm for 50 Hz service.

Alternators fall into 2 broad groups as follows:
(a) Rotating armature alternators – These alternators are confined to the smaller ratings of up to 20 kW due to limitations of skip rings and brushes.

(b) Revolving field alternators (brushless alternators) – Most generating sets of ratings over 20 kW make use of brushless excitation in which the revolving field is supplied with excitation from a rotating armature exciter and a shaft mounted rotating rectifier.

The Brushless Alternator

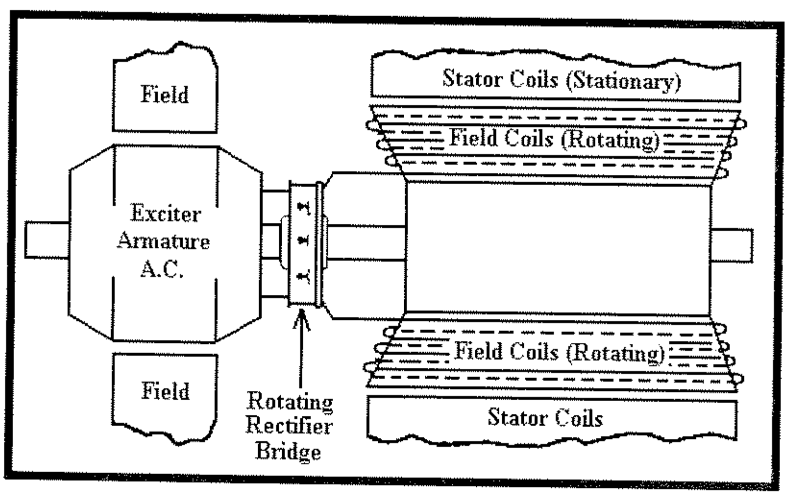


Figure 18. 1 (a) Brushless Excitation System

Before we look at the operating principle of the brushless alternator, we shall first examine the configuration of the alternator.

Configuration of the brushless alternator

The alternator configuration can be seen clearly in Figure 18.1 (a) which shows a layout of the brushless excitation system, and in Figure 18.1 (b) which shows a schematic diagram of the brushless alternator.

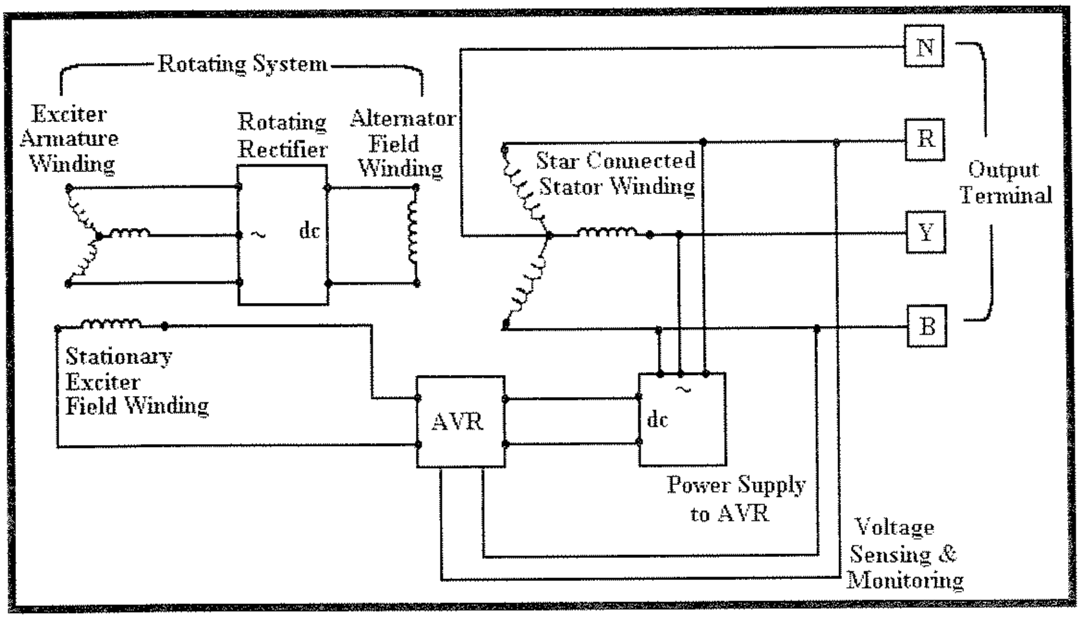


Figure 18.1 (b) Schematic Diagram of Brushless Alternator

The complete alternator consists of 4 main elements. They are:

(a) Main alternator

The main alternator has a laminated polar magnetic field core mounted directly on the shaft, and the field coils are wound directly on the poles. The stator of the main alternator carries the 3-ϕ output windings which are connected to terminals in a terminal box.

(b) Exciter (Excitation Alternator)

The exciter is an alternator of the rotating armature polar field type. The exciter field is supplied with a controlled direct current from the main alternator. The exciter armature is mounted on the same alternator shaft and is wound to give a 3-ϕ output.

(c) Rotating Rectifier

The exciter output is rectified by the rotating rectifier bridge to supply direct current to the main alternator field winding.

Note that the exciter with rotating rectifier does not require brushes to connect exciter output to the alternator field and exciter armature winding rotate together on the same shaft - this system replaces brushes, brush holders, commutators and slip rings normally associated with alternators, hence the name "brushless alternator".

(d) Automatic Voltage Rectifier (AVR)

The AVR is a solid state unit and is connected between the exciter field and the main alternator output terminals. It controls the exciter field (which in turn controls the main alternator field) in order to maintain a constant output voltage with changes of load, small speed variations and temperature.

Operating Principle of the revolving field brushless alternator

The principle of operating is best explained by the following steps:

(a) When the alternator first begins to rotate by the prime mover, it depends on the residual magnetism in its field poles to generate enough voltage to excite the exciter field so that the exciter can generate excitation current for the alternator field. By this means, both the exciter field and alternator field build up until the alternator is producing its rated voltage.

(b) The main alternator stator winding produces a.c. excitation power which is converted from a.c. to d.c. by the static rectifier (the self-excitation unit) to feed the exciter field.

(c) The AVR automatically controls the current in the exciter field winding which in turn controls the a.c. output of the exciter rotor winding.

(d) The exciter rotor output is then converted from a.c. to d.c. by rotating rectifiers which feed the alternator field windings.

(e) Finally, the alternator stator winding produces main a.c. output which is dependent on current in the rotating field winding.

(f) Sensing leads monitor the alternator output voltage for comparison with a stable reference voltage in the AVR. Any resulting error will cause the AVR to regulate the exciter field current to minimise the error and restore alternator output voltage to nominal value.

Permanent Magnet Generator (P.M.G)

Control of the a.c. generator's output voltage is effected by controlling the exciter field. The power supply for the exciter field may be obtained from a separate 3-phase permanent magnet generator (P.M.G), as shown in Figure 18.2.

Separate P.M.G as shown in Figure 18.2 has the following advantages

(a) Gives certainty of voltage build-up on starting.
(b) Improves the generator's steady-state overload capacity.
(c) Gives good fault clearance control, since the AVR power supplies do not collapse when short circuits are applied to the generator. This is particularly important for co-ordination of protection on supply distribution circuits.
(d) Affords fairly good voltage response, after large load-step changes.

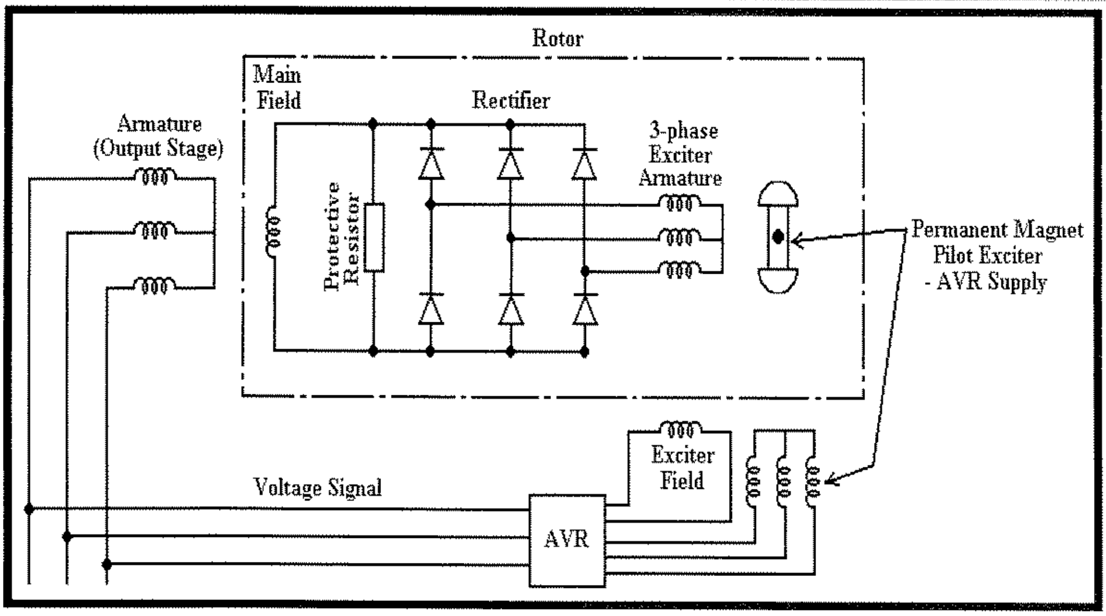


Figure 18.2 A.V.R. fed from a permanent magnet pilot exciter (P.M.G.)

18.6 CONTROL SYSTEMS

The primary function of the control system for a standby generating set is

(a) to detect a mains failure situation – by constantly monitoring the voltage of the normal power supply.
(b) to start up the generating set – a voltage drop of 20% - 30% will initiate the starting of the set.
(c) to transfer the load to the alternator – when the alternator has reached operating speed and nominal voltage, the alternator takes over the load. Between 5 to 10 sec will lapse before the alternator will supply the load.
(d) to supply the load for the duration of the power outage.
(e) to detect the restoration of the mains supply voltage detection units will automatically sense the restoration of main and initiate a close down programme operating the changeover device and engine shut off sequence.
(f) to transfer the load back to the mains – generating sets are normally fitted with mains return delay circuit which ensure that mains voltage is within acceptable limits for a preset period before the actual transfer of load.
(g) to shut down the generating set.

18.7 PROTECTIVE SYSTEMS

When an abnormal operating condition occurs in the engine, it is necessary to automatically shut down the engine in order to avoid costly damage to the engine and the alternator.

The number of protective functions employed is based on the requirements of individual installations. Minimum protection should include:

Engine	-	high coolant temperature
	-	low lubricating oil pressure
	-	overspeed
Alternator	-	overload protection

Inter-connection of Normal and Emergency Power Supplies

Figure 18.3 below shows the schematic connection of the normal power supply source with the standby generator.

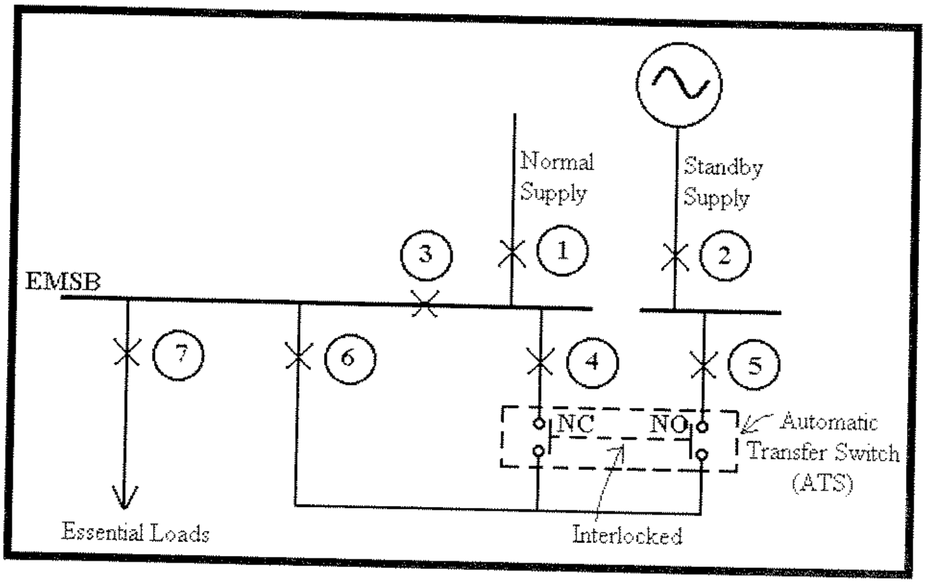


Figure 18.3 Essential Main Switchboard (EMSB) and Automatic Transfer Switch (ATS)

Under normal operating conditions breakers, 1, 2, 5, 6, 7 and the N/C (normally closed) contact of the automatic transfer switch (ATS) are closed. Hence the emergency load is connected to the normal power source through breakers 1, 4, N/C contacts, 6 and 7.

The normal power source is constantly monitored by a voltage sensing relay in the ATS. In the event of a normal power failure or a voltage reduction in the normal supply, the voltage sensing relay in the ATS will be activated to complete the engine start circuit. Once the engine is started and a steady speed is reached, the supply from the generator will be available at the ATS and sensed by it.

On sensing the generator supply, the ATS will open up the N/C (normally closed) contacts and close the N/O (normally open) contacts. This completes the changeover process and the emergency load is connected to the standby generator through breakers 2, 5, N/O contacts, 6 and 7.

As soon as the normal power supply is restored, the voltage sensing relay in the ATS picks up and after a short time delay, the emergency load will be transferred back to the normal supply source. After a further time delay, the standby generator will be shut down automatically by the control circuits provided in the generator control panel.

Automatic Transfer Switch (ATS)

A transfer switch is designed to connect the load to either of the 2 power sources. In it normal position, the switch connects the load to its regular power source. When the switch is operated to its emergency position, the load is connected to the standby generating set.

An emergency power system that is started automatically employs an ATS. Automatic operating of the switch is achieved by the use of a motor operator which, when commanded, will reconnect the load to the alternate source. The command to operate is usually provided from a voltage sensing relay.

Note that the ATS is designed so that the load can never be connected to both power sources at the same time – both mechanical and electrical interlocks are provided for this purpose.

Figure 18.4 shows a schematic diagram of a ATS.

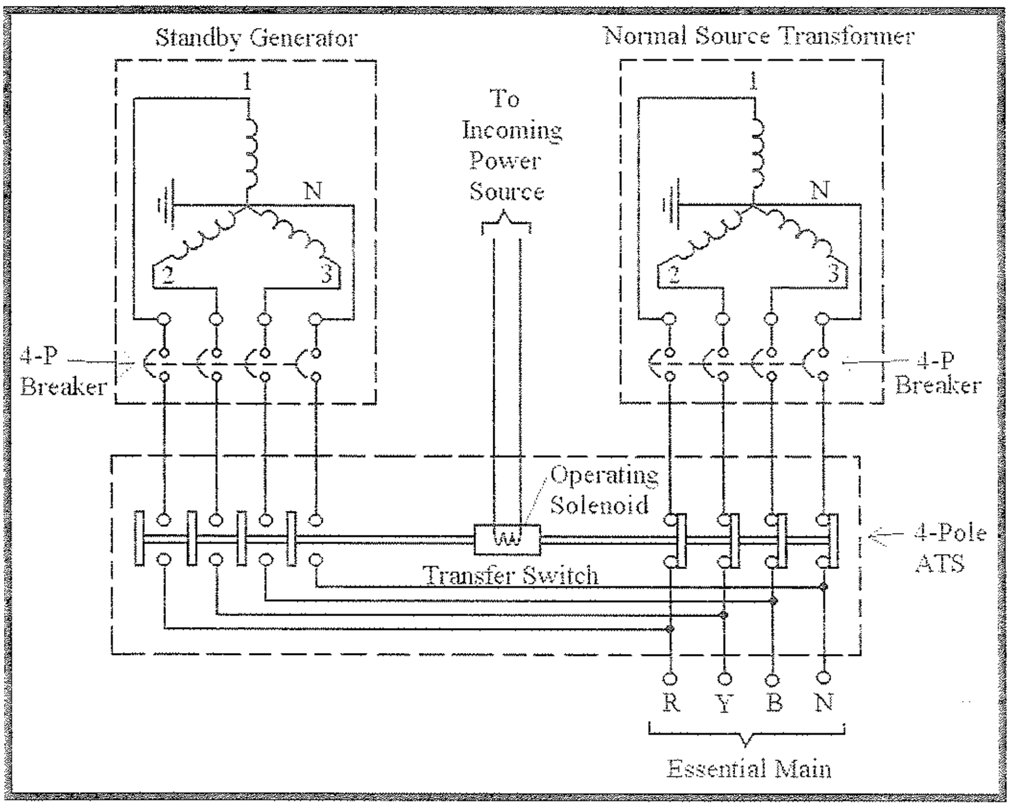


Figure 18.4   4-Pole Transfer Switch

18.8 AUTOMATIC VOLTAGE REGULATOR

The AVR is a solid state unit comprising a sensing input from the generator terminal voltage, a stable reference element; a comparator stage to detect the voltage error and an amplified output stage controlling the exciter field. Brushless generators thus controlled, will maintain close tolerance output voltage (typically ±2%) with voltage recovery to ±97% following a full load application of about half a second.

Transient Performance

The initial transient voltage dip which occurs on a generator when a load is applied is caused by the internal impedance generator and thus is usually much greater than the source impedance of the mains supply. It follows that transient voltage dips occurring when supplying the load from the standby system will be greater than when mains powered and the effect of this increased voltage depression on other running equipment may be significant even though recovery may be rapid.

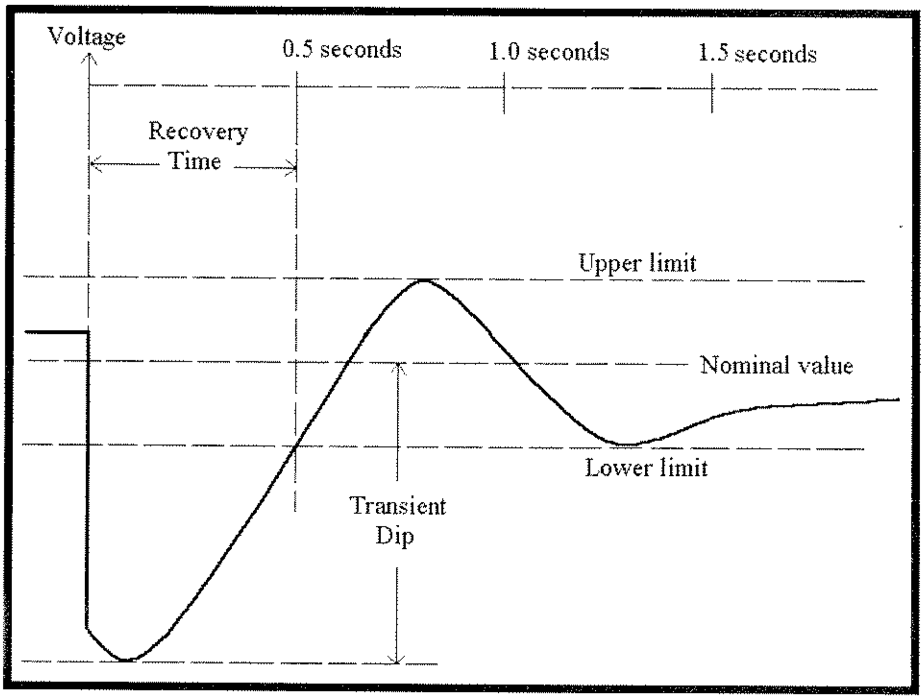


Figure 18.5

The general industrial installation the transient dip should be restricted to about 25%, but for more critical loads 15% or even 10% may be specified.

To meet these tighter requirements an oversize generator may be required, but the alternative approach is to reduce the magnitude of the load steps by more appropriate design of the installation. For instance, cage motors which take high dol starting currents might be equipped with reduced voltage starters or multiple load elements might be rearranged to start in sequence rather than all at the same time.

18.9 SIZING OF GENERATORS

Three (3) factors must be considered in the sizing of a standby generator, namely:

(a) Value of maximum continuous load.
(b) Maximum kW which can be applied in a single step.
(c) Maximum value of applied kVA in a single step relative to a given transient voltage dip.

The first factor concerns with the continuous maximum rating of the generator to be greater than the maximum load demand for essential loads.

The second factor concerns with the real power requirement during starting period of large motor. If the generator cannot provide enough capacity for real power requirement during starting, the motor will never be able to run up to full speed.

The third factor concerns with the problem of transient voltage dip caused by motor switching. For general industrial installations the transient dip should be restricted to about 25%, but for more critical load 15% or even 10% may be specified.

As the automatic voltage regulator (AVR) at the generator always maintains the terminal voltage of the alternator at its rated value at steady state. Existing loads which are already been connected would not cause voltage changes.

Switching in of large motors is the more severe cause of transient voltage dip.

Voltage dip can be computed if the transient reactance of the alternator is known:

$$\Delta V = \frac{\text{Starting kVA}}{\text{rated kVA of alternator}} \text{ x transient reactance (\%)}$$

$$= \text{starting kVA (per unit) x transient reactance (\%)}$$

The voltage dip characteristic of alternator may be obtained from manufacturers in order to calculate the voltage dip during starting of the largest motor.

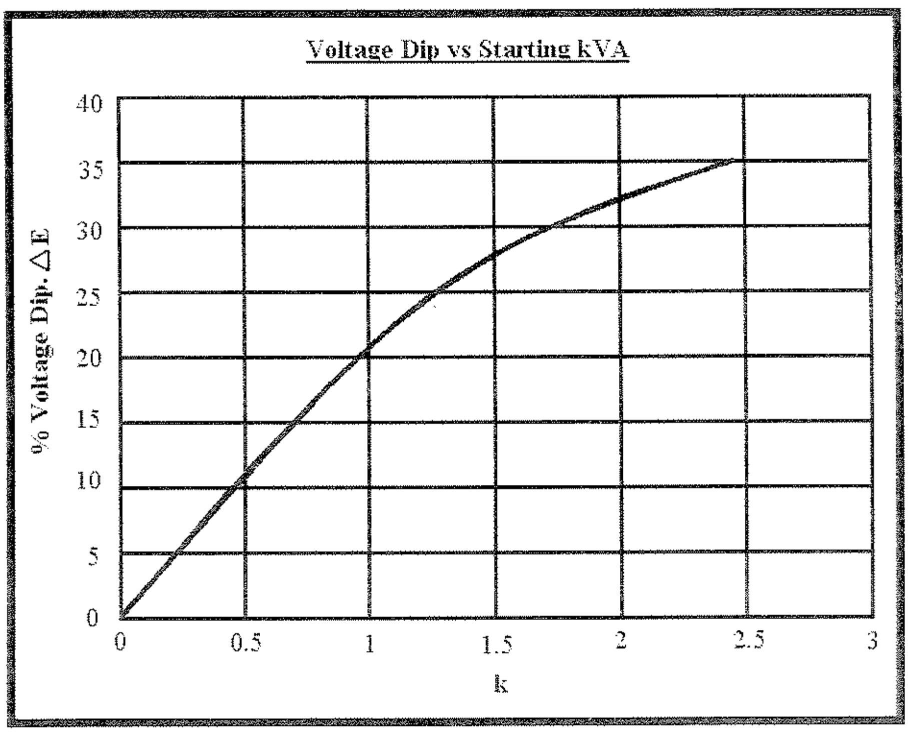


Figure 18.6 Curve of Voltage Dip Against Load for A Typical Generator

Starting kVA of Motors

The starting kVA of motors depending on the construction and the starting methods are derived to be as follows:

Type of Motor	Starting Method		Starting kVA
Squirrel cage	Direct on Line starter	:	$\frac{(\text{Rated kW / efficiency}) \times 7.5}{\text{Rated power factor}}$
	Star-Delta starter	:	$\frac{(\text{Rated kW / efficiency}) \times 2.5}{\text{Rated power factor}}$
	Auto-transformer starter (with tap ratio n)	:	DOL starting kVA x $(n)^2$
Wound rotor	Rotor resistance	:	$\frac{(\text{Rated kW / efficiency}) \times 2}{\text{Rated power factor}}$

18.10 PARALLEL OPERATION

The use of parallel running sets as a standby service complicates the control equipment considerably because in addition to the normal mains failure sequences, the separate sets must be synchronized and adjusted for load sharing.

Most automatic paralleling systems operate on the basis that on mains failure all sets start up, synchronise and take the load for the duration of the outage. Since the loads are usually of a variable nature, the system must monitor the total load and the individual share taken from each set, so that automatic adjustment of fuelling can take place to achieve satisfactory load sharing.

In some cases it may be considered advantageous to shut down some of the paralleled sets if the load falls to a very low level. The automatic removal of generating sets from the parallel running group and their re-introduction should load levels increase further complicates the control system and is normally only justifies in special cases.

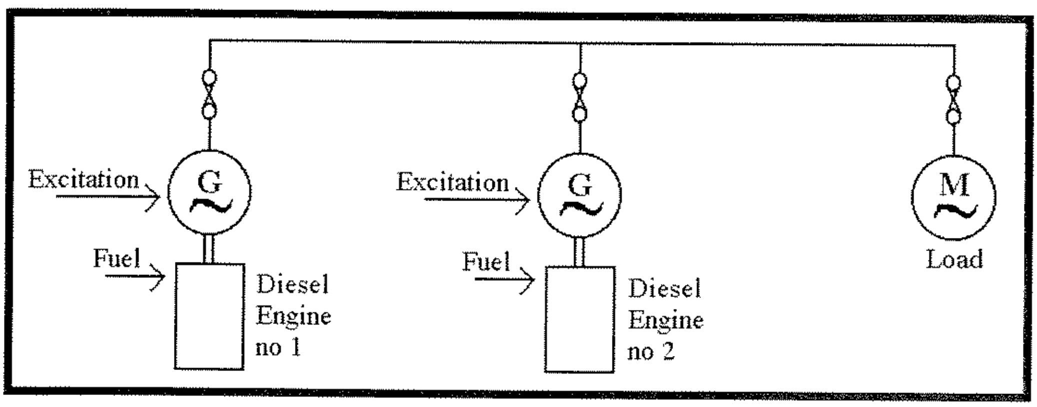


Figure 18.7 Load Sharing in Parallel Operation

Neutral Earthing for Parallel Operation

The neutral (or star point) of the alternators' windings must be earthed.

For parallel operation of generator sets, the star-point of only one generator is earthed to avoid the problems arising from the neutral currents. Alternatively, the star-points of all the generators can be connected to the same neutral busbar which is earthed.

18.11 EMERGENCY SWITCHBOARD

The output of the generator sets are connected to a switchboard known as the "emergency switchboard". All the equipment that require emergency electricity supplies e.g. lighting, lifts, sprinkler pumps are connected to this switchboard.

The emergency switchboard has two sources of electricity supply:

(a) From the main switchboard which takes its supply directly from normal source from power supply company or from the consumer's own transformers.

(b) From the generator set (s) circuit breakers

Figure 18.8 is a single-line diagram showing a typical emergency switchboard with the incoming and outgoing circuit breakers.

As Power Supply Company does not normally allow the paralleling of the generators' output with the Power Supply Company's supply. Therefore, the two incoming breakers (or contactors) have to be interlocked such that only one source is connected to the busbars of the emergency switchboard at any one time. Therefore, both the incoming breakers and the automatic transfer switch (ATS) must be the 4-pole type.

4-Pole ATS or Circuit Breakers

4-pole ATS or circuit breakers must be used for interconnection between two different sources (i.e. source A and source B) to prevent the problems of

(a) Nuisance tripping caused by spillage of neutral current from source A to source B as shown in Figure 18.8 (a).

    In an unbalanced 3-phase system, there will be a current flowing through the neutral wire. In a healthy system, the vector sum of the current in the 3-phases and the neutral will be zero. However, if 3-poles breakers are used as shown in Figure 18.8(a), the neutral current will break into two paths – one path passes through the source A while the other path is return through the source B. This causes an unbalance reading at both earth-fault relays and may create nuisance trippings.

    If 4-poles breakers or contactors are used, the neutral current will flow back only to one source.

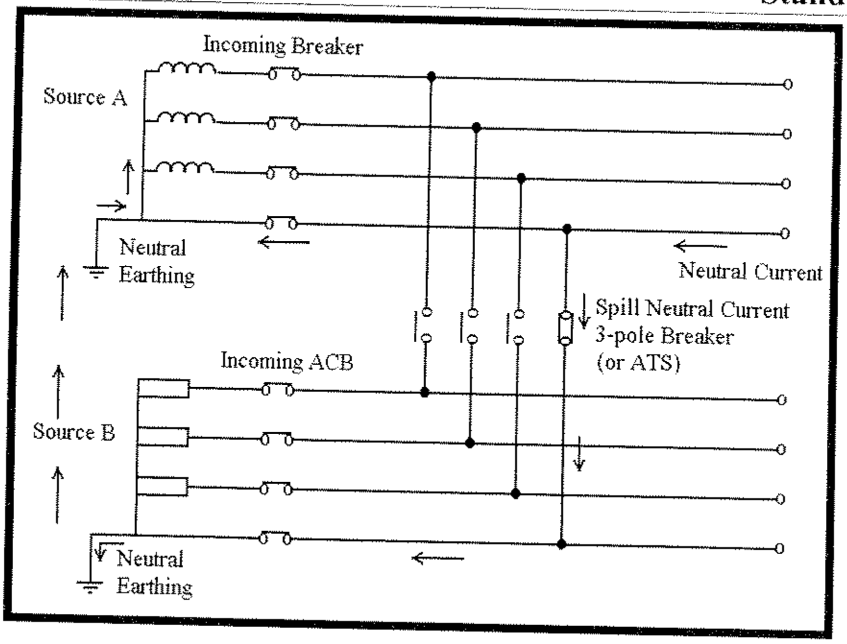


Figure 18.8 (a) Nuisance Tripping Caused by Spillage of Neutral Current From Source A to B

(b) De-Sensitisation of earth fault protection due to split of return earth fault current to source A and source B as shown in Figure 18.8 (b) when a phase to earth occurs in one of the circuit supplied by source A, the phase to earth fault current which has to return through neutral earthing electrode system may split to source B and source A due to the connection of neutral at the TP&N tie breaker or ATS at the interconnecting point.

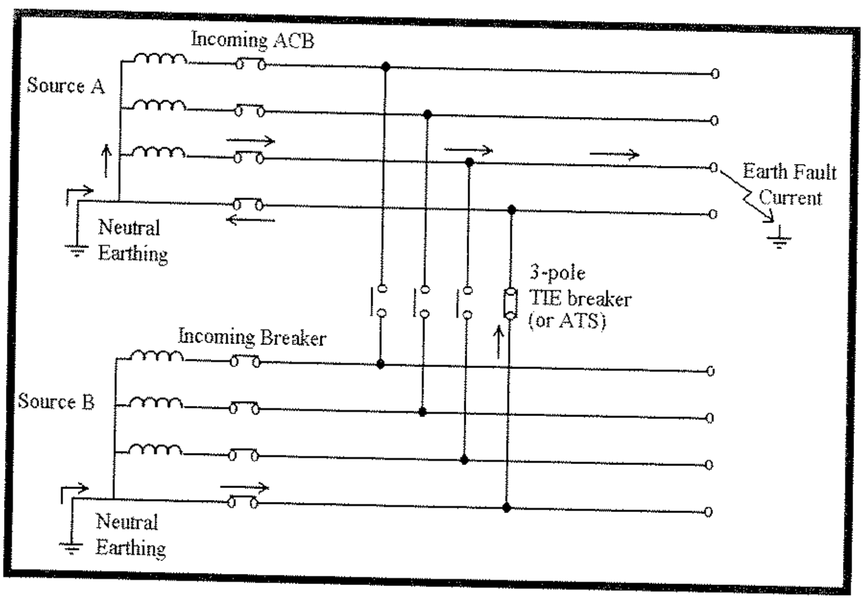


Figure 18.8 (b) De-Sensitisation of Earth Fault Detection

This may cause the phase to earth fault current seen by RCD at source A to be smaller and cause de-sensitisation of the earth fault relay or RCD, which may not operate.

However, on the other end, when the phase to earth fault current is sufficiently large, this current which split into two paths may caused RCDs for both source A and source B to operate simultaneously.

(1) Briefly explain the function of each of the following components of a standby generator:-

(a) Main Alternator
(b) Rotating rectifier
(c) Exciter

(2) The essential loads of a building are as follows:-

Fireman Lift :	25 kW at 400V, 3-phase with starting current 140A per phase
Fire pump :	100 kW at 400V, 3-phase with Star / Delta starter
Pressurisation Fan :	30 kW at 400V, 3-phase
Ventilation Fan :	30 kW at 400V, 3-phase
Emergency Power and Lighting :	82 kW balanced on 3-phase

If the transient reactance of the standby generator is about 20% and the voltage dip at the standby generator during the starting of motors is not to exceed 15%, determine the required capacity (in kVA) of the standby generator. Assume the power factor of all the loads to be 0.85.

(3) With a proper diagram, explain briefly the principle of the permanent magnet generator (p.m.g) and it advantages

(4) Explain briefly why 4-pole breakers or 4-pole Automatic Transfer Switch (ATS) must be used in the interconnection of two different sources.

(5) Explain briefly on: -

(a) Continuous rating
(b) Standby rating of a standby generator

(6) Assuming that the on-load fuel consumption of the standby generator is 0.2 litres per kVA per hour, estimate

(a) The total fuel consumption of the 350 kVA standby generator for 10 hours
(b) The number of hours that the diesel fuel contained in a 700 litres day tank can last if the generator is 750 kVA.

Voltage Dip consideration
→ ensure voltage dip less than 15% ~ 20%
$\Delta V = 15\% = \frac{\text{Starting kVA}}{\text{Generator rating}} \times Z_g(\%)$
∴ Genset rating = $\frac{\text{Starting kVA} \times Z_g(\%)}{\Delta V(\%)}$

CHAPTER 19
UNINTERRUPTIBLE POWER SUPPLY (UPS)

19.1 INTRODUCTION

(a) For the standby generator to start and take over the load, a short time interval (approximately 6 to 10 seconds) is required. During this time, all the essential circuits and hence the emergency equipment will be left without power supply.

(b) There are some critical loads in certain installations which cannot tolerate even a momentary power failure. Such equipment include important data processing and computer equipment, certain equipment in hospitals, air traffic control equipment, etc.

(c) These critical loads must therefore be provided with continuous power supply at all times. The equipment that can provide power supply without any break is called the No-Break Power Supply, and the static equipment is called the Uninterruptible Power Supply (UPS).

There are many methods used for providing "no-break" electricity supply and these include:

(a) A static electronic converter-inverter unit operating together with batteries.

(b) An alternator which is coupled to an A.C. synchronous motor which has two sources of electricity supply.

(c) An alternator which is coupled to a D.C. motor which is supplied from the mains (via a rectifier) and also from a battery bank.

(d) An alternator coupled to both a diesel generator and an A.C. synchronous motor.

19.2 MAIN COMPONENTS OF STATIC UPS

The Static UPS mainly consists of a:

- Rectifier / charger
- Inverter
- Battery
- Static transfer switch
- Bypass switch

(a) <u>The UPS Module</u>

The UPS module consists of a rectifier/charger unit and inverter unit with associated control logic, synchronising equipment, protective devices and accessories required to provide precise A.C. power.

(b) Rectifier/Charger Unit

The rectifier/charger unit is a portion of the UPS module, which contains all the equipment and controls necessary to convert input A.C. power to regulated D.C. power required for input to the inverter unit and for battery charging.

(c) Inverter Unit

The inverter unit is also a portion of the UPS module, which contains all the equipment and controls necessary to convert D.C. power (from the rectifier/charger or battery) to precise A.C. power required to supply power to the critical load.

(d) The Battery

The battery provides the UPS with a stored energy source. The battery will be of a heavy-duty industrial type designed for standby power service. The ampere-hour capacity should be sufficient to supply direct current to the inverter for the emergency period.

(e) The Static Transfer Switch

The static transfer switch employs solid state devices and operates in parallel with the bypass switch and allows uninterruptible transfer to the bypass supply should a UPS Module malfunction occur.

Static bypass switch can transfer the load automatically in less than 5m-secs compared to 20 to 100m-secs in the case of electromechanical transfer switch. This is required if even very short interruption of supply cannot be tolerated.

(f) Battery Disconnect Circuit Breaker

This circuit breaker is mounted in a separate enclosure. When the breaker is open, there will be no battery voltage present in the UPS module. Also, when the battery voltage reaches the minimum discharge level or when signalled by other control functions, the UPS module will be automatically disconnected from the battery by opening the battery disconnect circuit breaker.

(g) Disconnect Switch for the Static Transfer Switch

The function of this switch is to facilitate the disconnection of the static transfer switch in case of malfunction.

Operation of the UPS with Static Bypass

The schematic diagram of a static UPS with bypass is shown in Figure 19.1.

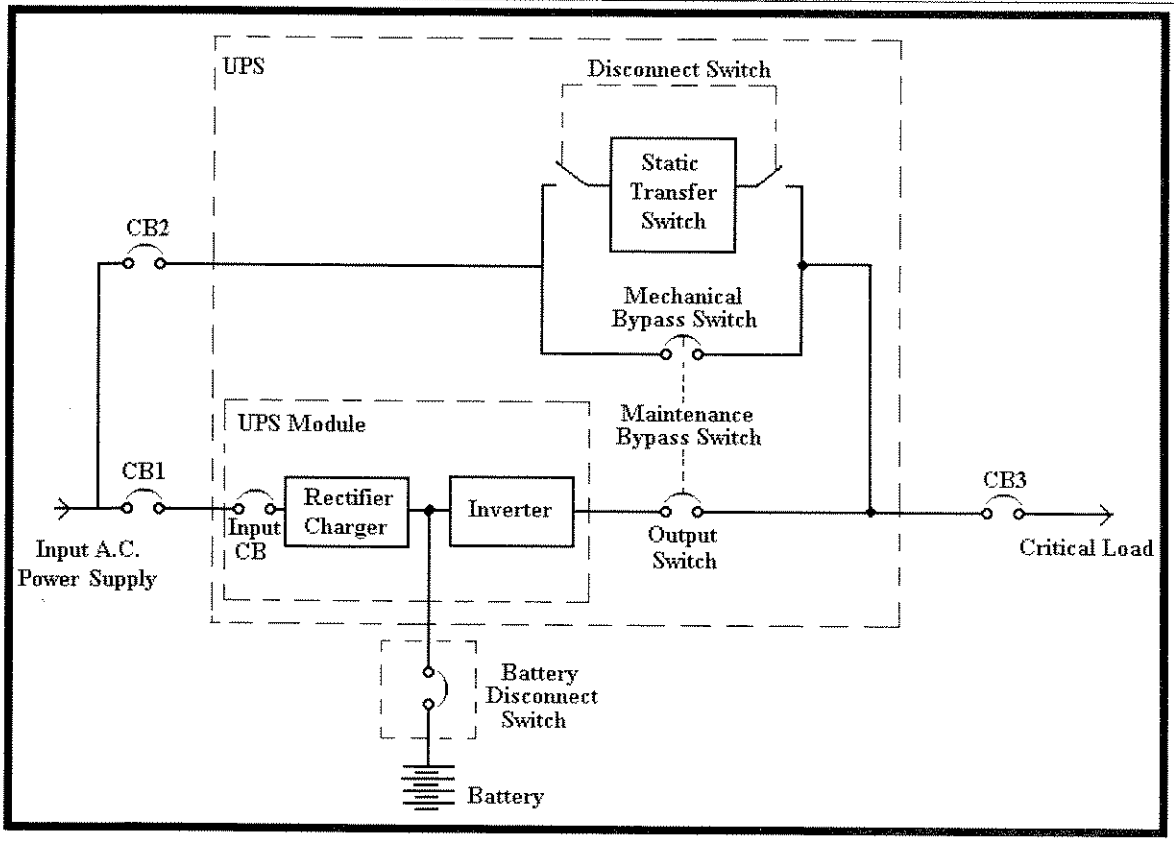


Figure 19. 1 UPS Single Line Diagram

The operation of the UPS can be described as follows:

(a) Under normal operating conditions, CB1, input CB, output switch, CB2, disconnect switch (for the static transfer switch) and CB3 are closed, and power from the primary A.C. source is supplied to the rectifier/charger unit.

(b) The solid-state rectifier/charger converts the incoming A.C. power to D.C. power.

(c) The rectifier/charger output is fed into the solid-state inverter and charges the battery so that the battery is always ready to take over the load at any moment of a power failure.

(d) The inverter converts the D.C. power to A.C. power which supplies the critical load.

(e) In the event of a failure in the primary A.C. power supply, input power for the inverter is automatically supplied from the battery with no interruption or no disturbance of the invertor output which supplies the load.

(f) When the primary A.C. power is restored, input power for the inverter and for recharging the battery automatically be supplied from the rectifier/charger output without any interruption or disturbance.

(g) Note that the A.C. voltage on the bypass line and the A.C. output from the inverter are kept in synchronism by the synchronising equipment in the UPS module. Also, any fault in the UPS module will be detected by a monitor.

(h) In the event of any fault in the UPS module, the monitor will send a signal to the static transfer switch.

(i) On receiving the signal, the static transfer switch will close and the bypass line will then be in parallel with the inverter output circuit.

(j) Immediately after the closing of the static transfer switch, the input CB and the inverter output switch will open, thus disconnecting the UPS module from the circuit.

(k) At the same time, the mechanical bypass switch will close and the static transfer switch will open.

(l) The power supply to the load is now maintained by the bypass line through the mechanical bypass switch.

Note:

The mechanical bypass switch may be used without the static transfer to make a transfer to bypass for maintenance and service purposes. A logic arrangement using overlap switching allows those breakers to transfer the load from the UPS bypass or vice-versa without interruption.

Reactor and Filter

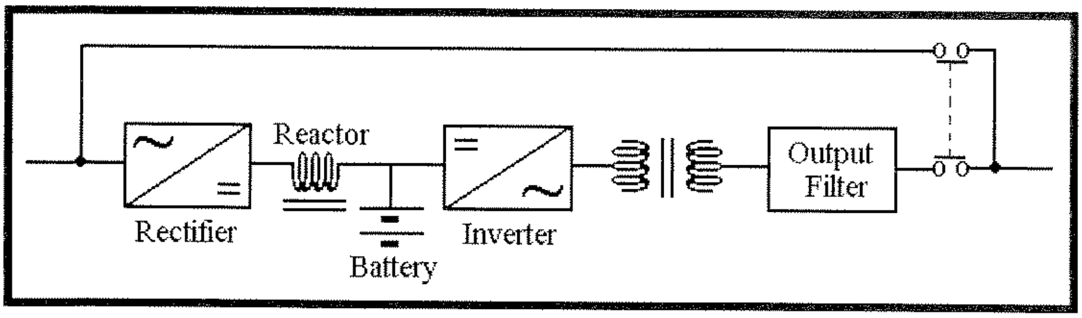


Figure 19. 2 (a)

(a) Reactor

A reactor is included to limit the ripple to a value acceptable to both the battery and the inverter.

(b) Output Filter

The inverter output passes through a filter network to reduce the harmonic content of the output to voltage to the level acceptance to the load.

(c) Input Harmonic Filter

Input harmonic filters for the rectifier are also required to ensure distorted harmonic currents do not flow to the source. Typical harmonic present will be 5^{th}, 7^{th}, 11^{th}, etc.

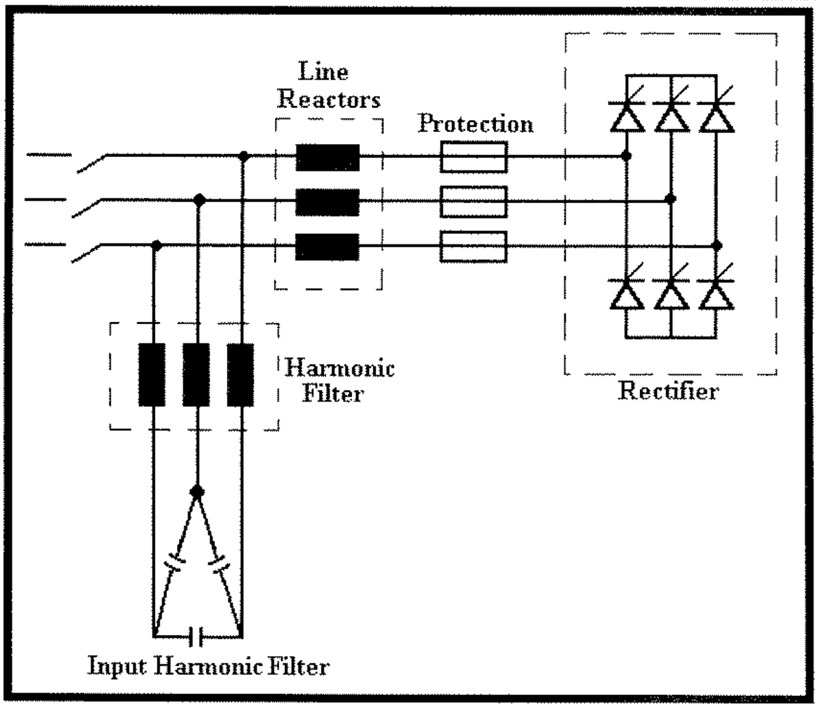


Figure 19.2 (b) Input Harmonic Filter

19.3 SELECTION OF UPS

Most of the problems experienced with static UPS systems arise because certain aspects of the load to be supplied by the system have not been fully understood at the time the system was specified. Apart from the voltage, number of phases, frequency and power rating of the load, the following characteristics are important.

(a) Steady State Voltage Regulation at UPS output

Most equipment designed for main operation will tolerate a 6-10% swing in voltage. However, if computers form part of the load, only 1% or 2% may be specified, depending on the transient load response required.

(b) Steady State Load in kW (or Continuos Load Requirement)

UPS input kW concerns with the continuous load requirement for the essential and critical load and the Battery recharge kW, the following formula may be used:

$$\text{UPS kW} = \frac{\text{UPS output load kW} + \text{Battery Recharge kW}}{\text{UPS efficiency}}$$

Taking into consideration of UPS efficiency,

$$\text{UPS kW} = k \times P$$

Where P = sum of the output continuous load in kW
k = 1.2 to 2

(c) Transient Load Response and Inrush Current

Time constants associated with the filter circuits in the inverter mean that the voltage regulating system cannot react immediately when a load is suddenly applied. The tolerance of the load in this respect varies considerably. Tungsten and fluorescent emergency lighting, for example, can tolerate complete loss of power for a few seconds, provided a visible blink is acceptable. On the other hand, some major computer manufacturers specify a voltage deviation limit of +10% and –8% for a few milliseconds only, provided that the steady-state voltage limits are closely controlled, say to within 2%.

In summary, the requirements are as follows:

(i) Transient Load Fluctuations

- The output voltage must be within +10% and –8%
- The return to steady state must be within 20 m-secs.

(ii) Transient Overloads

As the inverter of UPS is a power electronic device which can deliver only maximum of 2 x Rated full load current for short duration, for equipment started frequently, it is necessary to ensure that maximum transient current does not exceed 1.5 times the rated current I_n of UPS and if necessary, select UPS having a larger installed power.

Maximum transient current < 1.5 rated current (I_n of UPS).

(d) Load Linearity

Resistive loads including tungsten lighting are linear loads. Switched-mode power supplies (often used in the power input circuits of computers) constitute non-linear loads, and as such can pose a problem for the UPS system. They draw current from the static inverter only in short pulse. The inverter must therefore be able to supply these spiky currents, high in harmonics, without producing unacceptable harmonic voltages.
Therefore isolation transformer and output harmonic filters are often required on the output side of the UPS.

(e) Voltage Distortion on the UPS Output

The static inverter must provide a sinusoidal waveform of sufficient accuracy to meet the requirements of the load. The general industry standard for total harmonic distortion (THD) is 5% of the fundamental sine wave voltage. Inverter specifications usually demand this for linear loads – non-linear loads can increase the harmonic content.

As mentioned above, harmonic filters and isolation transformers may be required on the output side of the UPS.

(f) Frequency Tolerance

It is relatively easy to achieve an inverter frequency tolerance of 1%, controlled by an electronic oscillator, independent of load or input voltage. Some computer loads require accuracy of 0.05%, in which case crystal control is required.

(g) Dynamic Loads

Some types of loads, notably those containing constant-voltage transformers, exhibit a dynamic impedance characteristic, and from the viewpoint of the static inverter behave like a negative impedance. This can cause the voltage control loop of the inverter to become unstable, resulting in severe oscillations at a few Hertz. In practice, this is not usually a problem if the dynamic portion of the load does not constitute more than 10% of the total load. Some types of output filter are more tolerant of dynamic loads than others.

(h) System Reliability of UPS

System reliability of UPS is increased by the use of:

(i) Static bypass switch
(ii) Redundancy

System reliability of UPS is often given by UPS supplier in the form of Main Line Between Failure (MTBF) in numbers of hours.

Mean Time Between Failures (MTBF) of system is a measurement of the average time that a piece of equipment or system performs its function without requiring repair (although it may require routine scheduled maintenance).

A table showing typical MTBF from a UPS supplier is shown in Table 19.1.

System Configuration	**MTBF in hours**	
	Without Static Bypass	**With Static Bypass**
Basic UPS Module	21,000	261,000
2 lines in // without redundancy	15,500	177,000
2 lines in // with ½ redundancy	250,000	450,000
3 lines in // with ⅓ redundancy	166,000	430,000
2 rec/charger 1 battery 2 Inv. ½ redundancy	81,000	370,000

Table 19.1 Table of MTBF specified by UPS Manufacturer

Static Transfer Switch

The primary purpose of the static transfer switch (STS) is to allow virtually uninterrupted transfer of the critical load from A.C. power supply to another. It can switch at high speed in response to a small control signal, has very low resistance when turned 'on' and very high impedance when switched 'off'. A fast break-before-make switching scheme is employed to avoid overlapping transfers (connecting together the two sources).

The STS is based on a solid-state device, the thyristor or silicon controlled rectifier (SCR). The thyristor is a rectifier (i.e. it conducts in only one direction) which can be controlled by a relatively small gate current. If the gate current is flowing, then the main load current will also flow.

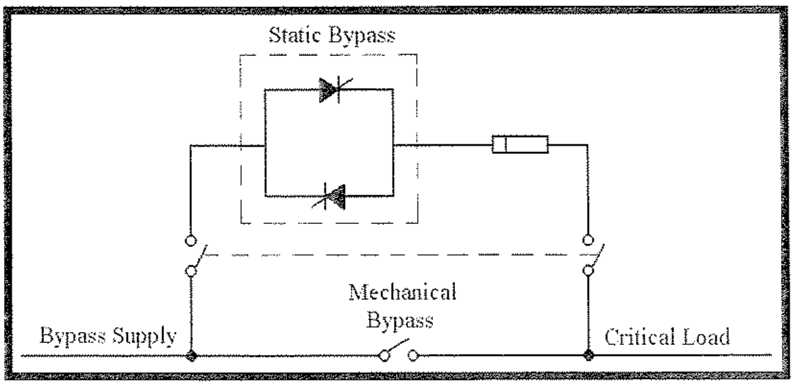


Figure 19. 3 Static Bypass Switch

Sensing circuits constantly monitor the states of the basic UPS module and feed the information to a supervisory microprocessor controller. Upon sensing the loss of the UPS supply, the microprocessor control provides gate current to the thyristor of the static bypass and cause it to provide electricity supply to critical load. The transfer is so fast (normally less than ¼ electrical cycle), that even the most sensitive electrical or electronic loads are unable to determine its occurrence.

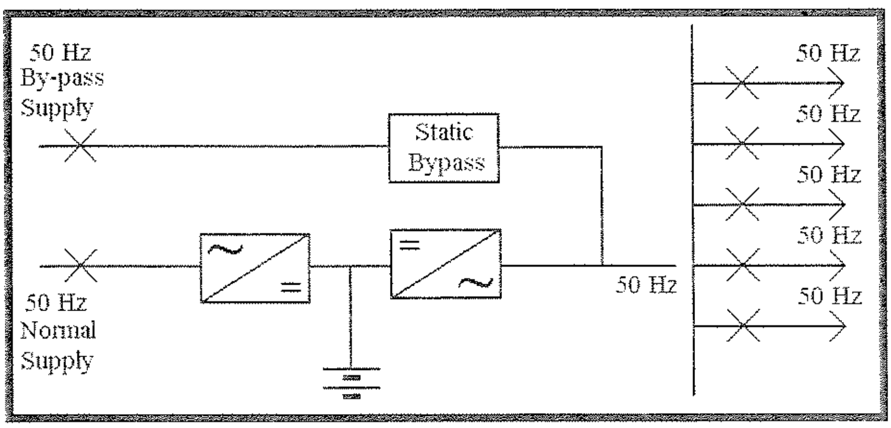


Figure 19. 4 UPS with Bypass

A typical arrangement of UPS with bypass is shown in Figure 19.5, it is to be noted that if the UPS is used as a frequency converter (from 50Hz to 60 Hz) to back up a supply to essential equipment at 60Hz then static transfer switch should not be used, parallel redundancy as shown in Figure 19.3 are often used in this environment.

Parallel Redundancy Systems

Extremely critical installations can often justify the cost of a parallel redundant system (as shown in Figure 19.5 and Figure 19.6). Parallel systems are often used in major data processing centers where large blocks of power are required. These multiple systems have one UPS system more than required by the load. The critical load can, therefore, be sustained even with loss or failure of any one of the individual systems. Synchronizing and monitoring of output voltage amplitude, frequencies, and phases is required within the systems to achieve satisfactory parallel operation. A static switching bypass, on 50 to 60 Hz units, although of lesser importance for reliability, may still be used for maintenance or momentary overload and fault clearing capability on the output side.

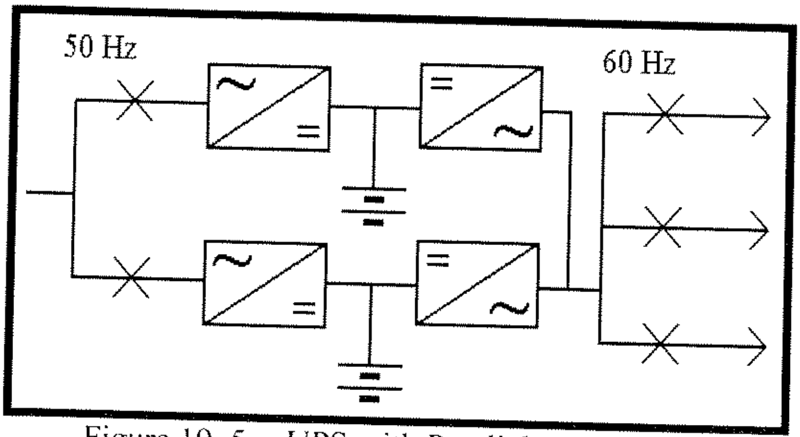


Figure 19. 5 UPS with Parallel Redundancy

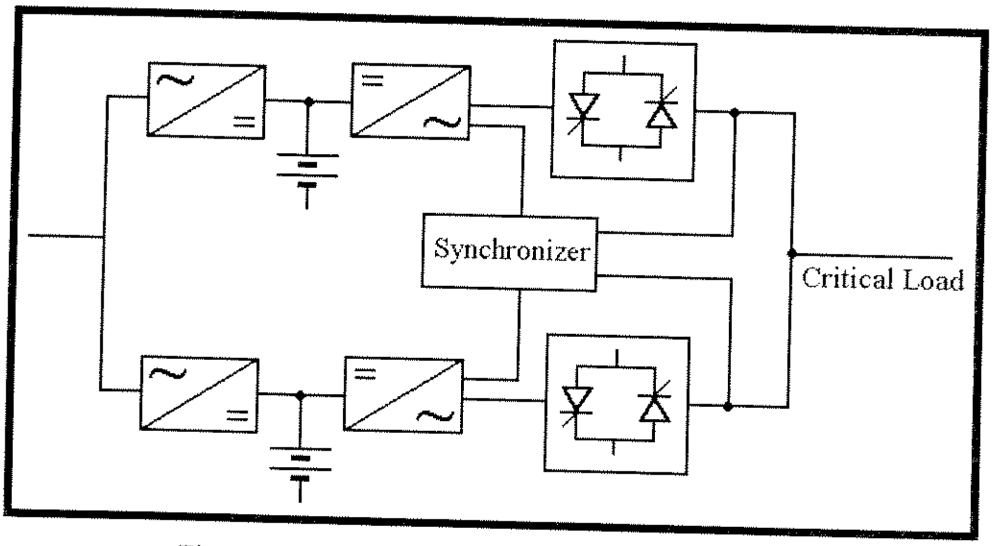


Figure 19. 6 UPS with Parallel Redundancy

Short Circuit Capacity of UPS and the Protection of UPS

As the inverter of UPS can deliver only 1.5 times to 2 times of its full load current for very short duration, improper sizing of circuit breaker with too large of trip rating may render improper protection. The trip rating of MCB or MCCB protecting the UPS and the output circuit of the critical loads of the UPS must not be sized more than 2 x Rated current of UPS (I_n).

The use of static by-pass switch can often enable the momentary operational overcurrent such as motor starting current, Inrush magnetising current of motors and instrument and rectifier transformers and filter capacitor charging current to be transferred to by-pass supply for short duration.

In addition, whenever there is a short circuit or earth fault on the DB of the critical loads, the use of static bypass switch transfer this fault current to the bypass supply and therefore is able to cause the upstream breakers to operate.

Without Static Bypass

Whenever static bypass switch is not provided, protection against short circuit, earth fault must be considered carefully by taking into account of the constraint of the power and current output of the inverter as shown in Figure 19.5.

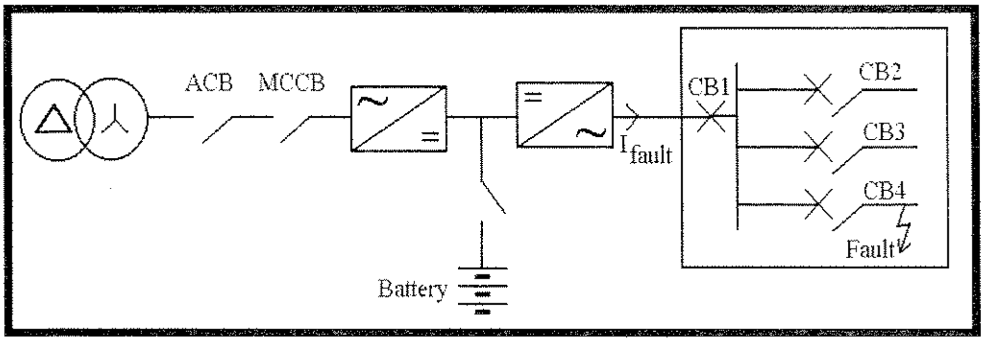


Figure 19. 7 Fault Discrimination for UPS without Static Bypass

Trip rating of circuit breaker CB1, CB2, CB3 and CB4 must not be larger than $2I_n$.

19.4 TECHNICAL SPECIFICATIONS OF UPS SYSTEMS

Input (Rectifier / Charger)

Voltage	-	380V, 400V or 415V +/- 10% 3-phase + neutral
Frequency	-	50 or 60 Hz +/- 5%
Startup "walk-in"	-	10 s to full load
DC voltage regulation	-	+/- 1%
DC ripple voltage	-	+/- 1%
Harmonic voltage distortion	-	THD (V) < 5% (total)

Output (Inverter)

Voltage	-	380V, 400V or 415V, 3- phase with neutral
Voltage regulation	-	+/- 1% for balanced load +/- 3% for 30% unbalanced load
Line drop compensation	-	0 to 3% adjustable
Transient response	-	+/- 5% for 100% step load change
Transient recovery	-	Return to within steady-state tolerances in less than 20 msec
Harmonic voltage distortion at the inverter output	-	THD (V) < 4% (total)
Phase displacement	-	120 deg. +/- 1 deg. for balance load. 120 deg. +/- 3 deg. for unbalanced load.

Frequency	-	50 or 60 Hz
Frequency regulation	-	+/- 1% adjustable for synchronisation with mains bypass. +/- 0.1% independent operation
Freq. Sync. Range	-	+/- 0.25 to 1 Hz , adjustable
Slew rate	-	1 Hz/s
Overload capacity	-	125% of full load for 10 minute minimum. 150% of full load for 1 minute minimum
Efficiency	-	90% minimum at full load.
Operating temp. range	-	-5 deg. to 40 deg. C
Audible noise	-	< 60 dBA

*Note: Users may need to consider the provisions of input and output harmonic filters and an isolation transformer on the output side of UPS.

19.5 MAINTENANCE OF STATIC UPS

Most UPS are installed because the load requires an uninterruptible source of power. Therefore, special precautions must be taken when isolating an UPS for maintenance. Be aware of the loads supplied by the UPS and notify necessary personnel that disconnection of the UPS is required for maintenance.

A static UPS is extremely reliable and requires very little maintenance of the inverter and battery charger. Before maintenance is carried out, the UPS should be completely isolated from input and output, including batteries. The procedures of using the static bypass switch must be followed in accordance to the manufacturer's manual.

Preventive maintenance consists of cleaning and inspection the UPS at regular periodic intervals. In dirty environments, the time between intervals should be decreased. The following items are recommended in the regular inspection and service schedule:

(a) Remove all input and output power from the unit before performing the maintenance.
(b) Discharge and ground all capacitors terminals in the inverter/charger.
(c) Inspect all parts for evidence of overheating and physical damage.
(d) Inspect terminals for loose or broken connections, or burnt insulation.
(e) Inspect and clean, as necessary, all intakes and exhaust openings.
(f) Check for liquid contamination (battery electrolyte, oil from capacitors, etc.).
(g) Check battery condition.
(h) Check and adjust voltage output and the frequency per manufacturer's specifications.

After the UPS has been reconnected, check the output voltage and frequency under load. Stimulate a power failure and check for proper system operation.

19.6 STANDBY GENERATOR FOR UPS

Although uninterruptible power supply systems (UPS) are capable of meeting the normal and emergency power requirements of essential and critical loads, the problem is the installation of sufficient battery capacity to provide a standby power for long period of time.

For longer duration of power requirement, a standby diesel generator is used to back up the UPS until the normal A.C. supply is restored. The role of the UPS storage batteries then becomes that of supplying the load until the standby generator starts up and the storage battery capacity is seized to meet full load requirements for about 10 minutes to 1 hour.

A typical arrangement of a standby generator as back-up to the static UPS is shown in Figure 19.8.

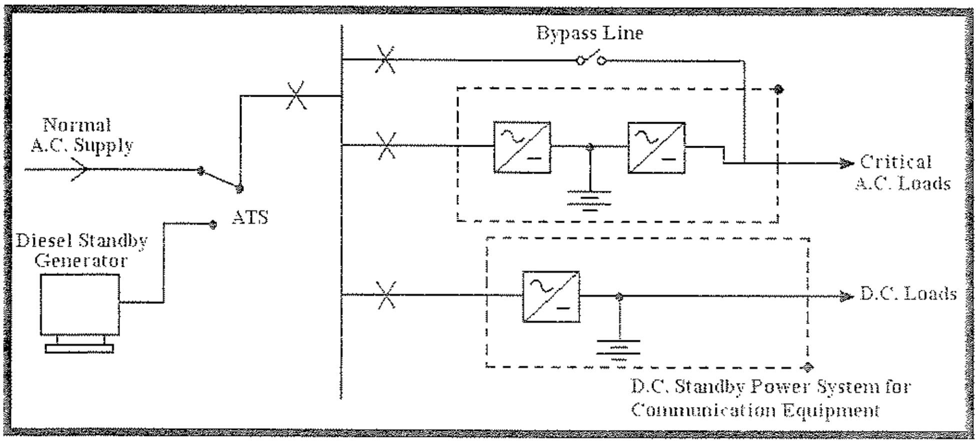


Figure 19. 8 A Typical Arrangement of Standby Power Supply System with Diesel Generator, UPS and D.C. Supplies for Communication Equipment.

Static UPS connected to the standby generating set can create some problems if it is not carefully dealt with. One is harmonic distortion caused by the use of thyristor-controlled circuitry in the rectifier and charger. The rectifier and charger take a non-sinusoidal current waveform because the thyristor delays the start of conduction in each half cycle. The resulting harmonic currents, of the order of 20%, react with the diesel generator impedance is to produce harmonic voltage distortion as shown in Figure 19.9.

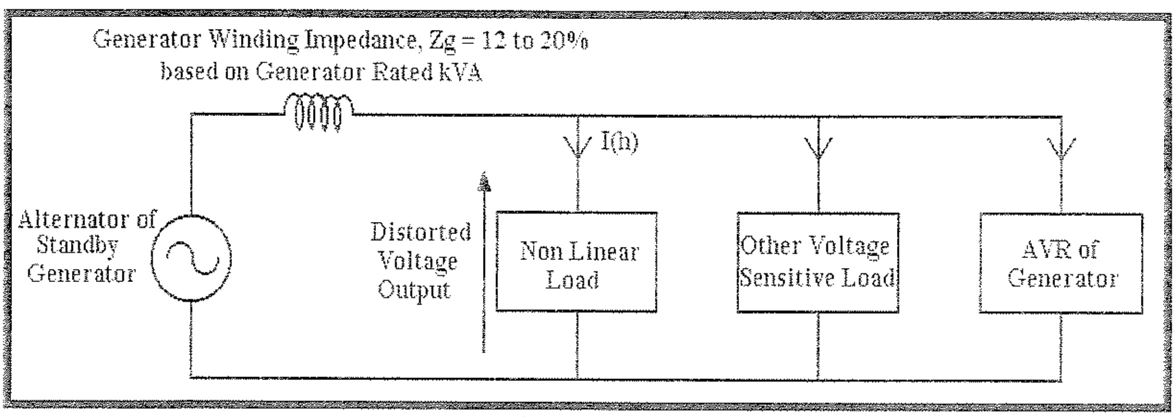


Figure 19. 9

Another problem is the risk of instability caused by UPS, the rectifier / charger output, when the voltage from the generator to the UPS rectifier falls for some reason, the control circuitry in the rectifier causes it to draw an increased current to maintain a constant power output to its load. The generator sees this as a negative impedance - a drop in voltage results in an increase in current. Unless the voltage control loop of the generator is specifically designed to counteract this problem, in stability will result.

Effects of Non- Linear Loads and UPS

The general term non-linear applies to loads which do not have a constant impedance to sinusoidally varying voltage. Variations in impedance may be due to the natural non-linear characteristic of the load or may be due to the switching action of circuit components such as occurring in the rectifiers or thyristors.

When the load current is not sinusoidal, the internal reactance drop in the generator windings will follow the non-sinusoidal shape of the current, so that actual terminal voltage of the generator will be the basic sine wave generated minus the non-sinusoidal voltage drop at the terminal which may affect the operation of other equipment.

Amount of harmonic distortion depends on how much the applied load is non-linear and the internal reactance of the generator winding.

Sizing of Generators for Non-Linear Loads and UPS

(a) It is difficult to generalize on the capabilities of standard generators for non-linear loads.

Rules of thumb, which involve the over-sizing of generating plant, are usually too rigid and overly simplistic.

Some would place the limit or non-linear load as 70% of generator rating, whereas others are more conservative in suggesting a limit at nearer 50%.

(b) But the crux of the problem is one of the generator impedances.

The current harmonics produced by non-linear loads are constant, but voltage distortion is the function of generator impedance.

There is no one value of impedance which can be used for all harmonic orders, the stator winding has varying reactance for each harmonic order.

(c) The main concern is the effect of the distorted voltage waveform on AVR as this could influence stability.

The AVR which fed from the main generator winding could be distorted by heavy distortion.

Example 19.1

For a computer load with harmonic spectrum as follows. Determine the appropriate power rating of the generator. Assuming that the impedance of the generator is 12% (0.12 p.u.)

Harmonic Order	Harmonic Current	Voltage Distortion (%)
H_3	75%	27%
H_5	40%	24%
H_7	15%	12.6%
H_9	8%	8.64%

Solution

(a) Voltage distortion at a particular harmonic frequency, h x f

$$h \times Z \times I_h$$

where, h = Order of harmonic
I_h = Current of h, harmonic
and Z = Impedance of Generator reactance at fundamental frequency 50Hz

For 3rd order harmonic, voltage distortion = 3 x 12% x $^{75}/_{100}$ = 27%

Similarly, for 3rd, 5th, 7th and 9th harmonic.

(b) Total Harmonic Voltage Distortion:

$$THD = \sqrt{(27)^2 + (24)^2 + (12.6)^2 + (8.64)^2}$$
$$= 39.24\%$$

(c) To target at 5% voltage distortion limit, the generator must be oversized to about (39.24 / 5%) = 8 times larger than the loads.

Note:

The above example shows that without harmonic filters, the high harmonic currents of the harmonic load has resulted in very big standby generator.

The readers may like to try to determine the kVA of standby generator for the harmonic load with input harmonic filters (i.e. UPS with input harmonic filters).

The result will show that with input harmonic filters for UPS which reduce the harmonic currents, the standby generator needs only be oversized to 1.8 to 2 times larger than the load.

(1) Draw a schematic diagram of an uninterruptible power supply (UPS) without a bypass line and indicate the main components. Briefly explain the operation of the UPS in the following situations:

(a) Failure of normal A.C. supply
(b) Restoration of normal A.C. supply after a power failure

(2) Draw a schematic diagram of uninterruptible power supply (UPS) with a bypass line. Briefly explain its operation under the followings conditions:

(a) Failure of normal A.C. supply
(b) Restoration of normal A.C. supply after a failure.
(c) Failure of UPS module

(3) The critical loads of an electrical installation are as follows:

Load 1 = 30kVA
Load 2 = 50kVA
Load 3 = 40kVA
Load 4 = 15kVA
Load 5 = 15kVA

If Load 5 has a transient inrush current equal to 5 times of its full load current for 20 m-second and is switched on once a day. Determine the required kVA of the static UPS. Assuming 20% future load extension and all loads are operating at 50Hz. Determine the required kVA capacity of the UPS.

(4) The electrical loads operating at 60Hz are supplied by a static UPS are as follows

Load 1 = 15kVA
Load 2 = 30kVA
Load 3 = 20kVA

Load 3 has a transient inrush current at 7.5 times of its full load current for 20 m-second. Assuming that future load expansion is 25%, determine the required kVA capacity of the UPS.

(5) For the UPS without a harmonic input filter, the harmonic current spectrum is shown in Table 19.2. Determine the appropriate kVA of the Standby Generator (with impedance, Z_g = 12%, based on Generator Base kVA) to ensure THD (V) is within 5% limit, the UPS rated kVA is 200.

Order of Harmonic	**5^{th}**	**7^{th}**	**11^{th}**	**13^{th}**	**17^{th}**	**19^{th}**	**THD(I)**
Harmonic Current, I_n (in per-cent) of a 6-pulse UPS (without input harmonic filter)	28%	8.1%	8.4%	4.5%	4.5%	2.3%	31%

Table 19.2

(6) For the UPS with a harmonic input filter, the harmonic current spectrum is shown in Table 19.3. Determine the appropriate kVA of the Standby Generator (with impedance Z_g = 12%, based on Generator Base kVA) to ensure THD (V) is within 5%, the UPS rated kVA is 200.

Order of Harmonic	**5th**	**7th**	**11th**	**13th**	**17th**	**19th**	**THD(I)**
Harmonic Current, I_n (in per-cent) of a 6-pulse UPS (with input harmonic filter)	3.5%	3.3%	6.3%	2.8%	3.5%	2.0%	9.21%

Table 19.3

References

(1) Code Of Practice For Electrical Installation In Buildings, Singapore Standard CP5:1998

(2) Singapore Standard SS482:Part 1:2000 For Electrical Switchboard

(3) British Standard BS EN 60947 And IEC 947-2 Standard For Moulded Case Circuit Breaker

(4) Singapore Standard SS97:Part 1:1994 For Residual Current Operated Circuit Breaker

(5) British EN60898 And Singapore Standard SS359 For Miniature Circuit Breakers

(6) JSP Switchgear Book, 8th Edition, By R. T. Lythall, Newnes-Butterworths