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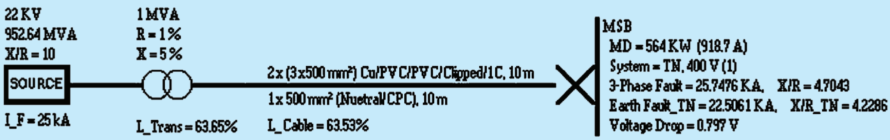
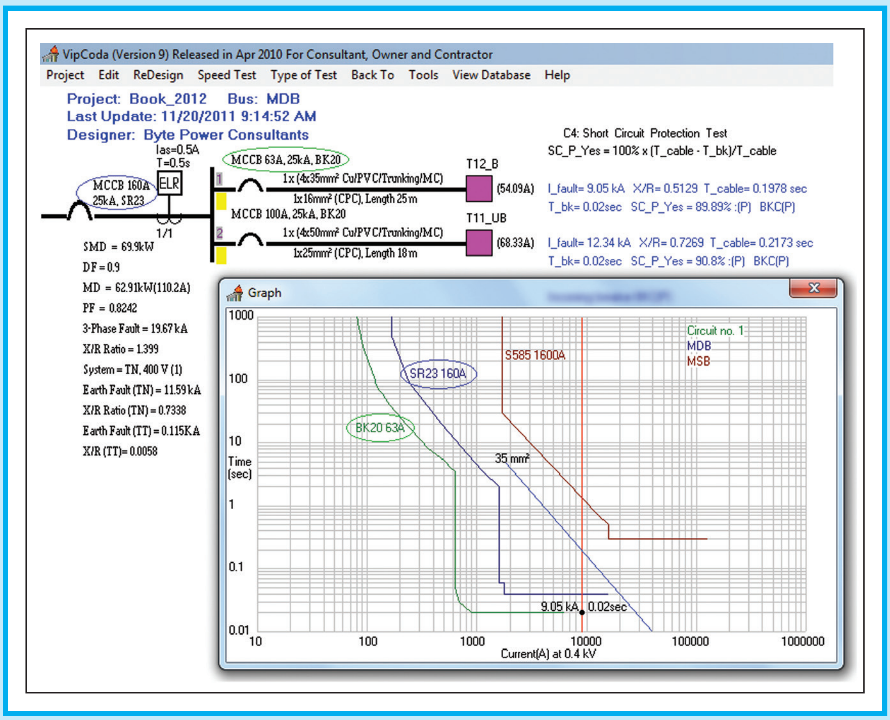
# Principles and Design of LOW VOLTAGE SYSTEM

Teo Cheng Yu

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## About this Book

As a clear and up-to-date guide, this book presents the principles and design for low-voltage system at both the device and system levels. It provides the characteristics, specifications and industrial standards for circuit breakers, cabling, earthing and fuses. Utility supply system, utility earthing system and consumer earthing system are introduced. Standard design procedures, the latest code of practice, IEE wiring regulations, overcurrent and earth-fault protection are illustrated through a series of comprehensive and interesting examples which are particularly useful for the practicing engineers and students. Applications of computer-aided design and simulation are also presented. Common technical terms, design formulae, touch voltage, per-unit calculation and model examination questions with solutions are provided in the appendixes.

## About the Author

**Teo Cheng Yu** received the B.Sc. in Electrical Eng. from National Taiwan University in 1971 and the M.Sc. in electrical machines and power systems from the University of London in 1974. He has worked in many areas of computer applications in power system since he joined the Imperial College, University of London as a research assistant from 1973 to 1974. Subsequently he was appointed engineer, executive engineer, senior engineer and project manager in the Public Utilities Board for 7 years. With the Nanyang Technological University for 24 years, he was appointed Head of Division of Power Engineering for 6 years. He was elected as the Chairman of the IEE Singapore Centre for 3 years and is Fellow of the IET, Fellow of IES and Fellow of IEM. He is the also author of three books in Pascal programming and the developer of a number of PC-based integrated simulators for the design, assessment and teaching of electrical system in buildings. He is currently the General Manager of Byte Power Consultants handling operational planning and simulation of a number of large HT and LV networks.

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# Principles and Design of Low Voltage Systems

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*To My Family*

**Yeo Shai Ing**

**Teo Ee Ee**

**Teo Guan Siew**

# Preface to Second Edition

In the undergraduate electrical engineering curriculum, much emphasis is placed on electronic, communication, control and computer engineering. Power engineering is also an essential field, which may be neglected in some universities. Besides the traditional topics such as three-phase circuit, magnetism, electromagnetic devices and DC machines, we introduce low voltage (LV) system including utility LV network, earthing arrangements and electrical installations from 15 kVA to 3000 kVA. Approximated by using a single-phase representation, the calculations of voltage drop, earth-fault and three-phase fault currents can be introduced.

It is felt that a basic understanding of earthing is essential and the various earthing arrangements available in the LV system are good examples for the illustration of system earthing. The majority of electrical engineering graduates will possibly encounter more applications in the LV system rather than the traditional generating and transmission system. The integration of LV system at both the device and system levels into the undergraduate curriculum of electrical engineering is therefore, relevant and practical.

In the second edition, Chapter 3 has been revised and the numerical expression for the degree of adequacy of the overcurrent and short-circuit protection are introduced. The concept of touch voltage and the requirements of electric shock protection for TT and TN-S system have also been revised in Chapter 4. For illustration, the assumptions made in all the examples are now clearly stated. The latest CP5, IEE wiring regulations and the relevant up-to-date IEC, BS and Singapore standards are referred. Common technical terms, design formulae, touch voltage, per unit calculation, tutorial questions and model examination questions with solutions are provided in the appendixes.

# Preface

A basic understanding of the earthing arrangements, in both the utility systems and consumer systems, and the principles and functions of low-voltage systems may be more relevant to the practising engineers. The majority of the electrical engineering graduates will possibly encounter more applications in the low-voltage systems. The integration of low-voltage systems into the undergraduate curriculum of electrical engineering is, therefore, timely.

This book presents the principles and design of low-voltage systems at both the device and system levels and is written for both practising engineers and undergraduate students. Throughout the book, references are made to the latest international standards. Thus, the up-to-date system requirements, specifications and technical data are made available to help engineers/students in the study as well as hands-on design of various low-voltage systems. The latest code of practice and the IEE Wiring Regulations are discussed and illustrated through a series of comprehensive and interesting application examples.

An overview to the utility supply systems and various key issues in the generation, transmission and distribution systems are given in *Chapter* 1. Characteristics, specifications and the relevant industrial standards for circuit breakers, cables and fuses are covered in *Chapters 2, 3* and *5*. In each chapter, the latest published IEC and BS standards are referred and application guidelines are included. Methods of system earthing, earthing arrangements in the transmission system and distribution system, and a detailed description of various earthing systems for electrical installations are provided in *Chapter 4*.

Standard design procedures, estimation of design currents and the design of various types of circuits are presented in *Chapter 6*. Hands-on design exercises of a 400-kVA and 2000-kVA installations are demonstrated together with the supporting calculations that verify the compliance of the requirements of earth fault and overcurrent protections. Sources of fault currents, manual calculations and systematic calculations of the fault current and its distribution using microcomputers are given in *Chapter 7* together with a practical case study. Application of the latest techniques of computer-aided design and simulation together with an attempt to automate the teaching and marking process using microcomputers are presented in *Chapter 8*.

The author wishes to acknowledge Miss Alice Chua Mei Fong for putting in considerable effort in the typing and editing of this manuscript. The author would like to thank Dr Duggal B R and Dr Gooi H B for reading through this book and making their useful suggestions. Recognition is also given to Mr. Thomas Foo Mong Keow and Mr. Yeoh Tiow Koon for their effort in compiling the relevant materials and in preparing all the diagrams in this book. The author, in addition, thanks Mr Teo Heng Lam for his good suggestions on the system earthing in Chapter 4.

Last but not least, the author thanks Professor Brian Lee for his good foresight in recognizing the significance of integrating electrical parts and the relevant standards into the engineering curriculum in 1981. This has provided the opportunity for the author to focus on the development and teaching of low-voltage systems since then.

Teo C Y

MacRitchie Reservoir / Yunnan Garden
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# Contents

# CHAPTER 1

# INTRODUCTION TO POWER SUPPLY SYSTEMS

Electrical supply is always available whenever you turn on a switch. After the switch has been turned on, the supply is always continuous and unlikely to be interrupted. In an urban city, the supply of electricity is rather reliable and one may take it for granted that electrical supply is always available. However, behind the scene of the reliable supply, there are many utility's managers, planners, engineers and technicians who are working around the clock utilising various supporting facilities and tools to enable the supply of electricity at a reliability of more than 99.99%.

## 1.1 ELECTRICITY SUPPLY INDUSTRY

The lead-time to construct a power station is five years. However, to optimise the total capital investment and operating cost, it is required to have a generation expansion planning for up to fifteen years ahead to determine the type, size and timing of generating units. It is also required to have a transmission system expansion planning to determine the transmission voltage and transmission network to match the proposed generation expansion plan. After the generating facilities and the transmission network have been installed and commissioned, it is the task of the operation engineers to carry out operation planning at intervals of several hours, a day and a week ahead. The system control engineers, with the supporting supervisory control and data acquisition (SCADA) facilities, monitor and control around the clock the whole generation, transmission and distribution system. Together with the engineers and technicians in various power stations, the system control engineers have to ensure that not only the real time electrical demand has to be met, but it has to be met at a minimum production cost.

A power flow diagram for a thermal power station is shown in Figure 1.1. The energy is converted from chemical to thermal form in the boiler; from thermal to mechanical in the turbine and then from mechanical to electrical in the generator. The voltage at the generator terminal is stepped up from 16 kV directly to 230 kV or 400 kV and the electrical power is transmitted through the 400/230-kV transmission network to various load centres. At each load centre, the voltage is stepped down and the electrical power is distributed through the 22 kV distribution network to various high tension (HT) and low-voltage (LV) consumers.

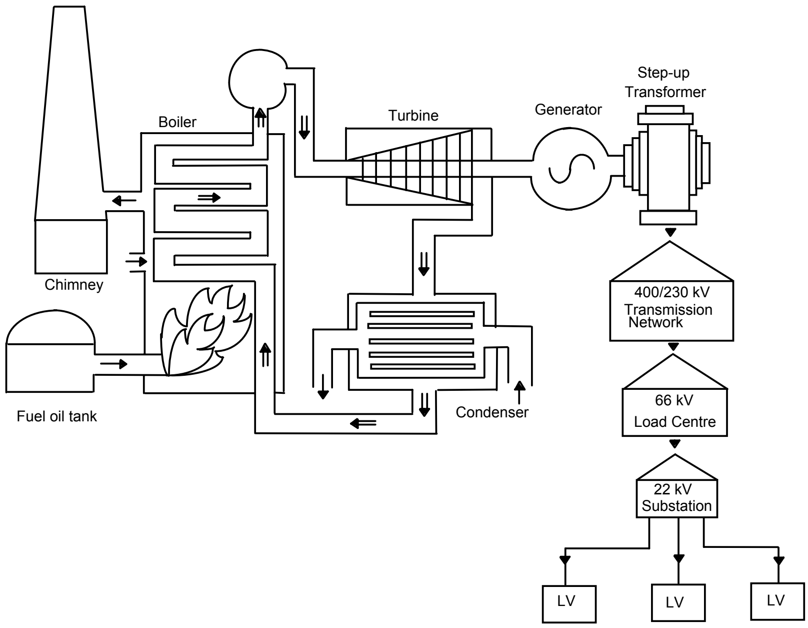


Figure 1.1 How electricity is brought to you

Electrical power systems, in comparison with many other systems, are the most expensive in terms of capital investment and operating cost. They are also the most influential in terms of seriousness of disruption on our mode of life in case of breakdown. In the past, the cost of distribution system was estimated to be roughly equal to capital investment in the generation facilities, and together, they represented over 80% of the total system investment. In recent years, these figures have changed to 50% for generating plants, 30% for distribution systems and 20% for transmission systems. Thus, for every $100 invested in the electrical infrastructure, $50 will be used for the construction of power stations, $20 for the transmission network and the remaining $30 for the distribution network to provide electrical supply to each consumer. In addition, the annual operation and maintenance costs including the fuel cost are about 230% of the annual capital investment cost. In other words, for every one-dollar invested in the generation, transmission and distribution plants, the utility has to spend another two dollars and thirty cents to operate them [Ref. 1, P 3].

The annual capital expenditure for an utility having a maximum demand of 1500 MW can easily be 300 to 400 million dollars of which 50% or 200 million dollars is to cater for the investment of power plants. The complete commissioning of a 1610-MW oil-fired power station in three stages over six years will represent a capital investment of some 1100 million dollars. The commitment to the complete commissioning of the whole 1610-MW station would also imply the requirement of an annual fuel cost of some 400 million dollars for the full operation of the station. It is not only a decision of the huge capital investment but also a commitment to revenue expenditure for twenty to thirty years.

After analyzing the characteristics of generating plants given in Table 1.1 and depending mainly on the expected load growth and the actual environmental constraints, the timing and the location of new power plant can be determined. The main objective of the system planner is to select the optimal plant type, size and timing such that the development and operation cost is minimized over the years under consideration and the annual load growth can be met reliably.

**Table 1.1 Characteristics of Generating Plants**

| TYPE | TYPICAL SIZE (MW) | COST INDEX | | THERMAL EFFICIENCY (%) |
|---|---|---|---|---|
| | | Capital Cost | kWh Cost | |
| Oil-Fired | 30-600 | 1.00 | 1.00 | 36-38 |
| Coal-Fired | 30-600 | 1.44 | 0.61 | 36-38 |
| Nuclear | 600-1000 | 1.78 | 0.16 | 31-32 |
| Gas Turbine | 20-110 | 0.56 | 1.36 | 27-28 |
| Combined Cycle | 90-300 | 0.85 | 0.88 | 41-48 |
| Diesel Set | 6-8 | 0.74 | 0.97 | 37-38 |

## 1.2 GENERATION SYSTEM

Unlike other energy supply systems, electric energy cannot be stored economically on any large scale. It has to be generated and utilised at the same time. There is, at all times, a balance between supply and consumption of electric power. Owing to the inherent slow response of boilers in thermal power stations, the system control engineers have to anticipate in advance, the electrical demand for the next 24 hours and to commit the generating plants accordingly to meet the forecasted demand. As there are differences in thermal efficiency of different generators installed in the system, some generators are capable of producing cheaper energy than others. Therefore, it is required to apportion the total demand among the generators in a manner that minimises fuel costs. It is the task of the system control engineers to decide when and which generating unit to run up or shut down and how much to load each unit. Recent advances in computer technology, mathematical modeling and optimisation techniques enable an optimal solution to be achieved through off-line computer programming or on-line real-time around-the-clock computer control.

Figure 1.2 shows a demand curve which represents the total load required by all the consumers at each half-hourly interval for a typical weekday. The peak demand of 1040 MW occurs at 11:00 am and the minimum load of 538 MW at 4:00 am. There are altogether twelve available generators in four power stations. These generators are of different capacities and have different thermal efficiencies. As shown in Figure 1.2, the system control engineer has assigned three 250-MW generators running through 24 hours without shut-down and three 120-MW generators and one 60 MW generator to start-up and shut-down at different hours of the day. The envelop of the generating capacity is a step function which represents the maximum running capacity that the generating system can deliver at each time interval. The excess capacity in MW resulted from the difference between the maximum running capacity and the load demand is known as spinning reserve at different time of the day. The task of the control engineer is not only to minimise the generation cost, but also to ensure the continuity of supply. At the same time he has to satisfy all the operating constraints in the generating units and limitations of the transmission network under normal and some abnormal conditions. Figure 1.3 shows the system frequency response due to the sudden loss of two generators at 1100 hours. In this scenario, as the system has adequate spinning reserve, the system frequency can recover to above 49 Hz after the shedding of 6% of the system load at 49.2 Hz and another 8% at 48.7 Hz [Ref. 2]. The operating cost including the generator start-up cost for a typical weekday for two different sets of operating schedules are shown in Figure 1.4 [Ref 3].

## 1.3 TRANSMISSION SYSTEM

The ideal arrangement for supply of electricity is to have a power station located right at the load centre and generate power at the utilisation voltage. Transmission system can then be eliminated. However, it is obviously not feasible to have a power station right in the city centre and also it is not technically feasible to generate power in a large scale at the utilisation voltage. An electrical system operated at 400 V can only supply up to a maximum demand of 3 to 4 MW. At a higher voltage of 22 kV, the maximum demand can be increased to 200 MW. For example, when the maximum demand in Singapore exceeded 192 MW in 1965, a higher voltage of 66 kV was implemented. Similarly when the maximum demand exceeded 781 MW in 1976, the transmission voltage was increased to 230 kV. The next higher voltage of 400 kV will be required to match the maximum demand of 5,000 MW in 1998. Higher transmission voltage has to be introduced mainly due to the increase in short-circuit current which exceeds the breaker's breaking capacity. By operating at a higher voltage, the number of transmission circuits can also be minimized. There are also other technical and economic reasons in determining the appropriate voltage level.

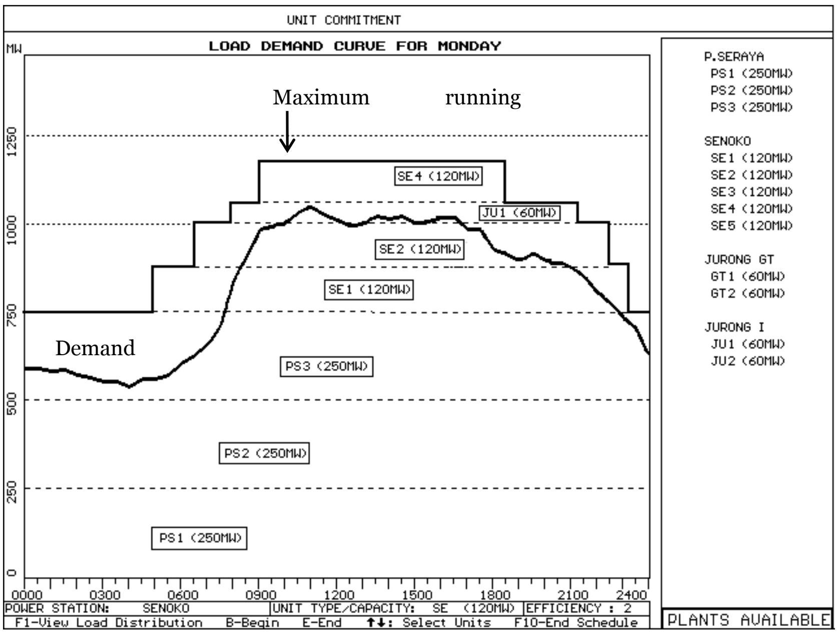


Figure 1.2 The engineer specifies unit commitment for Monday

Transmission of electrical energy by high voltage circuits is required in order to bring bulk energy from a remote source to a load centre and at the same time to interconnect between power stations. The interconnection would increase the reliability of supply and would provide the spooling of generating plants so that the standby capacity can be reduced. The most economic loading of generators can be achieved, and the overall production and transmission costs can be minimised.

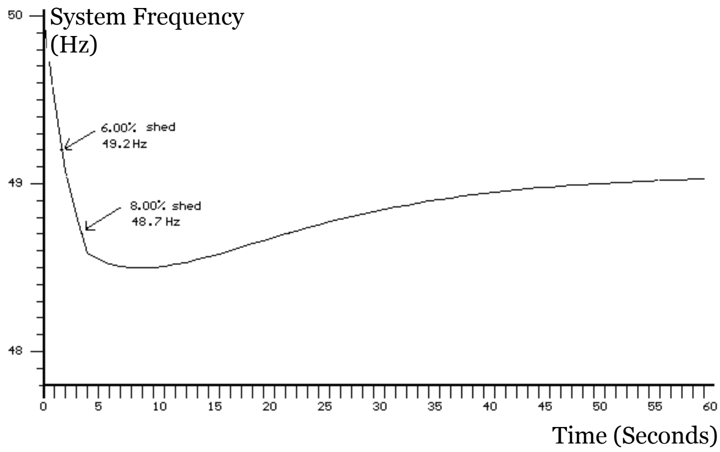


Figure 1.3 System frequency response with load shed

| Power Stations | | Unit COMMITMENT 1 | | | Unit COMMITMENT 2 | | |
|---|---|---|---|---|---|---|---|
| | Unit | Operating Period | Start-Up Cost ($) | Operating Cost ($) | Operating Period | Start Up Cost ($) | Operating Cost ($) |
| (250MW--3 Units) PN250 | 1 | 0000--2400 | 0 | 202,011 | 0000--2400 | 0 | 215,429 |
| | 2 | 0000--2400 | 0 | 202,011 | 0000--2400 | 0 | 215,429 |
| | 3 | 0000--2400 | 0 | 202,011 | 0000--2400 | 0 | 215,429 |
| (120MW--5 Units) SN120 | 1 | 0430--2400 | 1437 | 79,033 | 0800--2230 | 2476 | 69,640 |
| | 2 | 0600--2300 | 2015 | 72,607 | 0830--2100 | 2476 | 60,306 |
| | 3 | Unused | 0 | 0 | 1000--1630 | 3408 | 32,104 |
| | 4 | Unused | 0 | 0 | Unused | 0 | 0 |
| | 5 | Unused | 0 | 0 | Unused | 0 | 0 |
| ( 60MW--2 Units) | 1 | Unused | 0 | 0 | Unused | 0 | 0 |
| | 2 | Unused | 0 | 0 | Unused | 0 | 0 |
| ( 60MW--2 Units) | 1 | 0600--2030 | 1358 | 34,325 | Unused | 0 | 0 |
| | 2 | Unused | 0 | 0 | Unused | 0 | 0 |
| LOSS OF LOAD | - | EQ. | 0 | 29,837 | EQ. | 0 | 0 |
| | | | TOTAL OPERATING COST | 826,645 | | | 816,935 |
| | | | CENTS PER KWH | 4.20 | | | 4.15 |

Figure 1.4 Comparison of the daily operating costs

The total investment cost of a transmission system can also be substantial. An average annual investment of some 200 million dollars would be required for a typical 230-kV and 66-kV transmission network development [Ref. 4, P 54]. The comparison of capital costs to transmit firm capacities ranging from 750 MVA to 3000 MVA using transmission voltages at 230 kV and at 400 kV are given in Figure 1.5 [Ref. 5]. The essence of transmission network planning is to search for the least-cost expansion of transmission network within an acceptable reliability over a period of ten to twenty years. In general, the task of the actual planning involves choice of voltage levels; conductor types and sizes; voltage regulation and system fault levels; timing of new substations and substation sizes; network expansion configuration, and interconnection capacities.

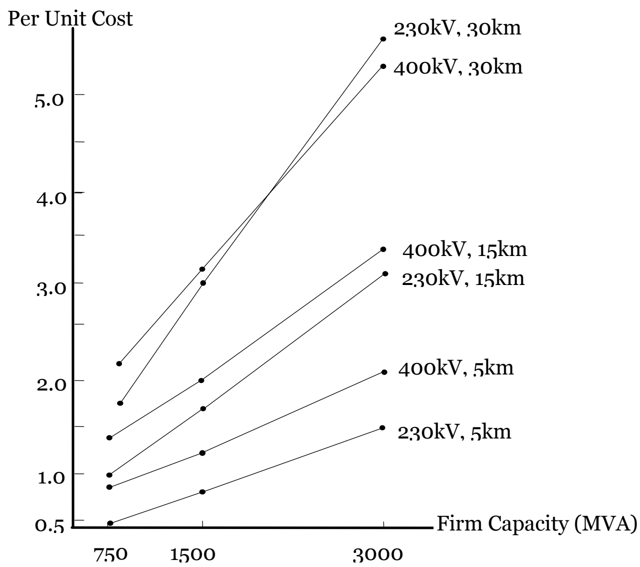


Figure 1.5 Comparison of transmission costs for different voltage levels

In the day-to-day operation, the engineer has to monitor and control the active and reactive power flows. The transmission voltage has to be regulated by switching on/switching off reactors at different times of the day. He also needs to ensure that all the generators are operating within their active and reactive capability limits. A load flow simulation at 1030 hours for a model 230-kV transmission network is shown in Figure 1.6. In this network, the engineer has to resolve three overloading circuits (one circuit from SNK to UJR and two other circuits from PSR to JUR) and a reactive limit violation at power station SNK. During fault conditions, the engineer has to identify the types of fault, isolate fault and restore supply to as many areas as possible within the shortest possible time [Ref. 6].

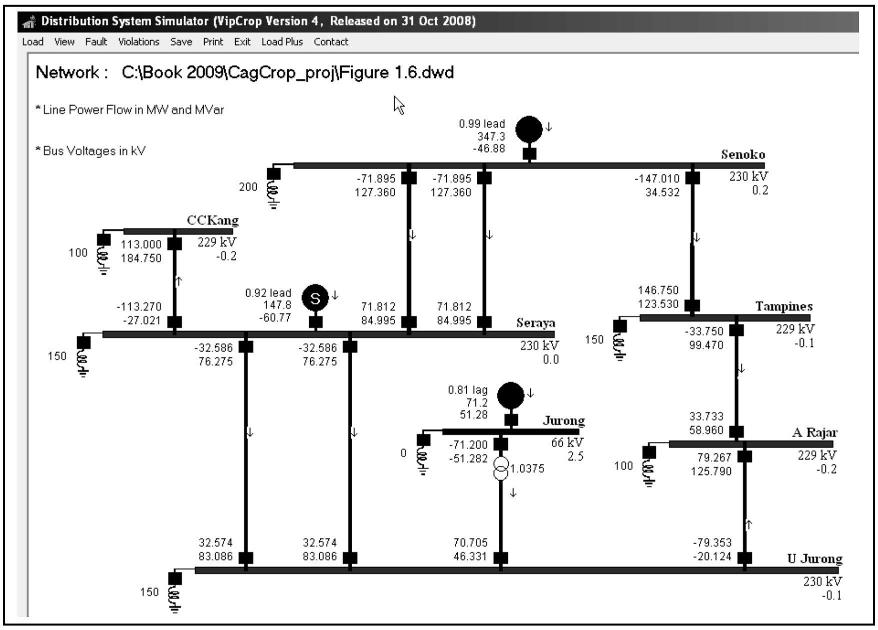


Figure 1.6 Load flow simulation at 1030 hours

## 1.4 DISTRIBUTION SYSTEM

The main function of a distribution system is to receive electric power from large, bulk power sources and to distribute electric power to consumers at various voltage levels with acceptable degrees of reliability. The most commonly used nominal voltages are 3.3 kV, 6.6 kV, 11 kV, 22 kV and 33 kV. Depending on the load density and the annual growth rate in a service area, the tendency is toward higher distribution voltage especially for urban areas which have an increasing consumption of electrical energy. By selecting a higher distribution voltage, appreciable savings in overall cost can be achieved if the load density within the service area is high. In Singapore, the primary distribution voltages adopted are 22 kV and 6.6 kV, and the secondary distribution voltage at utilisation level is 400 V. In the city centre or industrial estate, where the load density is high, it is distributed at 22 kV and stepped down directly to the utilisation voltage through 22/0.4 kV transformers. In areas where the load density is low, it is distributed at 6.6 kV and stepped down through 6.6/0.4 kV transformers. Part of a typical distribution network consisting of 22 kV/LV, and 6.6 kV/LV is shown in Figure 1.7. LV refers to the low-voltage system of 400 V.

A standard 66/22-kV intake substation has two to three incoming 66 kV circuits preferably to be fed from two separate sources. Depending on the size of the service area and the maximum estimated load in the area, the installed capacity of each intake substation in Singapore is either 150 MVA consisting of two 75-MVA 66/22-kV transformers, or 62.5 MVA consisting of two 31.25-MVA 66/22-kV transformers. Normally, each intake substation is built with a spare capacity for the third transformer to be installed when required. The standard size of the 22/6.6-kV transformer is 10 MVA and the 22-kV/LV or 6.6-kV/LV transformer is 1 MVA. The standard cable sizes are 10 MVA and 15 MVA for 22-kV circuits and 5.5 MVA for 6.6-kV circuit.

The distribution system should provide service with a minimum voltage variation and a minimum supply interruption. The overall system cost including construction, operation and maintenance of the system should be as low as possible and be consistent with the quality of service required in the load area. The system should be flexible to allow expansion in small increments so as to meet changing load conditions.

### 1.4.1 Schemes of Connection

The schemes of connection in a distribution network normally consist of radial, ring and network systems. In a radial circuit arrangement, an outgoing main feeder commences from the intake substation and feeds directly into the area in a multi-drop configuration as shown in Figure 1.8. The current magnitude is the greatest from substation A to B and then it gradually reduces along the cable route until it reaches its minimum loading level from substation E to substation F. As there is no duplication of equipment, it has the lowest capital cost as compared with other schemes of connection. However, the reliability of service continuity in a radial system is low. A cable fault occurring between substations A and B will result in the total supply failure from substations B to F, and the supply can be restored only after the cable from substations A to B has been repaired.

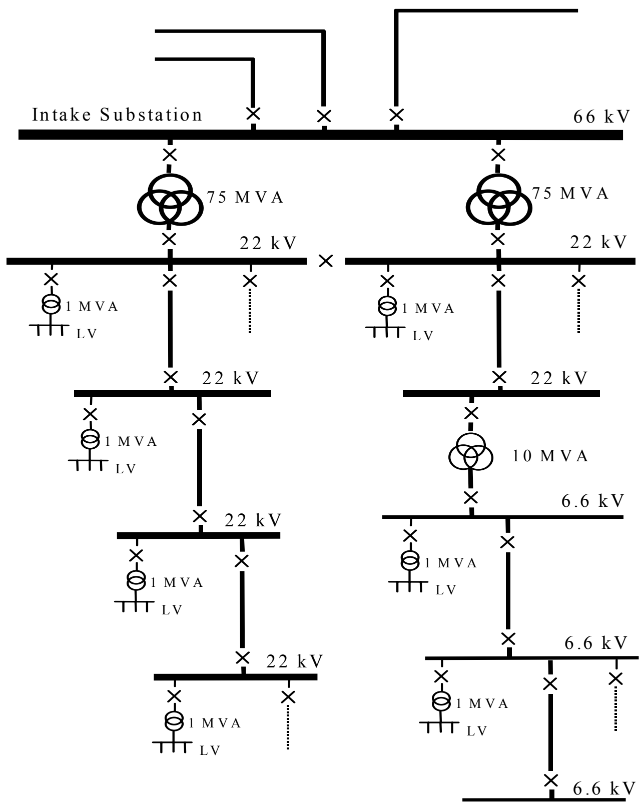


Figure 1.7 Part of a typical distribution network

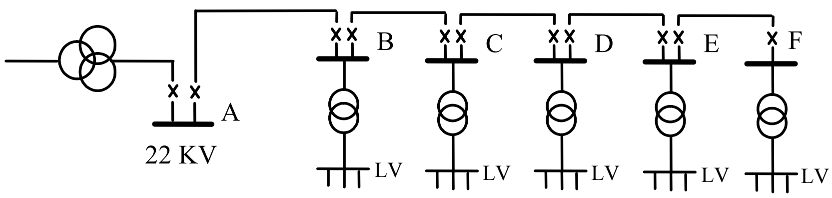


Figure 1.8 Radial circuit arrangement

To provide a better continuity of supply and to reduce the time taken in restoration of supply, the connection in the 22-kV network is normally arranged in a ring configuration as shown in Figure 1.9. The ring circuit commences from the intake substation, makes a loop through the area to be served and returns to the intake substation. There are normally five ring circuits from one intake substation and in each ring circuit, there are typically five 22/0.4-kV substations.

For illustration purposes, as shown in Figure 1.9, there are only two ring circuits. In each ring circuit, it provides a two-way feed to each 22/0.4 kV substation and therefore, at any one time, the tripping of any one circuit will not interrupt any supply in the whole ring. However, in order to enable the continuity of service, the cable size in each section of the ring should have adequate capacity to carry all the entire load in one ring. In other words, under normal conditions where there is no circuit out of service, all the circuits in a ring will be loaded to only 50%. To enhance the reliability supply and to cater for the loss of the intake substation, each ring circuit can also have a stand-by alternative feed from a separate source as shown in Figure 1.9. A 22-kV ring circuit arrangement integrating two separate 66/22-kV sources is shown in Figure 1.10 [Ref. 7]. A standby circuit which has one end at normally open position linking two ring circuits from separate sources such as the circuit between substations 'a' and 'aa' or substations 'g' and 'rr' is known as an interconnector network cut. This standby network can be closed to restore supply during the failure of one 66/22-kV source. A model 22/6.6-kV cable distribution network with two 31.25-MVA, 66/22-kV incoming transformers extracted from part of an urban utility system is shown in Figure 1.11. [Ref. 8] The loading in each circuit is given in MVA and at each substation, there are two 22/0.4-kV transformers or two 6.6/0.4-kV transformers which are not shown in the diagram.

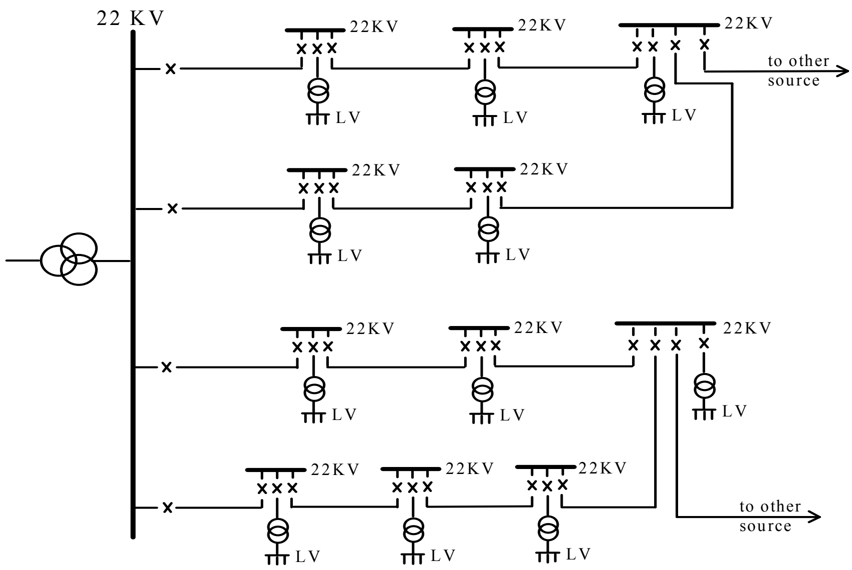


Figure 1.9 A typical ring circuit arrangement

### 1.4.2 Main and Backup Protections

The reliability of modern power distribution system has been increased by operating the network in a ring configuration and by interconnecting two or more sources. The incoming transformer, busbar at each intake substation, or each feeder in the network is normally provided with a main protection (also known as unit protection) and a backup protection on overcurrent and earth fault. The zones of each unit protection are shown in Figure 1.12. Once a fault is detected in the protective zone, all the breakers in the respective zone will be opened to isolate the fault. However, at times, supply interruption is still unavoidable mainly due to fault or overloading in the distribution network. If the fault can be detected and cleared by the unit protection, the fault is usually confirmed to be within the zone of the unit protection. Unfortunately, unit protection may not operate correctly or may not be installed for every zone in the distribution network. In this case, the clearing of the fault will have to depend on the backup overcurrent and earth fault protection. In an interconnected network, it is always a difficult task to grade the overcurrent/earth fault protection to satisfy fault discrimination at every location. Thus, there may be more breakers tripped than necessary to clear a fault and that the fault location may be difficult to determine. In these situations, the operation engineer has to rely on his knowledge of the distribution system, logical thinking and judgment to diagnose the type of faults and its location.

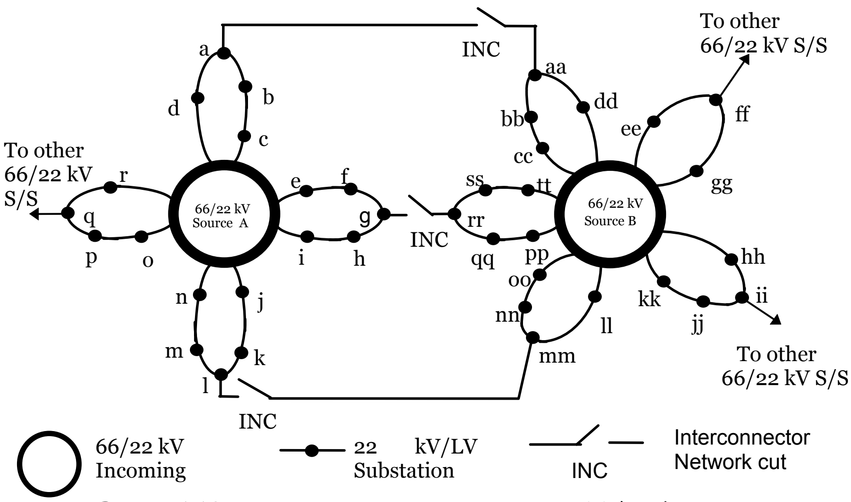


Figure 1.10 Ring circuits integrating two 66/22 kV sources

## 1.5 LOW-VOLTAGE SYSTEM

A low-voltage (LV) system refers to distribution voltages below 1000 V. Typical nominal voltages in this range are 240, 380, 400, 415, 440, 480, 550 and 600 V. In Singapore, a LV system refers to the three-phase four-wire system of 400 V between line-to-line, and 230 V between each line to neutral. LV is not only the distribution supply voltage, it is also the utilisation voltage of most of the electrical appliances. Consumers whose incoming supply is 22 kV or 6.6 kV will have to design and install their own HT and LV systems [Ref. 9]. For consumers taking LV supply from the utility, the LV system prior to incoming supply will be managed by the utility and these consumers have to design and install only their own internal LV network. Thus, both the utility and the consumers have to be involved in the design, installation and maintenance of the LV systems. Although individual LV construction schemes are small, the large number of such jobs carried out each year tends to absorb high capital and design resources in the industrial and commercial LV systems.

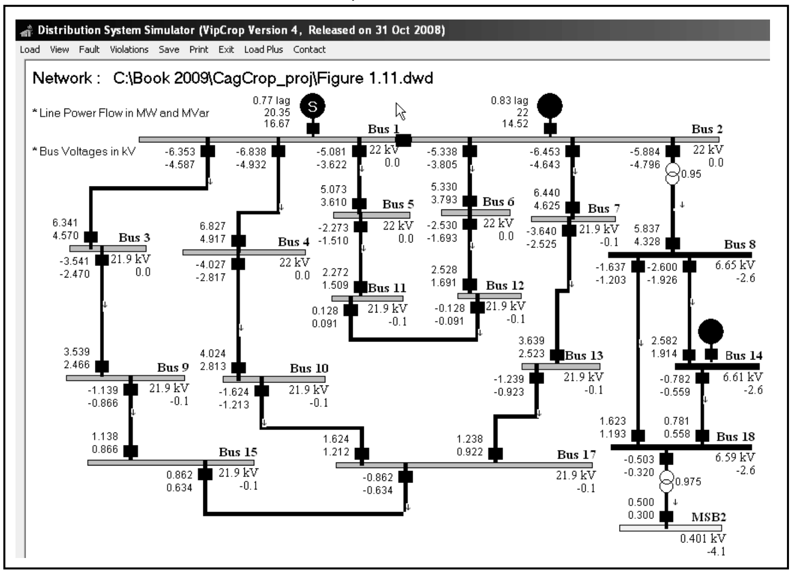


Figure 1.11 A model 22/6.6 kV distribution network

### 1.5.1 Utility LV Networks

The method of connection from the utility's LV network to each LV consumer depends mainly on the types of the existing network, load density and local utility's regulations. The practices adopted by one utility may not necessarily be the most economical under different circumstances for another utility. In Singapore, depending upon consumer's load requirements, electricity supply will be provided according to Table 1.2 [Ref. 9, P 9].

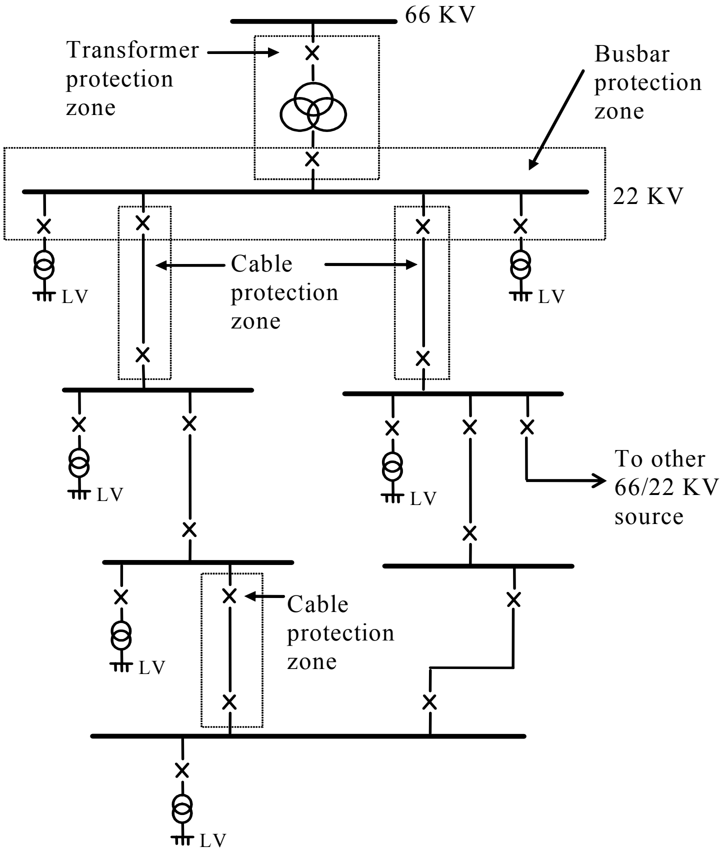


Figure 1.12 Zones of Unit Protection

**Table 1.2 Types of Electricity Supply**

| Maximum capacity (kVA) | Voltage (V) | Circuit Arrangement (phase) | (wire) |
|---|---|---|---|
| 23 | 230 | 1 | 2 |
| 2,000 | 400 | 3 | 4 |
| 30,000 | 22,000 | 3 | 3 |
| >30,000 | 66,000 | 3 | 3 |

For consumers taking supply at 22 kV or 66 kV, service connection will be fed directly from the utility's distribution network at the appropriate voltage levels. For consumers taking supply at 400 V at 1000 kVA, the supply will be fed directly either through a 22/0.4-kV or 6.6/0.4-kV transformer as shown in Figure 1.13. Most of the consumers taking LV supply less than 1,000 kVA will be fed through the utility's LV network. A typical 1,000-kVA LV board with six outgoing circuits is shown in Figure 1.14. Each outgoing circuit is a 4-core 300 mm$^2$ copper conductor XLPE cable protected by a 500-A fuse feeding a number of overground (OG) boxes in a radial configuration. Each OG box has five feeder units, consisting of one incoming feeder from the LV board, another feeder connecting to the next OG box and three service feeders each connected directly to one consumer or a group of consumers as shown in Figure 1.15.

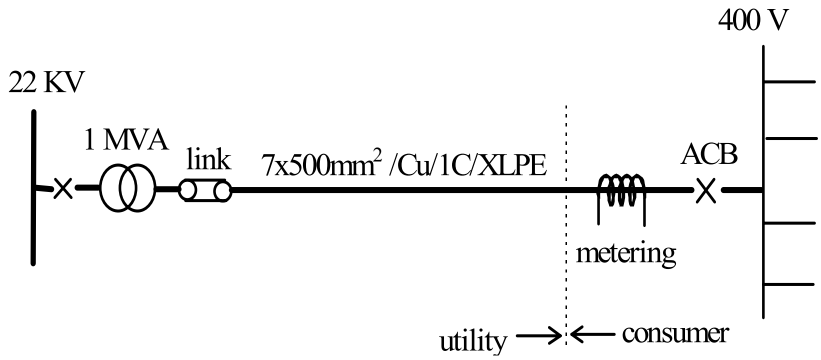


Figure 1.13 LV supply fed directly from transformers

The scheme of connection in the LV network is normally arranged in a ring configuration. However, each ring circuit is operated radially through an open link commonly known as network cut, as shown in Figure 1.16. Each network cut can be closed to provide an alternative feed to each radially operated ring circuit to facilitate cable outage due to fault or for maintenance. As shown in Figure 1.16, there are two additional network cuts known as LV interconnectors linking two LV substations. If one of the 22-kV/LV transformer fails, these LV interconnectors can be closed so that supply originally fed by the faulted transformer can be partially restored by utilising the spare capacity from the other 22-kV/LV transformer.

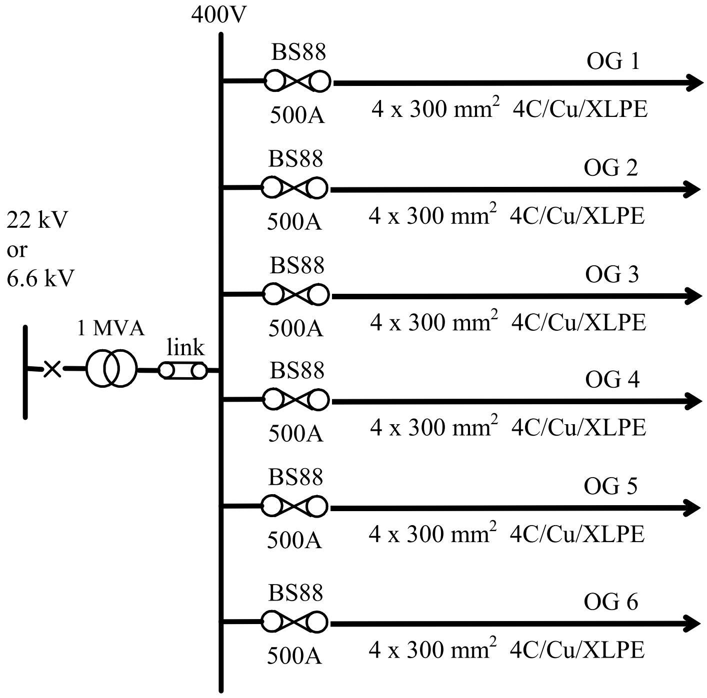


Figure 1.14 A typical LV board

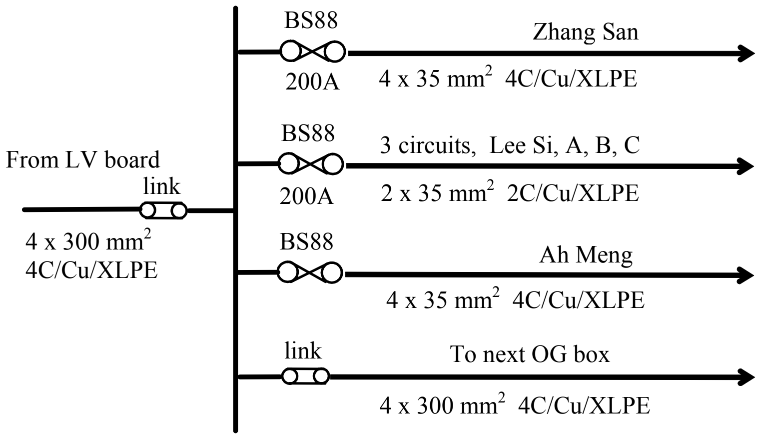


Figure 1.15 A typical OG box

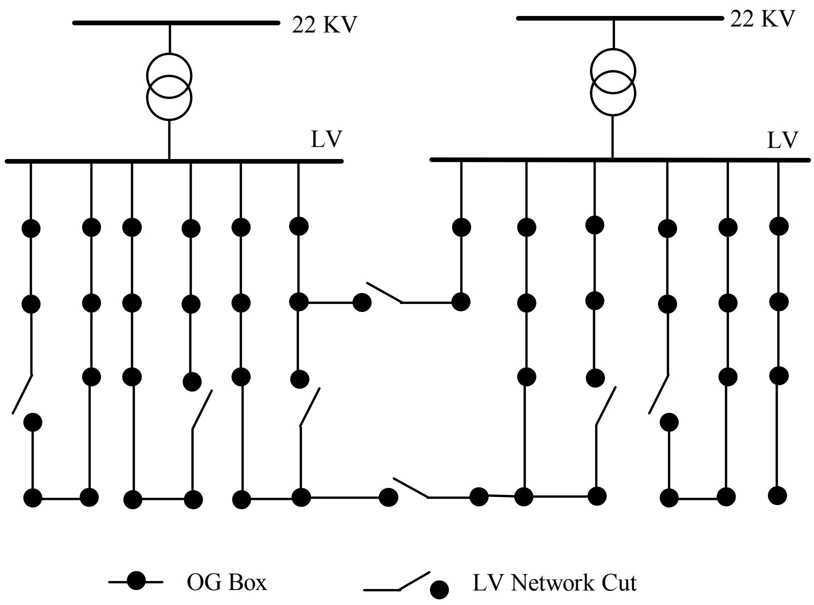


Figure 1.16 Radially operated LV network

### 1.5.2 Consumer Installations

The installation earthing and the LV system should be so arranged such that on the occurrence of a fault on any appliance, the voltage of any conductive part likely to be touched by an individual should not reach a dangerous level. In addition, every circuit should be protected adequately against overload and short-circuit currents. Many accidents and injuries that occur in electrical installations are due to insufficient knowledge of the electrical personnel in wiring system. Knowledge and appreciation of the implications of the wiring regulations or code of practice [Ref. 10], coupled with the rationale and principles covering the LV system will ensure that requirements for the safety of persons and property are met, and the LV system is designed and operated properly at minimum cost.

The LV system covers the design of the whole range of consumer installations from as low as 15 kVA to 2000 kVA for domestic, industrial and commercial buildings. A simple LV installation of a 300 kVA, 2-level shop-house is shown in Figure 1.17 and its tenant distribution boards in Figure 1.18. The LV installation of a 2,000-kVA, 8-level hotel building is shown in Figure 1.19. Due to voltage drop and economic reasons, for every high-rise commercial building over 24 levels, the electrical installation is normally implemented using an HV/LV system. For example, the electrical supply of a 72-level commercial building distributed by a combination of 22 kV and LV systems is shown in Figure 1.20. There are two 15-MVA, 22-kV feeders feeding directly from the utility's 22-kV distribution system to the consumer's intake 22-kV substation which is located at basement level B3. The other 22-kV substation is located at level L22 and it is fed from the intake 22-kV substation B3 using two 15-MVA 22-kV circuits. The supply at utilisation voltage is obtained from 22/0.4-kV transformers located at various strategic levels such as level B2, level L9, level L35 and level L61 as shown in Figure 1.20.

All the 22/0.4 kV transformers are fed directly from the two 22-kV substations at B3 or L22 using the transformer/feeder circuit arrangement and there is no 22-kV switchgear at various strategic floors. The LV supply will then be fed from the various strategic floors upwards or downwards to individual levels using busways or feeder risers.

### 1.5.3 Scope of This Book

This book covers the principles and designs related to LV systems in buildings. At the device level, it covers the principles, characteristics, specifications and the relevant industrial standards of cables and various types of protective devices such as miniature circuit-breakers, moulded-case circuit-breakers, air-circuit-breakers, residual current operated circuit-breakers and fuses. Code of practice and application guides for the selection of various types of devices, the design of various circuits and the sizing of conductors are also introduced. At the system level, the source earthing system and the consumer earthing system are explained and reasoned with reference to the IEE wiring regulations and the relevant code of practice for earthing.

Earth fault protection and protection for electric shock are illustrated with application examples. Sources of fault current and the approach and formulae for the calculation of various types of short-circuit currents which may occur in the LV system are given and described in details using practical examples. Step-by-step design procedures and examples are provided and the applications of computer-aided design to eliminate the routine and repetitive design works are introduced. The suggested approach of the computer simulation tests under a series of loading conditions enables the designers to visualise the performance of the LV system designed by them and to experience any consequences due to the design errors.

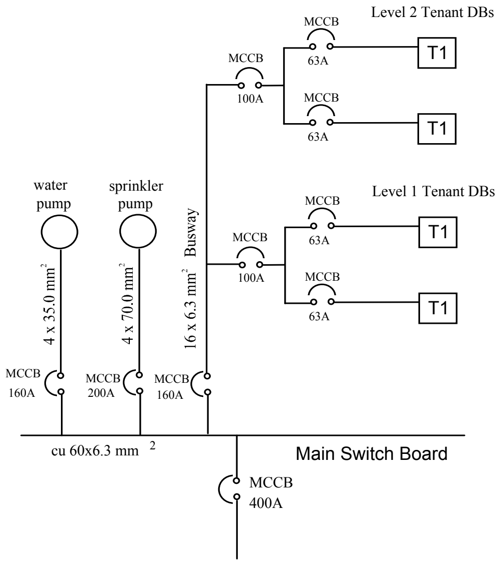


Figure 1.17 Single-line diagram for a 2-level shophouse

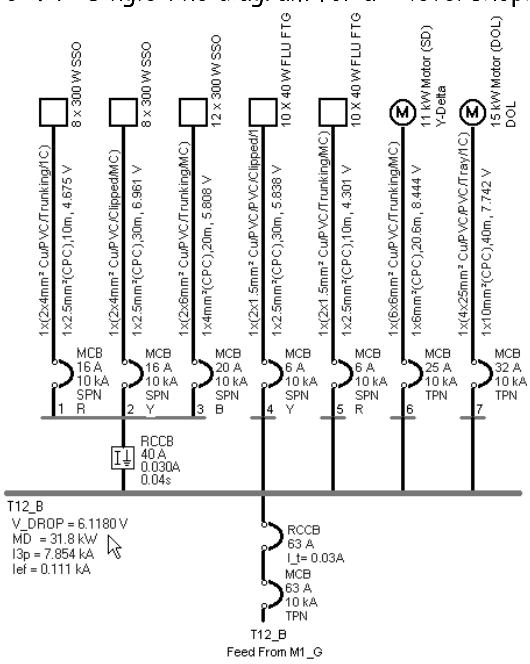


Figure 1.18 Tenant distribution board T1

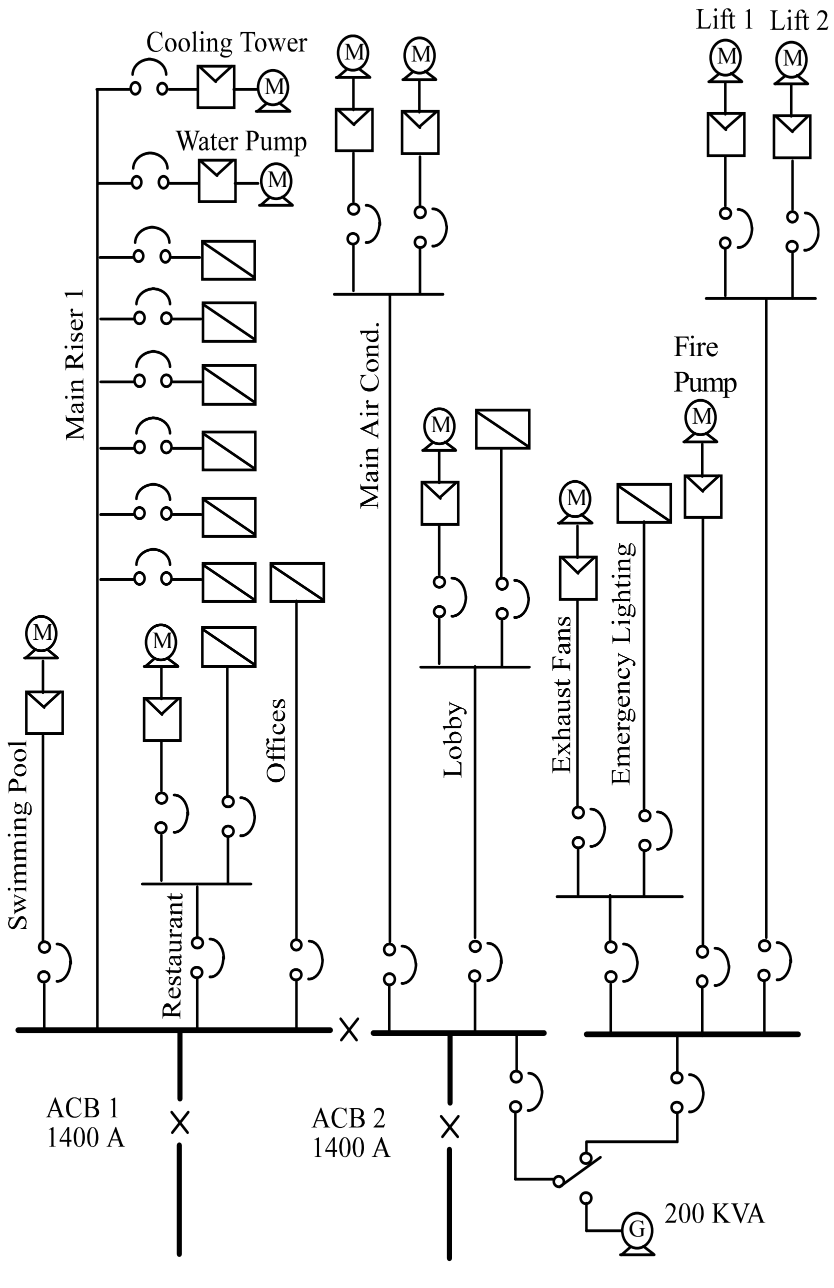


Figure 1.19 LV supply of an 8-level hotel building

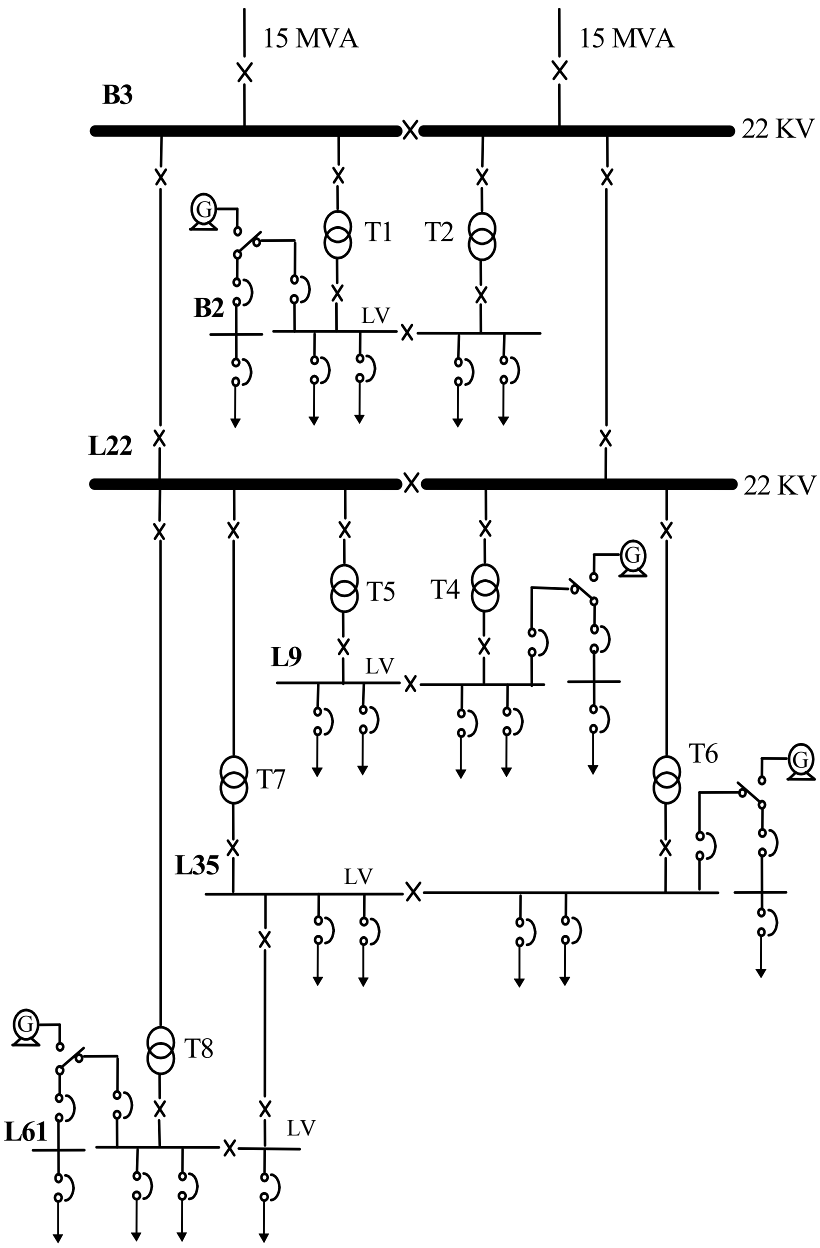


Figure 1.20 22 kV/LV supply of a 72-level building

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**CHAPTER 2**

# CIRCUIT BREAKERS

To provide adequate overcurrent protection, each circuit should be equipped with a circuit breaker for automatic interruption of supply in the event of overload current and fault current. The circuit breaker installed in a circuit should break any fault current flowing in the circuit before such current causes danger due to thermal or mechanical effects produced in the circuit or the associated connections. The breaker shall satisfy the condition that the breaking capacity should be greater than or equal to the prospective short-circuit current or earth fault current at the point where the breaker is installed. A circuit breaker is a mechanical switching device which should fulfil the following specifications .

- It should be capable of being safely closed in on any load current or short-circuit current within the making capacity of the device.
- It should safely open any current that may flow through it up to the breaking capacity of the device.
- It should automatically interrupt the flow of abnormal currents up to the breaking capacity of the device.
- It should be able to carry continuously any current up to the rated current of the device.

## 2.1 SPECIFICATION AND OPERATION

The rated current ($I_N$) of a circuit breaker is the current that it can carry continuously, generally for a duration of more than eight hours. The rated current must not cause a temperature rise in excess of the specified values when the ambient temperature is between $-5^0C$ to $40^0C$. Different temperature rise limits are specified for different parts of a circuit breaker. A circuit breaker will not operate (trip) if the current passing through it is 105% to 113% of its rated current [Ref. 1, P 23], [Ref. 2, P 27]. It will take one to two hours to trip if the current passing through it is 130% to 145% of the rated current [Ref. 1, P 23, Ref. 2, P 27].

**Breaking Capacity**

The breaking capacity of a circuit breaker is the maximum current (in r.m.s.) that flows through the breaker and the breaker is capable to interrupt at the instant of initiation of the arc during a breaking operation at a stated voltage under prescribed conditions. The breaking capacity is usually expressed in kA or MVA. Typical values range from 3 kA to 43 kA.

**Making Capacity**

The making capacity of a circuit breaker is the maximum current that will flow through the breaker and the breaker is capable of withstanding at the instance during a closing operation at a stated voltage under prescribed conditions. Typical values range from 1.4 to 2.2 times the r.m.s. value of the breaking capacity.

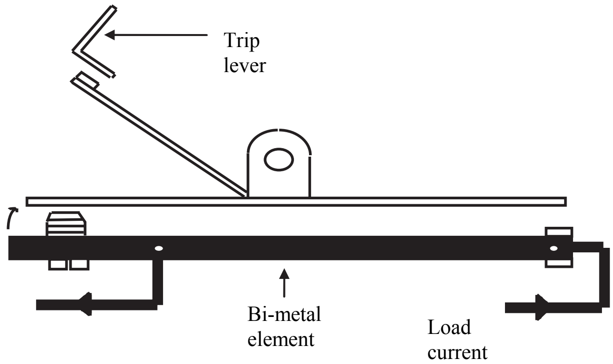



Figure 2.1 Principle of tripping by a bi-metal

**Tripping Mechanisms**

To provide overload and short circuit protection, most circuit breakers have a bi-metallic overload trip and an electromagnetic trip. The overload trip is a thermal trip which works with a bi-metal. The bi-metal consists of two metal strips of different temperature coefficients of expansion which are rolled one on the other. The bi-metal is deflected when heated by the current flowing through it. Figure 2.1 shows a schematic drawing of this operation. The deflection of the bi-metal depends on the current magnitude and its duration. After a pre-determined deflection, which means after a certain time depending on the current magnitude, it will activate the tripping mechanism. The deflecting bi-metal directly opens the contacts or gives a signal to the switching mechanism to open the contacts. The characteristic of the thermal trip can be widely influenced by the design of the material and the shape of the bi-metal. The bi-metal can be directly heated by the load current flowing through it or it can be heated indirectly by a heater winding. The time-current characteristic of the thermal trip is illustrated in Figure 2.2.

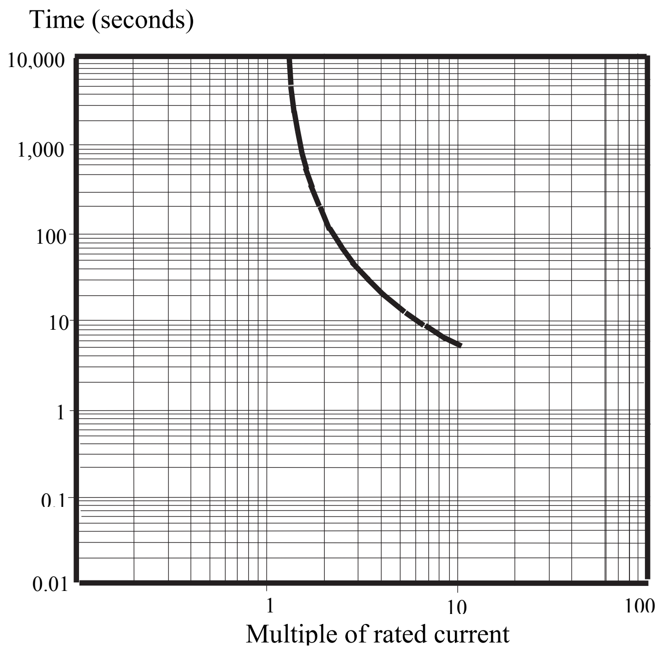



Figure 2.2 Time-current characteristic of a thermal trip

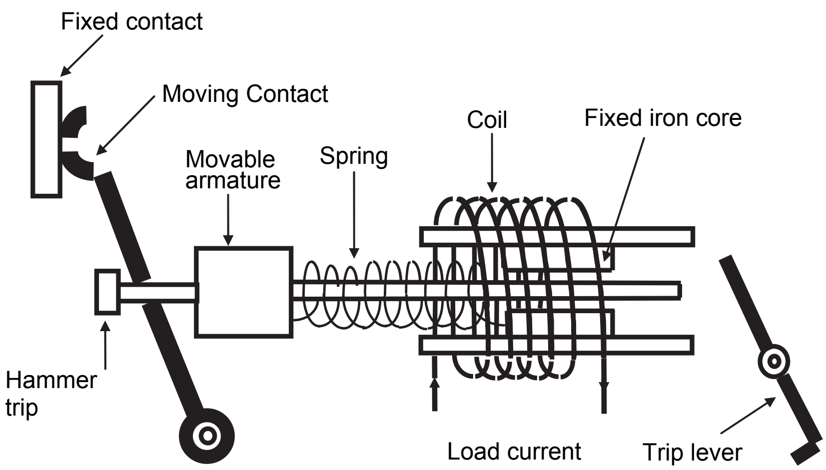



Figure 2.3 Principle of tripping by an electromagnetic device

As shown in Figure 2.3, the electromagnetic trip consists essentially of a coil through which the load current flows. Inside this coil, there is a fixed iron core with a movable armature. If the current exceeds a pre-specified limit, the armature will be attracted against the force of the spring. The switching mechanism is actuated by the lever on the right hand side and provides the opening of the breaker contacts. Furthermore, on the left side, a hook which is provided for the direct opening of the contacts will accelerate the speed of operation.

Figure 2.4 shows the time-current characteristic of the electromagnetic trip. With lower overload currents, only the thermal trip is active. For higher current, as shown in Figure 2.4, the electromagnetic trip operates at a current which is equal to 4 times the rated current. In this sample curve, the breaker must not trip for a currrent less than 4 times the rated current, and it must trip for a current equal to or greater than this value. The tripping time is about 0.05 s. For higher current, the operating time is shorter and is between 0.05 s to 0.01 s.

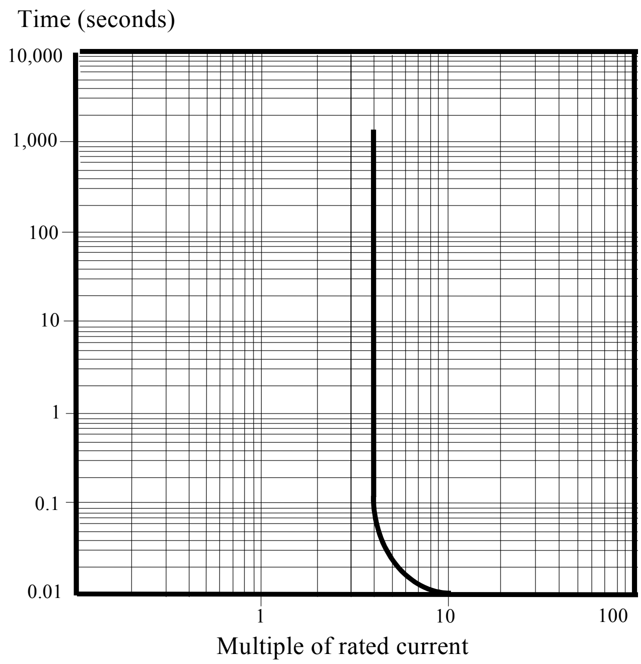



Figure 2.4 Time-current characteristic of an electromagnetic trip

The manufacturer of a circuit breaker can modify the characteristic of the bi-metal tripping curve and can also decide the magnitude of the current for the electromagnetic trip. Figure 2.5 shows the combined curve of two tripping devices whose characteristics are shown in Figure 2.2 and from Figure 2.4.

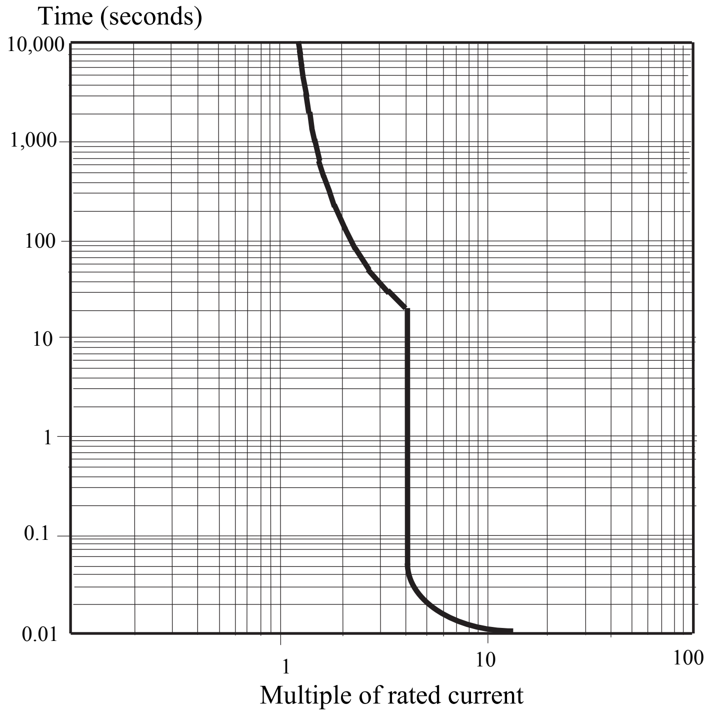



Figure 2.5 Time current characteristic of the combined tripping

**Principle of Arc Extinction**

The contact system comprises separate main and arcing contacts as shown in Figure 2.6. The arcing contacts are fitted with arc runners to assist the upward movement of the arc into the arc chute. The arc, initiated across the arcing contacts, is forced upwards by the electromagnetic forces and by the thermal action. The roots of the arc travel rapidly along the arc chute. Here, its length is rapidly and considerably extended by the splitter plates in the arc chutes. The arc is thus extinguished by lengthening, cooling and splitting.

To interrupt short-circuit current, two different methods of breaking are used, namely the zero point extinguishing system and the current limiting system. The zero point extinguishing system can only be used in a.c. systems and the current-limiting system can be used for both d.c. and a.c. systems. Figure 2.7 shows the difference between the two systems by comparing the arc voltage and the effective short-circuit current.

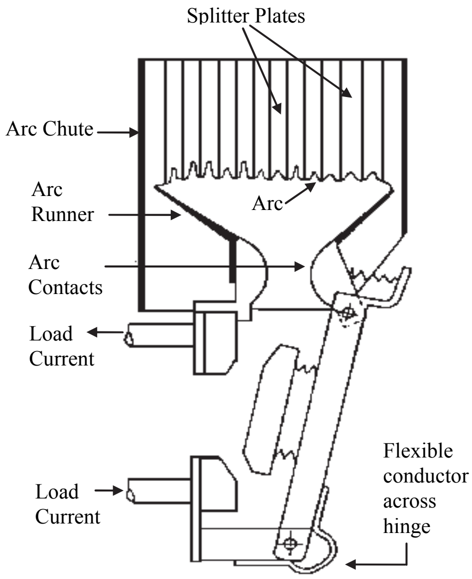


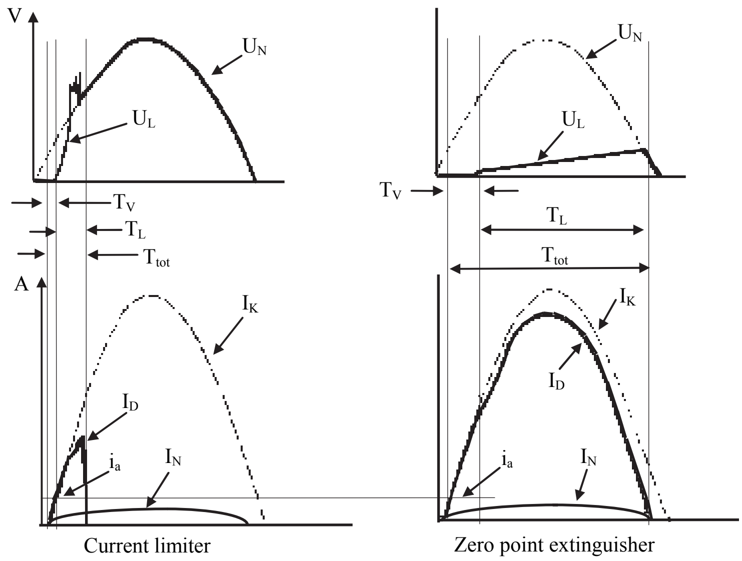

Figure 2.6 Principle of arc extinction

**Industrial Standards**

Circuit-breaker standards are numerous as most countries have their own national standards for each type of circuit-breakers. However, progress in the International Electrotechnical Commission (IEC) has led to the agreed IEC Standards to be the base of their own national standards. The most generally applicable IEC standard for low voltage circuit-breakers is IEC 947-2 : 1992 [Ref. 3].

The current British Standard (BS) has integrated with the European Standards (EN) and is now abbreviated as BS EN. The latest British standard for low-voltage circuit breakers is BS EN 60947-2 : 1992 [Ref. 1]. In Singapore, Singapore Standards (SS) are referred along with IEC Standards and British Standards.

Low voltage circuit-breaker standards in the United States of America are in general not equivalent to IEC specifications, and their ratings and test criteria are not directly comparable. The relevant standards are issued by the American National Standards Institute (ANSI), the Institute of Electrical and Electronics Engineers (IEEE), Underwriters Labs (UL) and the National Electrical Manufacturers Association (NEMA).




| | |
|---|---|
| $U_N$ | = rated voltage |
| $U_L$ | = arc voltage |
| $I_K$ | = prospective short-circuit current |
| $I_D$ | = short-circuit current limited by the miniature circuit breaker |
| $I_N$ | = rated current |
| $T_V$ | = pre-arcing mechanical operating time |
| $T_L$ | = arcing time |
| $T_{tot}$ | = total time required for interrupting a short circuit (break time) |
| ia | = tripping current |

Figure 2.7 Comparison of two methods of breaking

## 2.2 MINIATURE CIRCUIT-BREAKERS

The miniature circuit-breakers (MCB) are used extensively for the protection of final circuits in domestic and commercial installations. They offer these circuits better protection, particularly when overload conditions are being considered than the fuse alternatives. Most MCBs are provided with two types of tripping mechanisms, namely the bi-metallic thermal trip and the electromagnetic trip. With the electromagnetic type of tripping, the switch can be closed again immediately after it has tripped. Obviously, it may trip again if the cause is still there. With the thermal trip, the switch cannot be closed again for a minute or two as the heater element and the bi-metallic strip have to cool down first.

MCBs are available for both single-phase and three-phase circuits. In a single-phase circuit, a single-pole MCB may be used in the live conductor or a two-pole MCB connected in the live and neutral conductors. Three or four-pole MCBs are used for protection in three-phase supplies. If a fault current flows through even one pole of an MCB, all the three poles will be operated. This prevents single phasing, which may result in damage to 3-phase motors. A cross-sectional view of a typical single-phase MCB is shown in Figure 2.8.

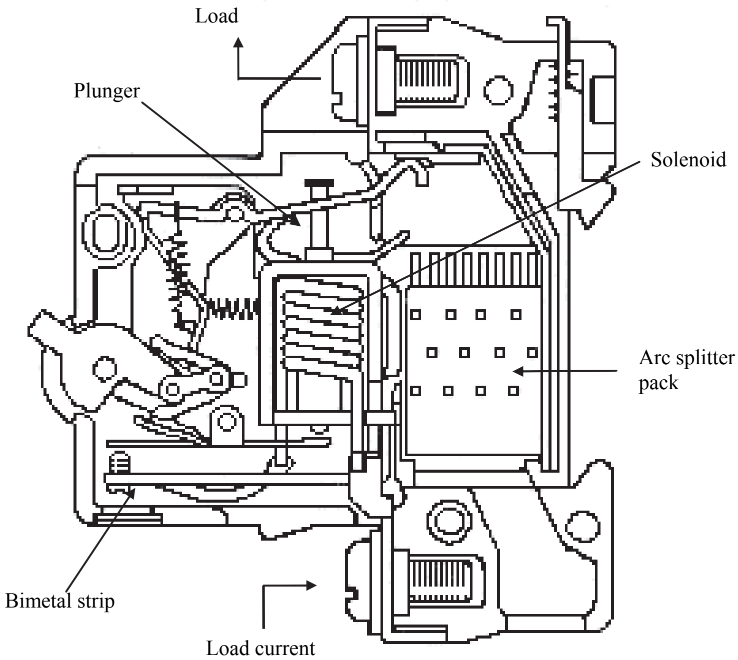



Figure 2.8 Cross-sectional view of a MCB

The main standard for MCBs is BS 3871 : Part 1 [Ref. 4]. This standard covers MCB ratings up to 100 A, breaking capacities up to 9 kA and voltage ratings up to 415 V. This standard, however, has been withdrawn from 1 July 1994 and is superseded by BS EN 60898 : 1991 [Ref. 2] which is similar to IEC 898 : 1995 and SS 359 : 1996 [Ref. 10]. The BS EN 60898 covers MCBs having a rated voltage not exceeding 440 V, a rated current not exceeding 125 A and a rated short-circuit capacity not exceeding 25 kA. These circuit-breakers are used for protection in electrical installation in buildings and similar applications. They are designed for use by uninstructed people and to be maintenance free.

**Rated Voltage**

Based on BS EN 60898 [Ref. 2], the preferred values of rated voltages are 400 V/230 V. Values of 380 V/220 V and 415 V / 240 V should progressively be superseded by the values of 400 V / 230 V.

**Current Rating**

The preferred values of rated current are :

6, 8, 10, 15, 16, 20, 25, 32, 40, 50, 63, 80 100 and 125 A.

**Short-circuit Capacity**

Instead of specifying the breaking capacity, the standard specifies the values of the short-circuit capacity. The short-circuit capacity refers to the prospective current expressed by its r.m.s. value which the MCB is designed to make (close), to carry for its opening time and to break under the specified conditions. The standard values of rated short-circuit capacity are 1.5, 3, 4.5, 6 and 10 kA. For values above 10 kA, up to and including 25 kA, the preferred value is 20 kA.

**Instantaneous Tripping**

Based on the standard range of instantaneous tripping, MCBs are classified into three types given in Table 2.1. In BS3871, they are classified as type 1 (2.7 $I_N$ to 4 $I_N$ ), type 2 (4 $I_N$ to 7 $I_N$ ) and type 3 (7 $I_N$ to 10 $I_N$ ). Another older European standard classified them as type L, G and U. Type L is similar to type 1 and types G and U are similar to type 2. In BS 3871:1984, it specifies a category of duty, namely M1 (1 kA), M3 (3 kA), M6 (6 kA) and M9 (9 kA).

**Table 2.1 Range of Instantaneous Tripping**

| Type | Instantaneous Tripping Current |
|---|---|
| B | Above 3 $I_N$ up to and including 5 $I_N$ |
| C | Above 5 $I_N$ up to and including 10 $I_N$ |
| D | Above 10 $I_N$ up to and including 50 $I_N$ |

**Time-current Characteristics**

An MCB shall have a fixed and un-adjustable time/current characteristic calibrated at 30$^0$C given in Table 2.2. Typical time-current characteristics of type C MCBs from 5 A to 100 A are shown in Figure 2.9. These characteristic curves are identical to type C MCBs. By referring to the curve of the 100 A and by transferring the Y-axis from amperes to the multiples of the rated current of the MCB, the generalised time-current characteristic curves are shown in Figure 2.10 incorporating type 1, type B, type C and type 3.

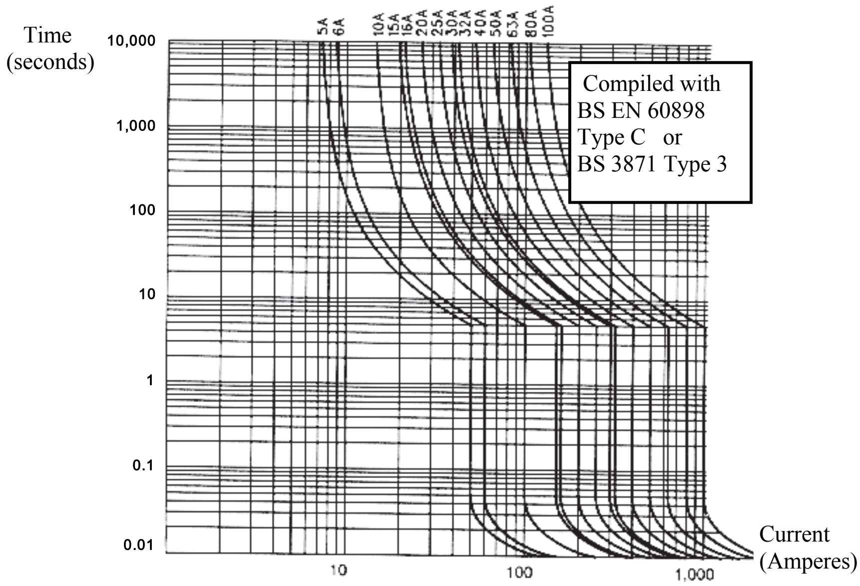



Figure 2.9 Typical time-current characteristic for type C MCB

**Table 2.2 Time-current Characteristics of MCB by BS EN 60898**

| Test | Type | Test Current | Initial Condition | Test Period | Result |
|---|---|---|---|---|---|
| 1 | B, C, D | 1.13 $I_N$ | Cold* | t $\geq$ 1 h (for $I_N \leq$ 63 A)<br>t $\geq$ 2 h (for $I_N >$ 63 A) | No tripping |
| 2 | B, C, D | 1.45 $I_N$ | Right after Test 1 | t < 1 h (for $I_N \leq$ 63 A)<br>t < 2 h (for $I_N >$ 63 A) | Tripping |
| 3 | B, C, D | 2.55 $I_N$ | Cold * | 1 s < t < 60 s ($I_N \leq$ 32 A)<br>1 s < t < 120 s ($I_N >$ 32 A) | Tripping |
| 4 | B<br>C<br>D | 3 $I_N$<br>5 $I_N$<br>10 $I_N$ | Cold * | t $\geq$ 0.1 s<br>(i.e. Instantaneous tripping does not occur) | No tripping |
| 5 | B<br>C<br>D | 5 $I_N$<br>10 $I_N$<br>50 $I_N$ | Cold * | t < 0.1 s<br>(i.e. Instantaneous tripping occurs) | Tripping |

* Cold means without previous loading and at 30$^{o}$C.

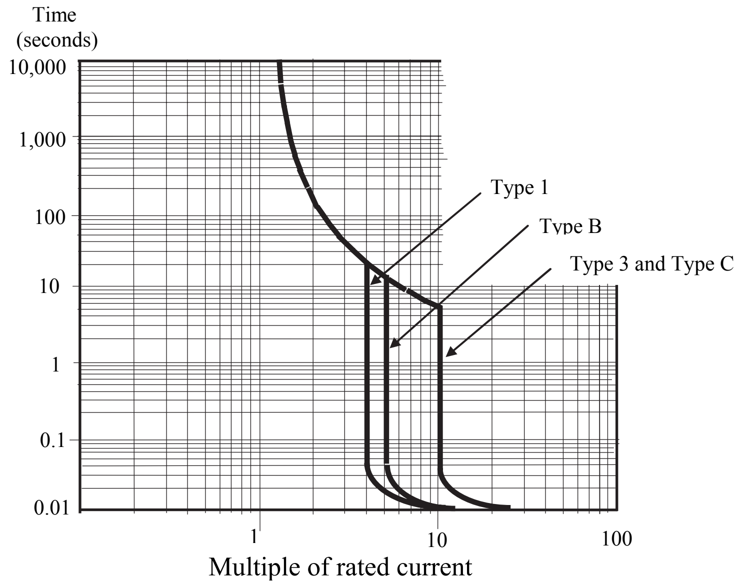



Figure 2.10 Generalised time-current characteristics for MCB

## 2.3 MOULDED CASE CIRCUIT-BREAKERS

Moulded case circuit-breakers (MCCB) are required for installations which have higher fault level or higher current ratings exceeding 125 A. This circuit-breaker is defined as an air-break circuit-breaker, designed to have no provision for maintenance, having a supporting and enclosing housing of mould insulating material, forming an integral part of the circuit-breaker. Improvements in material science and better understanding of factors influencing the performance of MCCBs have led to the production of very compact MCCBs. It has basically three main elements, namely, the tripping unit, the switching unit and a current interrupting unit. The switching unit is normally held at 'on' position by a latching device. Tripping this latch activates the spring which opens the breakers. It has a built-in thermal tripping and an electromagnetic tripping. The thermal element which senses the overload current has inverse time characteristic. The electromagnetic tripping gives instantaneous operation on high fault currents. The sensors operate the tripping mechanism and release the latch.

MCCBs have several advantages over ordinary switches and fuses in the control and protection of circuits and apparatus. They have a repeatable non-destructive performance and are safe in operation under fault conditions. In the case of the triple-pole MCCB, it has built-in mechanism to simultaneously open all three phases for a single-phase fault. All breakers have, as a standard feature, the ability to disconnect automatically under overload conditions, via bi-metallic thermal tripping in each pole. An essential feature of all MCCBs is the quick make-and-break operation known as 'trip-free' operation which is independent of the action of the operating personnel. This feature is particularly important, when the operator closes a circuit on fault.

These circuit-breakers are mainly used to protect main feeder cables for incoming supply to sub-circuits/distribution boards and for large motor circuits. For installation, MCCBs are suitable as free-standing units, or for building into compact cubic-type switchboards. Auxiliary items such as shunt trip elements, status switches, interlocks and motor-operated mechanism for remote operation can all be integrated into the MCCB. The usual current ratings are from 15 A to 1500 A at voltages up to 600 V. The breaking capacity ranges from 10 kA to 65 kA. The built-in thermal tripping and electromagnetic tripping can also be adjusted separately within a given range after installation. An installed 400-A MCCB is shown in Figure 2.11a. The internal construction and the dismantled parts of a 300 A MCCB are shown in Figure 2.11b. Part of a typical switchboard integrating a number of MCCBs is shown in Figure 2.12.


Fig 2.11a An Installed 400-A MCCB

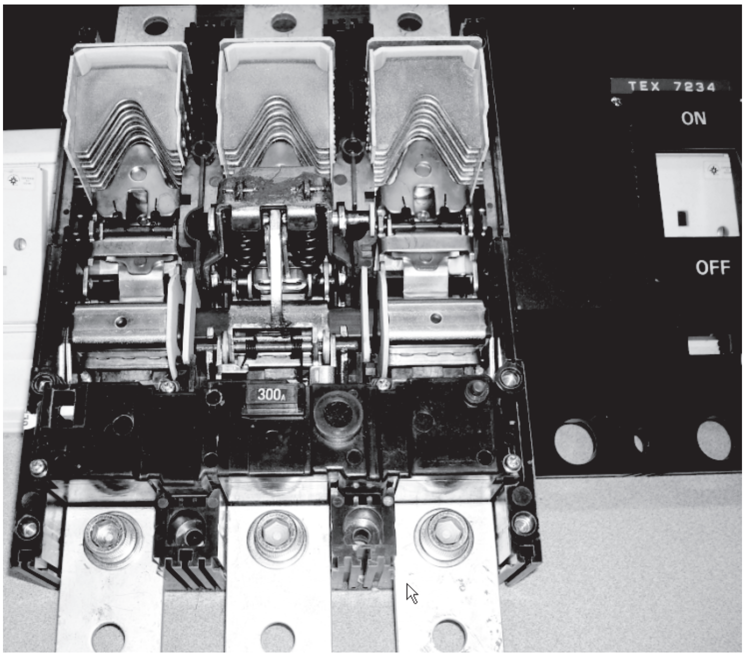



Fig 2.11b  A 300-A MCCB with cover removed

**MCCB Standards**

The main industrial standards for MCCBs are BS EN 60947-1 [Ref. 5] and BS EN 60947-2 [Ref. 1].  These two standards define the characteristics, conditions for operation, methods for testing and the requirements for circuit breakers with rated voltages up to and including 1000 V a.c. or 1500 d.c.  These two standards were derived from IEC 947-1 and IEC 947-2 [Ref. 3].  The older standard BS 4752 was superseded by BS EN 60947.

Under BS EN 60947, there is no specification on the preferred voltage or preferred current.  However, the characteristic of the over-current opening release is specified as follows at a reference temperature of $30^{0}C \pm 2^{0}C$.

(a) At 1.05 times the current setting 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 less than 63 A, the duration of 2 hours should be reduced to 1 hour.

As there are no other standard values specified in BS EN 60497, the followings are some typical technical data for reference.

| | |
|---|---|
| Current rating | : 10, 16, 20, 32, 40, 50, 63, 80, 100<br>200, 300, 400, 630, 800, 1250 A |
| Rated voltage | : 380, 400, 415 V |
| Rated breaking capacity | : 10, 20, 25, 35, 65, 85 kA (r.m.s.) |
| Rated making capacity | : 17, 44, 53, 63, 84, 143 kA (peak) |

Figure 2.12 Part of a switchboard integrated with three MCCBs

The time-current characteristic of a typical MCCB is shown in Figure 2.13 indicating the range of adjustments for both the thermal tripping and electromagnetic tripping. Range 'a' refers to an ambient temperature of

$20^0C$ and range 'b' refers to $40^0C$. Range 'c' refers to the magnetic release at 5 $I_N$ and range 'd' refers to 10 $I_N$. The design engineer has to specify either range 'c' or 'd' when ordering.

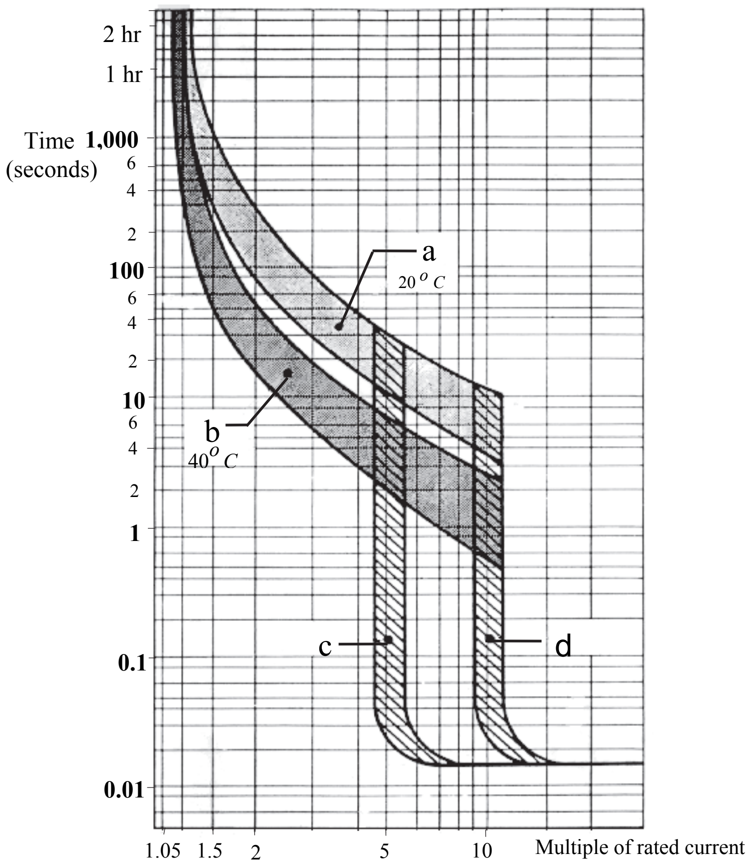



Figure 2.13 Time-current characteristic of a typical MCCB

## 2.4 AIR CIRCUIT-BREAKERS

One of the oldest forms of automatic protective device is the air circuit-breaker (ACB). It consists of an operating mechanism, main contacts, arcing contacts, arc chute and a built-in overcurrent tripping device. The name ACB is normally applied to large breakers that do not fall into the category of MCB or MCCB, although both MCB and MCCB are also air-break circuit-breakers. The ACBs are characterised by their sturdy construction, ample electrical clearances, availability in high-current-carrying, interrupting and making ratings. The tripping devices are adjustable to meet the required pick up setting and operating time. Various shapes of time-current characteristics are also available.

The air circuit-breakers are intended primarily for application in main switchboards to protect the incoming circuit fed by either a local generator or the low voltage side of a transformer directly from the power utility. They are also applicable for an individual branch-circuit protection where the highest quality device is required and where special time-current characteristics are necessary for co-ordination. These circuit-breakers are constructed for longer life than the other types of low-voltage circuit breakers and are, therefore, suitable for many more operations. However, unlike the MCCB or MCB, this type of equipment needs regular inspection and maintenance.

Fig 2.14a A 3000-A ACB at operating position

The ACB is currently covered under BS EN 60947 [Ref. 1, Ref. 5] with the same specification as that described in section 2.3 for MCCB. Typically, an ACB manufacturer produces breakers with current ratings in the range 800 to 5000 A and a breaking capacity up to 120 kA. The followings are some typical data for reference.

| | |
|---|---|
| Rated voltage | : 400, 415, 690 V |
| Rated current | : 800, 1250, 1600, 2000, 3200, 5000 A |
| Rated breaking capacity | : 40, 65, 80, 120 kA (r.m.s) |
| Rated Making capacity | : 84, 143, 220 kA (peak) |

A typical 3000-A ACB at loading position is shown in Figure 2.14a and the zoom-in view in Figure 2.14b. A cross-sectional view of a typical ACB is shown in Figure 2.15 and the time-current characteristics in Figure 2.16.

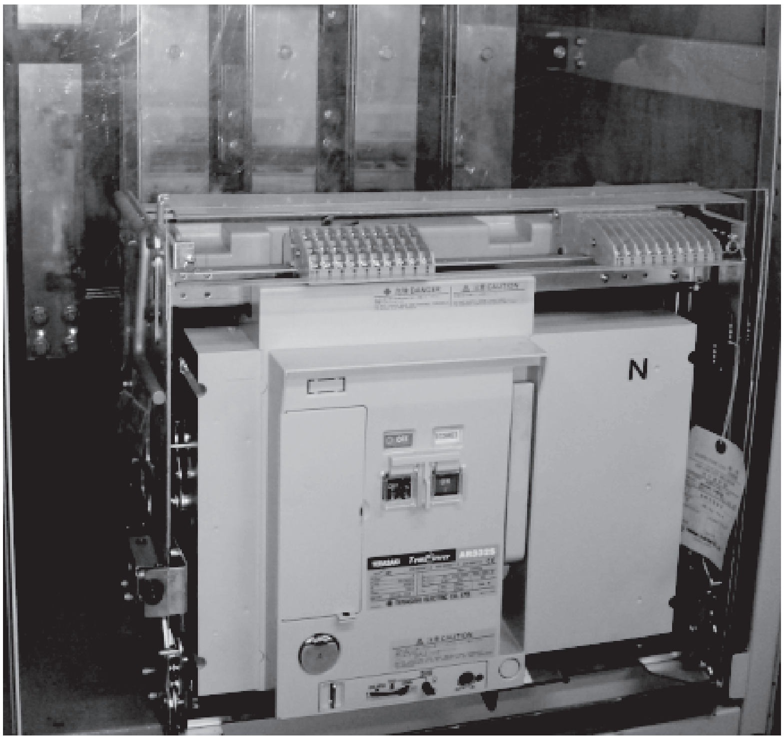



Figure 2.14b A zoom-view of the 3000-A ACB

## 2.5 RESIDUAL CURRENT-OPERATED CIRCUIT-BREAKERS

The Residual Current-operated Circuit-Breakers (RCCB) are primarily designed to protect against 'indirect contact' electric shock. The term 'indirect contact' refers to the contact of the supply voltage indirectly through the touching of the exposed-conductive-part such as the metallic enclosures of electrical appliances, the metallic conduit, trunking or cable tray. These exposed-conductive-parts are insulated from the live conductor and are connected to the earthing terminal and thus, should be at the earth potential. However, during an earth fault, as there is an earth fault current flowing from the live conductor through the exposed-conductive-parts to earth, the exposed metalwork may be at a high potential relative to earth. Touching the exposed-conductive-parts at this instance may cause an electric shock if its potential to earth exceeds 50 V. Furthermore, if it is a high impedance earth fault, the magnitude of the earth fault current may not activate the overcurrent protective device. Thus, a current will continue to flow to earth, possibly generating heat and causing fire. RCCB is designed to detect such a residual current (i.e. earth leakage current), to compare it to a reference value and to open the protected circuit when the residual current exceeds this reference value.

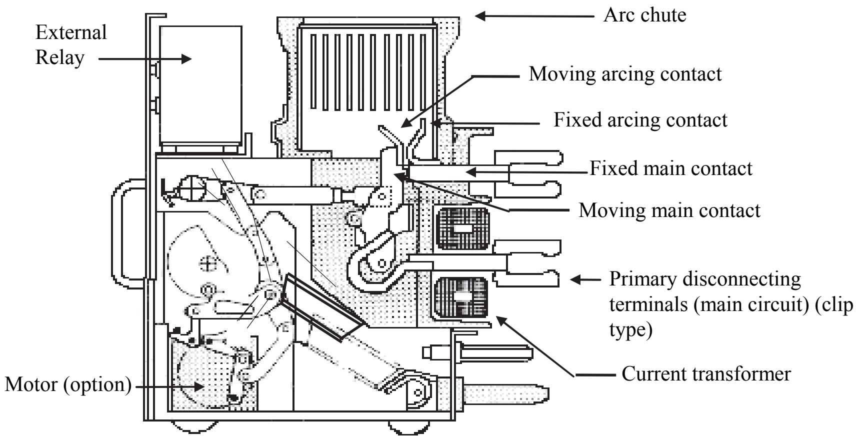



Figure 2.15 A cross-sectional view of an ACB

In this way, a RCCB provides an excellent protection against the risk of electric shock and provides an excellent protection against the possibility of fire resulting from earth fault currents which tend to persist for lengthy periods without operating the overcurrent protective device. The primary function of a RCCB is to give protection against 'indirect contact'. However, for RCCBs having operating residual currents not exceeding 30 mA, there is an additional benefit, should other methods of protection fail, the RCCB will provide a high degree of protection to a user making direct contact with a live conductive part.

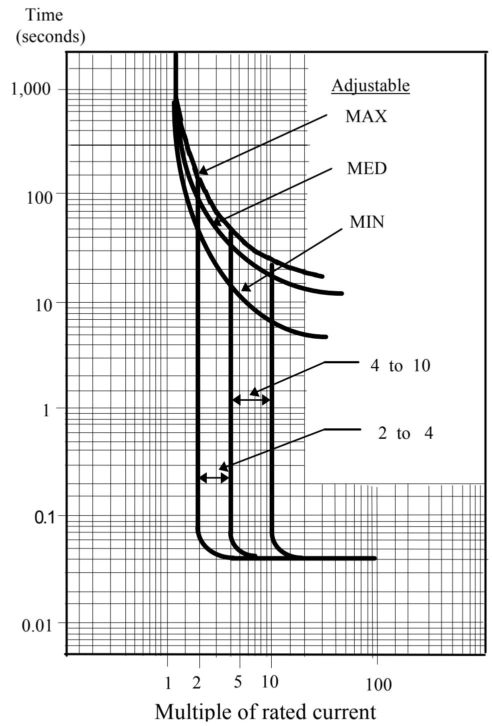



Figure 2.16 Time-current characteristics of a typical ACB

**Principle of Operation**

Figure 2.17 shows that an earth leakage current of 2 A passing through the live conductor on its way to earth, but not returning through the neutral. The difference between the phase and neutral currents is thus the earth leakage current. The principle of operation of a RCCB is shown in Figure 2.18. The main contacts are closed against spring pressure and the loaded spring provides the energy to open the contacts when the retaining mechanism is tripped. Phase and neutral currents pass through identical coils wound in opposite directions on a magnetic core, so each coil provides equal but opposite ampere-turns and no magnetic flux is set up when the currents are equal. Earth leakage current increases the phase current, which provides more ampere-turns than those from the neutral coil, and an alternating magnetic flux is set up in the core. This induces an e.m.f. in the search coil, which results in a current flowing in the trip coil, and the main contacts are tripped. For circuit breakers operating at low residual currents, an amplifier may be used. The main contacts are mechanically operated and the trip mechanism may become stiff with age. Frequent testing is advisable, and a test circuit is included to provide an artificial residual current.

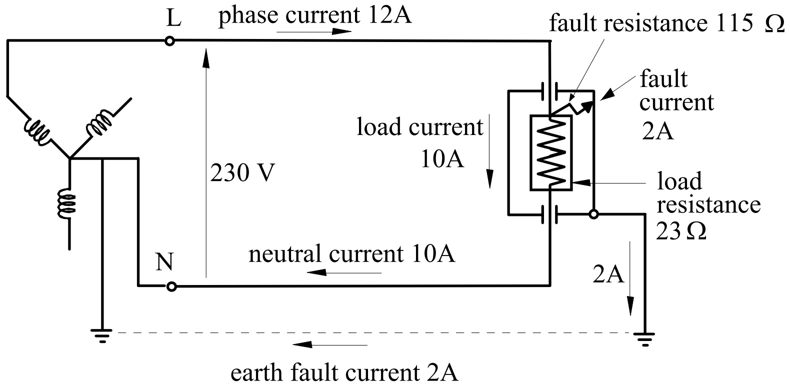



Figure 2.17 The earth leakage current

Although the operating principle of a RCCB has been described in a single phase circuit, the same principle applies equally well to a three-phase RCCB. In a 3-phase 4-wire system, the circuit arrangement in the magnetic core is modified as shown in Figure 2.19. The red, yellow and blue phases and the neutral wire are wound on the common core in such a way that the search coil senses the phasor sum of the four currents (i.e. red, yellow, blue and neutral). In this arrangement, the magnetic flux produced by the current in the neutral will be compensated by the magnetic flux produced by the unbalanced current in the phase conductors.

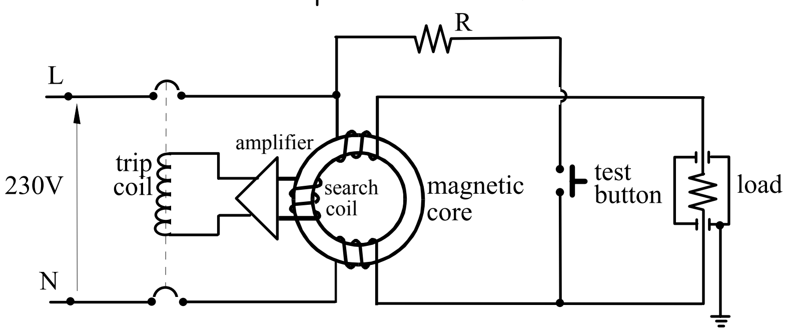



Figure 2.18 Principle of the operation of RCCBs

RCCBs are not designed to have a high breaking capacity and in fact, they have only a limited breaking capacity. They are therefore, not a replacement for other overcurrent protective devices which are designed to interrupt high fault currents. However, RCCBs are type-tested to ensure that they will withstand large fault currents that may pass through them at close position. Thus, it is normally recommended to have an overcurrent protective device connected in series with the RCCB.

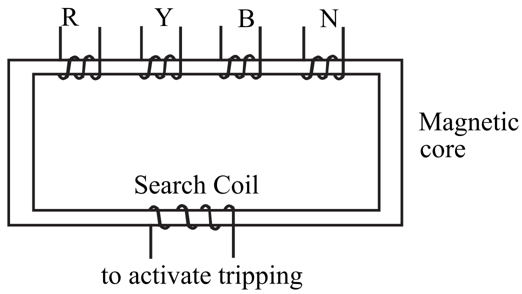



Figure 2.19 Detecting leakage current in a 3-phase 4-wire system

**RCCB Standards**

There are four standards for RCCBs namely, BS 4293 : 1983 [Ref. 6], IEC 755 : 1983 (1992) [Ref. 7], IEC 1008-1 : 1990 [Ref. 8] and Singapore Standard SS 97 : 1994 [Ref. 9]. BS 4293 specifies the requirements for residual current-operated circuit breakers having a rated voltage not exceeding 660 V, a rated current not exceeding 125 A and a rated frequency not exceeding 400 Hz. IEC 755 applies to residual current-operated protective devices for a rated voltage not exceeding 440 V and a rated current not exceeding 200 A with a rated residual current up to 20 A intended principally for protection against electric shock. IEC 1008 -1 applies to RCCBs for household and similar uses for a rated voltage not exceeding 440 V and a rated current not exceeding 125 A with a rated residual current up to 0.5 A intended principally for protection against electric shock. The Singapore Standard SS 97 is just an endorsement of the IEC 1008 -1. Based on IEC 1008, RCCBs are specified as follows :

**Preferred rated voltage**

| | |
|---|---|
| Single-phase, phase-to-neutral | : 230 V |
| Three-phase, three-wire | : 400 V |
| Three-phase, 4-wire | : 400 V |

**Preferred rated current ($I_N$)**

10, 13, 16, 20, 25, 32, 40, 63, 80, 100, 125 A

**Rated residual operating current ($I_{\Delta N}$)**

0.006, 0.01, 0.03, 0.1, 0.3, 0.5 A

**Standard value of residual non-operating current ($I_{\Delta N0}$)**

0.5 $I_{\Delta N}$

**Minimum value of the rated making and breaking capacity**

10 $I_N$ or 500 A whichever is greater

**Rated conditional short-circuit current**

This is the prospective short-circuit current passing through the RCCB at close position and the RCCB can withstand under the specified conditions.

3, 4.5, 6, 10, 20 kA

**Maximum break time**

0.3 s for residual current equal to $I_{\Delta N}$
0.15 s for residual current equal to 2 $I_{\Delta N}$
0.04 s for residual current equal to 5 $I_{\Delta N}$
0.04 s for residual current equal to 500 A

**Other requirements**

- RCCBs shall be protected against short-circuits by means of circuit-breakers or fuses.
- RCCBs are essentially intended to be operated by uninstructed persons and designed to be maintenance free.

## 2.6 APPLICATION EXAMPLES

The low-voltage supply to a two-storey shophouse is shown in Figure 1.17 and Figure 1.18. MCCBs are used in the main incoming circuit and the three outgoing circuits at the main switchboard as shown in Figure 1.17. For the tenant DB T1 as shown in Figure 1.18, one MCCB and one RCCB are used at the incoming circuit, and both single-phase and three-phase MCBs are used for all the outgoing circuits.

**Examples 2.1**

A distribution board(DB) has a RCCB rated at 63 A with a residual operating current $I_{\Delta N}$ = 0.03 A, and three final circuits, each protected by a type C MCB rated at 25 A as shown in Figure 2.20. Determine the operating time of the RCCB and MCB under each of the following conditions :

a) A constant overload of 28 A for 1 hour in the first circuit.

b) A sustained short-circuit current of 2000 A from live-to-neutral in the second circuit.

c) A high impedance sustained short-circuit current of 63.75 A from live-to-earth in the third circuit.

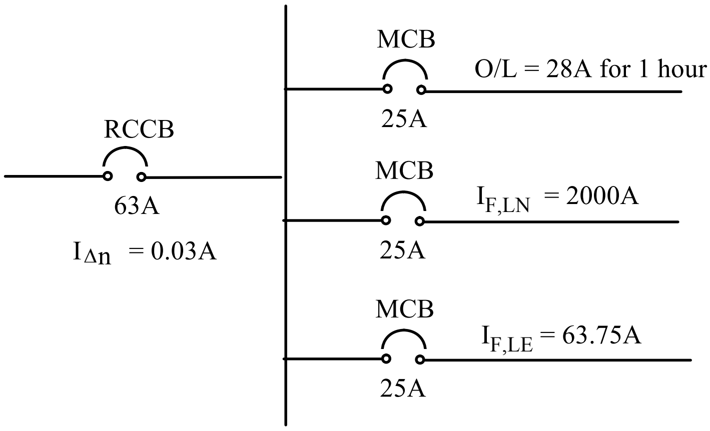



Figure 2.20 A simple DB

**Solution**

a) The RCCB will not operate since the phasor sum of the overload currents is zero. The 25-A MCB will not operate since the overload is less than 1.13 $I_N$. From Table 2.2, tripping should not occur at I = 1.13 $I_N$ and for t $\geq$ 1 hr. This can also be verified by examining the time-current characteristics shown in Figures 2.9 or 2.10.

b) The RCCB will not operate since the short circuit is from live-to-neutral which has a zero phasor sum. The short-circuit current is 2000/25 = 80 $I_N$ which is more than 10 $I_N$. From Table 2.2, the operation time of the MCB is less than 0.1 s.

c) The residual current is 63.75/0.03 = 2125 $I_{\Delta N}$ which is greater than 5 $I_{\Delta N}$. Based on IEC 1008, the maximum break time for a residual current more than 5 $I_{\Delta N}$ is 0.04 s. If the RCCB fails to operate, the MCB will operate according to Table 2.2 within 60 s since the earth fault current is 63.75/25=2.55 $I_N$. The operating time obtained from Figure 2.9 or Figure 2.10 is 50 s.

**Example 2.2**

Determine the type of protective device and the required breaking capacity for a circuit supply to a 3-phase motor which is rated at 20 kW, 95% efficiency and 0.85 power factor. This motor has a DOL starter. The main switchboard is fed by a 1-MVA, 22-kV/LV transformer which has a leakage impedance of 5% as shown in Figure 2.21. Determine the current rating of the circuit breaker for ambient temperatures of $20^0C$ and $40^0C$ respectively. The time-current characteristic curve of the protective device is shown in Figure 2.13.

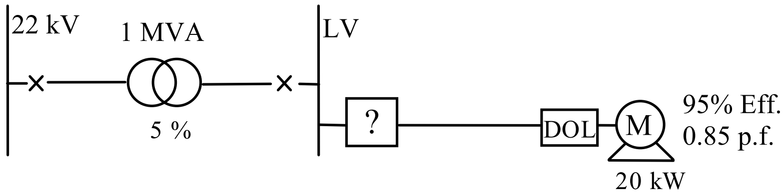



Figure 2.21 Determine the type of protective device

**Solution**

Let the design current be the full load current :-

$$I_B = I_{F.L.} = \frac{20 \times 10^3}{0.95 \times 0.85 \times \sqrt{3} \times 400} = 35.75 \text{ A}$$

For a DOL starter, the motor starting current is seven times the full load current(i.e. 250 A). This high starting current will be reduced to the full load current within 10 s. The 5% impedance of the 1 MVA transformer with respect to the voltage at 400 V is

$$Z = 5\% \times (400^2 / 1 \times 10^6) = 0.008\ \Omega$$

The maximum current that may pass through the breaker occurs during a 3-phase fault at the breaker terminal. The current per-phase during the 3-phase fault at the breaker terminal is:

$$I_{F,3\text{-phase,breaker terminal}} = (400 / \sqrt{3}) / 0.008 = 28.867 \text{ kA}$$

Thus, the type of protective device should be a MCCB with a breaking capacity more than 28.867 kA. A MCCB with a breaking capacity of 35 kA is selected. For an ambient temperature of $20^0C$, a 63-A MCCB is adequate. The starting current expressed as a multiple of the breaker rating is :

$$I_S = \frac{250}{63} = 3.97 \times I_N$$

From Figure 2.13, the operating time of the breaker is 18 s which is greater than the starting duration of 10 s and thus, this breaker will not trip during motor starting.

For an ambient temperature of $40^{0}C$ as shown in Figure 2.13 and for the operating time of 10 s, the corresponding current multiplier is 2.2. Thus, the current rating of the MCCB should be greater than $I_{min}$ :

$$I_{min} = \frac{250}{2.2} = 113 \text{ A}$$

Thus, a current rating of 200 A is selected.

**Example 2.3**

The low-voltage supply to a high-rise block is shown in Figure 2.22. A short circuit occurs inside a final distribution board at the top floor. The fault current is 200 A.

(a) What is the operating time of the incoming protective device at the final DB under the following assumption?

(i) a type B MCB rated at 32 A
(ii) a type 3 MCB rated at 32 A
(iii) a RCCB rated at 40 A with $I_{\Delta N}$ = 0.03 A

(b) Determine the operating time of the MCCB rated at 300 A at the main switchboard of the block.

(c) Determine the operating time of the BS 88 fuse rated at 400 A at the PUB substation.

**Solution**

(a)
(i) For a type B MCB rated at 32 A, the fault current expressed as a multiple of the rated current is :

$$I_F = \frac{200}{32} = 6.25 \ I_N$$

The operating time obtained from Table 2.2 or from Figure 2.10 is less than 0.1 s.

(ii) For a type 3 MCB rated at 32 A, the fault current is :

$$I_F = \frac{200}{32} = 6.25\ I_N$$

The operating time is 8 s obtained from Figure 2.10.

(iii) For a RCCB rated at 40 A with $I_{\Delta N} = 0.03$ A, the RCCB will not operate if the fault current of 200 A is due to a live-to-neutral fault. If it is a live-to-earth fault, the operating time is 0.04 s, since the residual current is 200/0.03 = 6667 $I_{\Delta N}$.

(b) The MCCB rated at 300 A will not operate unless it is an earth fault and the MCCB is equipped with an earth fault relay.

(c) The BS 88 fuse rated at 400 A will not operate at a current of 200 A.

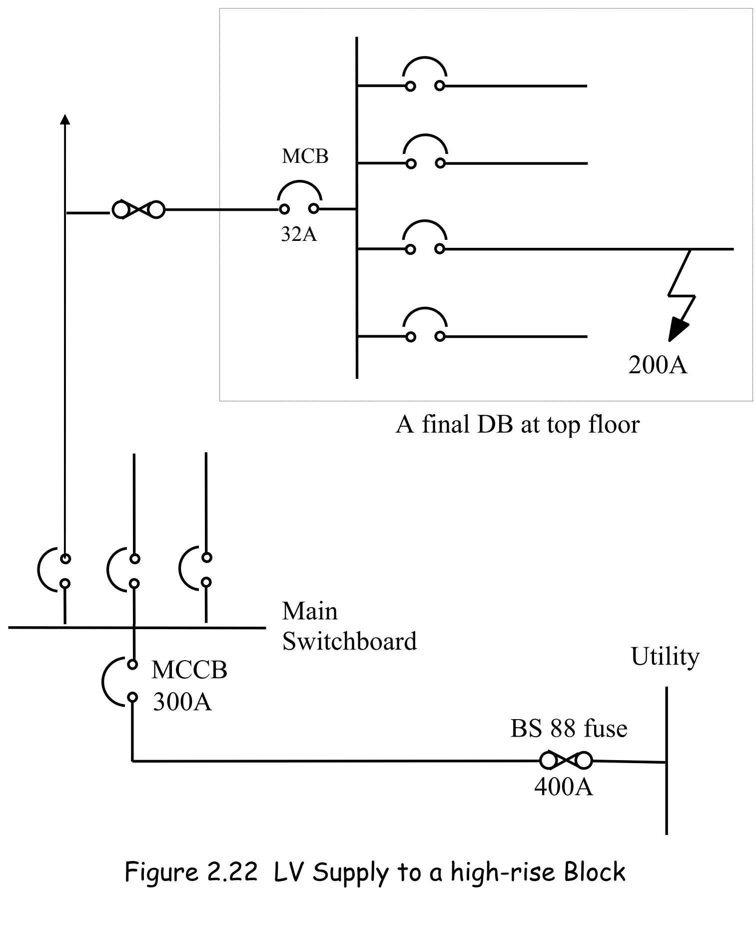



Figure 2.22 LV Supply to a high-rise Block

## 2.7 REFERENCES


[1] BS EN 60947-2 : 1992, "Low voltage switchgear and controlgear, Part 2. Circuit Breaker", The British Standard, 1992.

[2] BS EN 60898 : 1991, "Circuit breakers for overcurrent protection for household and similar installations", The British Standard, 1991.

[3] IEC 947-2 : 1989, "Low voltage switchgear and controlgear Part 2 : Circuit Breakers", International Electrotechnical Commission, 1989.

[4] BS 3871 : Part 1 : 1965 (1984), "Miniature air-break circuit breakers for a.c. circuits", British Standard, 1984.

[5] BS EN 60947-1 : 1992, "Low voltage switchgear and controlgear Part 1. General Rules", The British Standard, 1992.

[6] BS 4293 : 1983, "Residual current-operated circuit-breakers", The British Standard, 1983.

[7] IEC 755 : 1983 (1992), "General requirements for residual current operated protective devices", International Electrotechnical Commission, 1992.

[8] IEC 1008-1 : 1990, "Residual current operated circuit-breakers without integral overcurrent protection for household and similar uses (RCCB's), Part 1 : General Rules", International Electrotechnical Commission, 1990.

[9] SS 97 : Part 1 : 1994, "Residual current circuit breaker without integral overcurrent protection for household and similar uses (RCCB's)", SISIR, 1994.

[10] SS 359 : 1996, "Circuit breakers for overcurrent protection for household and similar installations", SISIR, 1996.

## CHAPTER 3

## CABLE AND SIZING OF CONDUCTORS

Cables are the means by which electrical energy is distributed from its source to its point of use. A cable can be defined as a length of insulated single conductor or of two or more such conductors each provided with its own insulation which are laid up together. The insulated conductor or conductors may or may not be provided with overall covering for mechanical protection. A single-core cable refers to a cable that has only one insulated conductor with its own cable sheath, and a multi-core cable refers to a cable that has multiple cores of insulated conductors within one common sheath. Figure 3.1 illustrates a twin-core, pvc-insulated, pvc-bedded, steel-wire-armoured, pvc-sheathed cable made to BS 6346 : 1989 [Ref. 1]. Cables also form an essential part of communications, security and control systems. Cables for these systems must be chosen to avoid interference from the power cable [Ref. 2, Ref. 4].

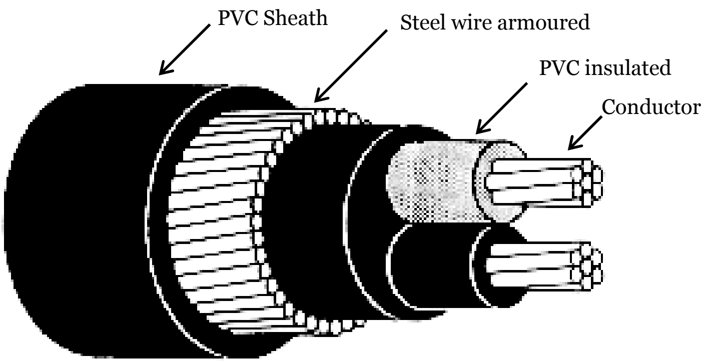



Figure 3.1 A PVC-insulated steel-wire-armoured cable

### 3.1 CABLE CONSTRUCTION

The conductor of a cable refers to one conductor or several conductors which provides electrical paths. They are fabricated from metals having low resistivity. A conductor may be formed from solid material or made up from a number of strands of smaller wire. Conductors are made in a number of standard metric cross-sectional areas in the range from 1.5mm$^2$ to 1000 mm$^2$.

The two common types of conductor material are copper and aluminium. The specific resistance of copper and aluminium at $70^0C$ is 0.017 and 0.0283 respectively, both expressed in $\Omega$ per $mm^2$ per metre. In recent years, aluminium has become a major alternative to copper as a conductor material because of its attractive price. However, aluminium has a higher specific resistance than copper and is therefore, not a good conductor compared to the same size of the copper conductor. For the same current rating, a 300 $mm^2$ aluminium cable is approximately equivalent to a 185 $mm^2$ copper cable under the same conditions of installation.

**Insulation**

The insulation surrounds each conductor to prevent direct contact between individual conductors and earth. The type of insulation will depend on the voltage of the system, the operating temperature of the conductors, and the mechanical and environmental conditions affecting the cable during both installation and operation. Typical types of insulation materials are; polyvinyl chloride (pvc), rubber, cross-linked polyethylene (XLPE), powdered mineral, and oil impregnated paper tapes.

A conductor and its immediate insulation is colloquially known as a core. A cable may comprise a single core with or without further mechanical protection or a number of cores laid up together and held in position by a sheath or tape binding.

Cable cores are generally identified by colour code : red, yellow, blue for phase conductors, black for neutral and green/yellow for circuit protective conductors (earth conductors) according to BS 6004 : 1991 [Ref. 3]. The rated voltage of a cable is normally expressed as $V_0/V$ when $V_0$ is the voltage between any insulated conductor to earth and V is the voltage between phase-conductors of a multi-core cable or of a system of single-core cables. Low-voltage power cables are generally rated at 450/750 V [Ref. 3] or 600/1000 V [Ref. 1] regardless of the voltage used, be it 120 V, 230 V, 240 V or 400 V.

**External Protection**

Wiring cables intended for installation in a conduit, trunking or similar enclosures are usually insulated single-core cables and are unsuitable for installation in other circumstances. Other types of cable are provided with further external protection.

External protection applied over the various cores of the cable (one core or more) is intended to provide protection against mechanical damage and hostile environmental attacks. It is also intended in the case of power cables, particularly HV cables, to provide resistance to the considerable mechanical forces which may occur under short-circuit fault conditions. In the case of conductors insulated with oil impregnated tapes, the external sheath is usually made of extruded lead or lead alloy, designed to form a anti-moisture protection for the hydrotropic insulation. For other cables, the external protection may comprise metallic or plastic sheaths, or a combination of these, with a layer of metallic armour being provided where extra mechanical protection is required.

### 3.2 CABLE TYPE AND SELECTION

To meet various electrical and environmental operating conditions, multitude types of cable which are available for incorporation in the low-voltage system are required. Guidance on the selection of types of cables is given in Chapter 52 and Appendix 4 of the IEE Regulation [Ref. 2], or CP5 [Ref. 4].

The current carrying capacity of a cable must be sufficient to cater for the maximum sustained current which will normally flow through it. The insulation must be adequate to deal with the voltages of the system and it must not be damaged by the heat produced by the current flow, high ambient temperatures or by heat transferred to it from hot objects. Voltage drop requirements and short circuit thermal stresses must also be catered for.

Due to electromagnetic effects, certain types of cable are precluded from use in specified circumstances. Regulation 521-02 [Ref. 2] forbids the use of single-core cables having steel armour on a.c. systems.

Environmental conditions may require cables which are capable of operation in the presence of water or moisture, or when subjected to fire risk, or in extremes of temperature. It may have to operate under mechanical stress and vibration. If the environment is such that the cable is subjected to such hazards, cables should be selected with appropriate insulation and sheathing materials. The commonly used low-voltage cables are as follows :

- Non-armoured pvc-insulated cables installed in conduits and trunking systems for internal wiring.

- Non-armoured pvc-insulated and pvc-sheathed cables for general indoor use, particularly in domestic and commercial installations.
- Armoured pvc-insulated cables for mains and sub-mains applications (i.e. utility's low-voltage circuits buried underground).
- Fire resistant cables or mineral insulated metal sheathed cables used in areas of extreme temperatures or for circuits supplied to fire-fighting equipment.
- Heat, oil and flame retardant (hofr) cables are intended for use in severe conditions : examples of these are csp (chlorosulphinated polyethylene) and pcp (polycholoroprene) sheathed cables.

While many relevant factors need to be taken into account, probably the most significant factor in cable selection and installation is temperature. Most of the insulating materials and sheath cables are liable to failure in the presence of excessive temperatures. All wires used in cable making have a resistance which, when current is passed through it, give rise to heat. Cable selection, therefore, is primarily related to the size of the cable that will carry the required current without the temperature of the surrounding insulation rising above a critical level that will result in the breakdown of the insulation.

PVC insulated cables to BS 6004 [Ref. 3] for example, are suitable only as long as the conductor temperature does not exceed $70^{O}C$, whereas mineral insulated cables to BS 6207 : 1991 [Ref. 5] fitted with high temperature terminations can be operated up to $135^{O}C$.

**Test Voltage on Completed Cable**

All completed cables from factory shall be subjected to voltage tests. An a.c. voltage shall be applied between conductors, and between each conductor and the sheath which shall be earthed. The voltage shall be increased gradually and maintained at the full value for 5 minutes without breakdown of the insulation according to Table 3.1.

**Table 3.1 A.C. Testing on Completed Cables**

| Voltage Rating | Test Voltage between Conductors, V (r.m.s.) | Test Voltage between any Conductor and Earth, V (r.m.s.) |
|---|---|---|
| 600/1,000 | 3,000 | 3,000 |
| 19,00/3,300 | 10,000 | 5,800 |
| 3,800/6,600 | 17,000 | 9,800 |
| 6,350/11,000 | 25,000 | 14,400 |
| 12,700/22,000 | -- | 30,000 |

**Test Voltage after Installation**

Any voltage test after installation should be made with d.c. voltage. The voltage should be increased gradually to the full value and maintained continuously for 15 minutes according to Table 3.2. No breakdown should occur.

**Table 3.2 D.C. Testing after Installation**

| Voltage Rating | Test Voltage between Conductors, V (d.c.) | Test Voltage between any Conductor and Sheath, V (d.c.) |
|---|---|---|
| 600/1,000 | 3,500 | 3,500 |
| 1,900/3,300 | 10,000 | 7,000 |
| 3,800/6,600 | 20,000 | 15,000 |
| 6,350/11,000 | 34,000 | 25,000 |
| 12,700/22,000 | - | 50,000 |

**Standard Size of Conductor**

In the United States of America, the standard cable sizes are expressed in AWG/MCM. It is rather difficult to get one-to-one equivalent to the standard sizes expressed in $mm^2$. Table 3.3 is, therefore, provided for quick reference.

**Table 3.3 Standard cross-sections of round copper conductors**

| ISO cross-section, ($mm^2$) | AWG/MCM | |
|---|---|---|
| | Size | Equivalent cross-section, ($mm^2$) |
| 1.5 | 16 | 1.3 |
| 2.5 | 14 | 2.1 |
| 4 | 12 | 3.3 |
| 6 | 10 | 5.3 |
| 10 | 8 | 8.4 |
| 16 | 6 | 13.3 |
| 25 | 4 | 21.2 |
| 35 | 2 | 33.6 |
| 50 | 0 | 53.5 |
| 70 | 00 | 67.4 |
| 95 | 000 | 85 |
| - | 0000 | 107.2 |
| 120 | 250 MCM | 127 |
| 150 | 300 MCM | 152 |
| 185 | 350 MCM | 177 |
| 240 | 500 MCM | 253 |
| 300 | 600 MCM | 304 |

### 3.3 CURRENT RATING OF CABLE

The current rating of a cable is determined by a number of factors, namely

- Ambient temperature
- Maximum allowable conductor temperature
- Conductor material
- Insulation material
- Installation methods

A cable rated at 30 A can also be loaded up to 40 A or 45 A without any problem except that the conductor's temperature is increased. The temperature at which the conductors of a cable are allowed to operate continuously without damage to the cables and for a reasonable service life, depends on the insulation material used and the construction of the cable. For example, pvc insulated cables to BS 6004 [Ref. 3] are suitable for use where the conductor temperature under normal load conditions does not exceed $70^{O}C$. It is not a normal practice for the design engineer to determine directly the likely operating temperature of a range of cables. The designer relies therefore, on the tabulated current carrying capacities ( $I_t$ ) such as those in Appendix 4 of the IEE Regulation [Ref. 2] or CP5 [Ref. 4]. These tabulated values will ensure that excessive temperatures are not reached. It should, however, be pointed out that the tabulated current ratings are based upon a given set of conditions :

- An ambient temperature of $30^{O}C$.
- The heating effect of adjacent cables is not considered.
- The cable is installed in a way that corresponds to the rating table being used.
- There is no surrounding thermal insulation.

Let us define the above conditions as the preferred operating conditions. Should any of these conditions be changed, the cable rating has to be adjusted according to the appropriate correction factor. A cable rated at 30 A in one set of conditions may be suitable for carrying only 10 A or 15 A in other conditions. A cable may be seriously damaged, leading to early failure, if it is operated for any prolonged period at a temperature higher than the specified value.

**<u>Ambient Temperature Correction Factor</u> ($C_a$)**

Tabulated cable ratings are based upon $30^{O}C$, as this is the temperature most commonly experienced in normal occupied premises. However, even in such buildings, a higher temperature can occur in the vincinity of heating equipment or other sources of heat. The designer must, in such cases, apply a suitable correction factor.

For an ambient temperature higher than the specified temperature of 30$^0$C, the rate of flow of heat out of the conductor will be lower than that of the specified condition. This will increase the conductor's operating temperature above the value permitted. This means that the current-carrying capacity of the conductor has to be reduced to compensate for the reduction in the heat lost from the conductor.

Correction factors for ambient temperature in determining the current-carrying capacity of a cable are provided in Table 4C1 of IEE Regulation [Ref. 2] or CP5 [Ref. 4]. For a general purpose, pvc- insulated cable with a conductor operating temperature of 70$^0$C, the correction factors for a range of ambient temperatures are summarised in Table 3.4.

**Table 3.4 Temperature Correction Factors for pvc Cable**

| Ambient Temperature $^0$C | 25 | 30 | 35 | 40 | 45 | 50 |
|---|---|---|---|---|---|---|
| Correction Factor $C_a$ | 1.03 | 1.0 | 0.94 | 0.87 | 0.79 | 0.71 |

For example, a four-core pvc-insulated cable enclosed in trunking has a tabulated current capacity of 80 A. If the ambient temperature is 50$^0$C, the current rating is reduced to 80A x 0.71 = 56.8 A. The ambient temperature refers to the temperature of the cable surrounding media and does not include the temperature of the equipment. This factor has to be applied even if only a short length of the cable route is installed in the area that has a higher ambient temperature.

**<u>Grouping Correction Factor</u> ($C_g$)**

Cables installed in the same enclosure or bundled together will get warm when all are carrying current. Those close to the edges of the enclosures will be able to release heat outward but will be restricted in losing heat inwards towards other warm cables. Cables in the centre of the enclosure may find it difficult to lose heat at all and will thus increase the conductor temperature. Table 4B1 of IEE regulations [Ref. 2] or CP5 [Ref. 4] gives correction factors for cables installed in close proximity or bundled together. Correction factors for groups of more than one circuit of a single-core cable, or more than one multi-core cable are summarised in Table 3.5. These correction factors have to be applied to the tabulated current-carrying capacities depending upon how the cables or circuits are grouped.

**Table 3.5 Grouping Correction Factor**

| No. of circuits or multi-core cables | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Bunched and clipped direct | 1 | 0.8 | 0.7 | 0.65 | 0.6 | 0.57 |
| Single layer clipped direct and touching | 1 | 0.85 | 0.79 | 0.75 | 0.73 | 0.72 |
| Single layer clipped direct and Spaced * | 1 | 0.94 | 0.90 | 0.90 | 0.90 | 0.90 |

* spaced by a clearance between adjacent surfaces of at least one cable diameter.

If the conductors are more than twice their overall diameters apart, no correction factor needs to be applied. However, the factor has to be applied even if only a short length of cable route is grouped. Thus, it may be necessary to use a number of separate entries to an enclosure in order to keep the cables concerned adequately separated so that the grouping factor need not be applied.

**Example 3.1**

A heater rated at 230 V, 3 kW is to be installed using twin-with-earth pvc-insulated and sheathed cable clipped direct in a roof space that has an ambient temperature of 40$^0$C. The circuit is protected by a 15-A MCB. The cable is bundled with four other twin-and-earth cables for a short distance as shown in Figure 3.2. Determine the minimum tabulated current rating of the circuit and the size of the conductor.

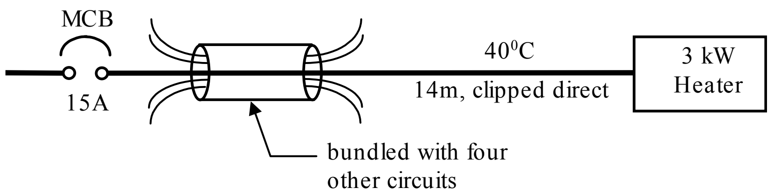



Figure 3.2 Circuit for Example 3.1

**Solution**

The design current is :

$$I_B = \frac{3000}{230} = 13 \text{ A}$$

The current rating of the protective device ($I_N$ ) is 15 A. From Table 3.4, the temperature corrective factor at 40$^0$C is :

$$C_a = 0.87$$

From Table 3.5, the grouping factor of five circuits is :

$$C_g = 0.6$$

The minimum tabulated current rating $I_{t,\,min}$ for the circuit is :

$$I_{t,\,min} = \frac{I_N}{C_a \times C_g} = \frac{15}{0.87 \times 0.6} = 28.74 \text{ A}$$

From Table 4D2A of IEE Regulation [Ref. 2], column 6, a 4 mm$^2$ cable which has a tabulated current rating of 36 A is selected. It should be noted that although the design current is only 13 A, a 4 mm$^2$ cable rated at 36 A is selected. In fact, for the same design current of 13 A under the preferred operating conditions, a 1 mm$^2$ cable rated at 15 A is sufficient.

**Example 3.2**

Determine the minimum tabulated current rating of a multi-core, pvc-insulated cable connected to a 3-phase motor rated at 400 V, 15 kW, 0.8 power factor and 90% efficiency. This motor is subjected to frequent start/stop and is operating at an ambient temperature of 35$^0$C as shown in Figure 3.3.

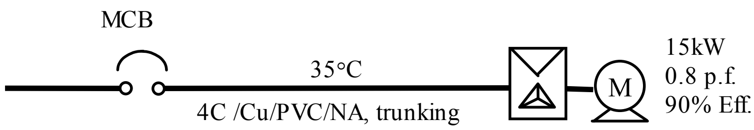



Figure 3.3 Circuit for Example 3.2

**Solution**

The design current is :

$$I_B = \frac{15 \times 1000}{0.8 \times 0.9 \times \sqrt{3} \times 400} = 30.07 \text{ A}$$

For frequent start/stop, it is suggested that the minimum circuit rating be selected from 1.25 to 1.4 of $I_B$. Let us select the higher value of 1.4 and thus the minimum tabulated circuit rating is 1.4 x 30.07 = 42.10 A. To incorporate temperature correction, the minimum tabulated circuit rating is :

$$I_{t,min} = \frac{42.10}{0.94} = 44.79 \text{ A}$$

From Table 4D2A of IEE Regulation [Ref. 2], column 5, a 10 $mm^2$ 4-core cable which has a tabulated current rating of 46 A is selected.

**Thermal Insulation Correction Factor ($C_i$)**

To reduce the energy cost for heating, ventilation and air-conditioning (HVAC), many new buildings are now provided with better thermal insulating material for roofs and cavity walls to reduce the heat loss. As thermal insulation is designed to limit heat flow, a cable in contact with it will tend to become warmer than the preferred operation conditions. IEE Regulation 523-04 [Ref. 2] recommends that for a single cable which is likely to be surrounded by thermally insulating material over a length of 0.5 m, the thermal correction factor ($C_i$) is 0.5 times the tabulated current carrying capacity for that cable clipped direct to a surface (method 1). If the surrounded length is less than 0.5 m, the correction factor ($C_i$) can be higher than 0.5 [Ref. 2, P78], [Ref.4, 99].

**Example 3.3**

The circuit is the same as that for Example 3.1, except that the cable has to pass through a thermal insulation area over a length of 2 m. Determine the minimum tabulated current rating of the circuit and the size of conductor.

**Solution**

The minimum tabulated current rating for the circuit is :

$$I_{t,min} = \frac{I_N}{C_a \times C_g \times C_i} = \frac{15}{0.87 \times 0.6 \times 0.5} = 57.47 \text{ A}$$

From Table 4D2A of IEE Regulation [Ref. 2], column 6, a twin-core cable of 10 $mm^2$ which has a tabulated current of 63 A is selected.

Examples 3.1 and 3.3 illustrate that for a design current of 13 A, the cable size has to increase substantially due to three correction factors from 1 $mm^2$ (15 A) to 4 $mm^2$ (36 A) and to 10 $mm^2$ (63 A). Thus, the designer should, as far as possible, rearrange the cable route, to avoid grouping, high ambient temperature and thermal insulation area so that no correction factor needs to apply.

## 3.4 VOLTAGE DROP CALCULATION

A design engineer must have a working knowledge of voltage drop calculations, not only to meet the relevant code, but also to ensure that the voltage applied to the electrical appliances is maintained within proper limits. Most electrical appliances are designed to operate within a voltage tolerance of $\pm$ 10%. The utility supply regulations normally ensure that the voltage variations at the supply intake are kept within $\pm$6% of the declared nominal voltage. The designer must therefore, ensure that the voltage drop from the supply intake to the terminals of any appliance does not exceed 4% of the declared nominal voltage. Thus, all electrical appliances can be operated safely and be fully functional within their design voltage tolerance of $\pm$10%. IEE Regulation 525-01 [Ref. 2] specifies that the voltage drop between the origin of the installation and the fixed current-using equipment should not exceed 4% of the nominal voltage of the supply.

Consideration should be given to both the steady state and transient conditions. Transient conditions refer mostly to the motor starting period, and a greater voltage drop may be accepted provided that the voltage variations should not exceed those specified in the relevant standards or the equipment manufacturer's recommendation.

### Tabulated Voltage Drop Constant (TVD)

Figure 3.4 shows a voltage drop of 7 V from the sending end to one terminal of the appliance when the circuit is carrying its rated current $I_R$. This voltage drop is due to the resistance of 1.4 m$\Omega$ for the live conductor. Let us define this voltage drop in one conductor, one way as the line-to-neutral voltage drop. We can therefore multiply this line-to-neutral voltage drop by 2 to obtain the total voltage drop at the terminals of the appliance under the assumption that in a single phase circuit, the value of resistance in the neutral conductor is the same as the live conductor. This is usually true as the conductor's material, size and length are identical to those of the live conductor.

The voltage drop in the single-phase circuit as shown in Figure 3.4, can be written as :

$$\begin{aligned} V_{drop} &= I_R\,(1.4\ \mathrm{m}\Omega \times 100 + 1.4\ \mathrm{m}\Omega \times 100) \\ &= I_R\,(1.4\ \mathrm{m}\Omega \times 2) \times 100 \\ &= I_R\,(2.8\ \mathrm{m}\Omega) \times 100 \\ &= I_R \times TVD \times 100 \end{aligned}$$

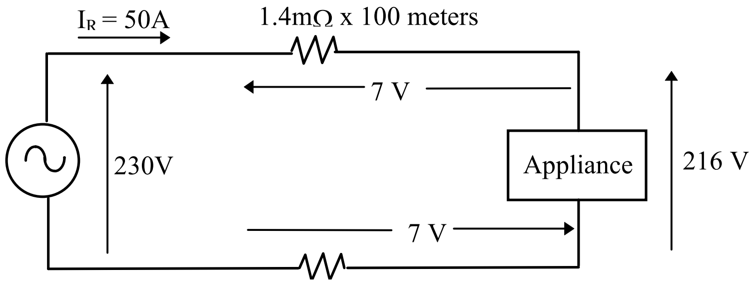



Figure 3.4 Illustration for Voltage Drop Calculation

TVD (i.e. 2.8 mΩ) is in fact the tabulated voltage-drop constant that appeared in the cable tables of Appendix 4 of the IEE Regulation [Ref.2]. This tabulated voltage-drop constant (TVD) is expressed in mΩ per ampere per metre run (i.e. for a current of 1 A and for a distance of 1 m along the route taken by the cables). For cables having conductors of 16 $mm^2$ and lower, as the values of reactance are very much less than the values of resistance, the inductance can be ignored, and only the values of $(mV/A/m)_r$ are tabulated. For cables having conductors greater than 16 $mm^2$, the impedance values $(mV/A/m)_Z$ are tabulated together with the resistive component $(mV/A/m)_r$ and the reactive component $(mV/A/m)_X$. To simplify the voltage drop calculation for single-phase circuits, the values of $TVD_r$ and $TVD_x$ are so arranged that $TVD_r$ is twice the value of the per-phase cable resistance and $TVD_x$ is also twice the value of the per-phase cable reactance.

For three-phase circuits, the line-to-line voltage is equal to $\sqrt{3}$ multiplied by the line-to-neutral voltage. Similarly, the line-to-line voltage drop is also equal to $\sqrt{3}$ multiplied by the line-to-neutral voltage drop. Thus, for three-phase circuits, the values of TVD are also arranged as $\sqrt{3}$ multiplied by the values of the per-phase cable resistance and the per-phase cable reactance.

**Voltage Drop Formulae**

For most practical cases, the voltage angle difference between the sending end and the receiving end is almost zero, and the line-to-neutral voltage drop, [Ref. 6, P 97, P 629] in a circuit, taking into account the per-phase current ( I ), the power factor (cosθ), and the values of the per-phase resistance(R) and reactance(X) is :

$$V_{drop} = I\,R\cos\theta + IX\sin\theta$$

**Example 3.4**

A 3-phase motor with a full load current of 102 A, and a power factor of 0.8 is to be fed by four single-core, pvc-insulated, copper conductor, non-armoured cables, clipped direct on a non-metallic surface at 75-metre run as shown in Figure 3.5. Determine the size of conductor if the permissible voltage drop from the MCB to the motor terminal is 2%.

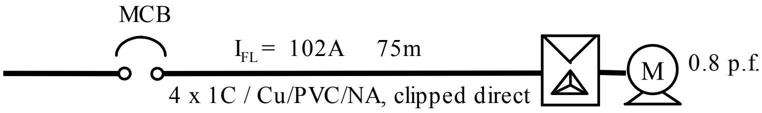



Figure 3.5 Circuit for Example 3.4

**Solution**

Let the design current $I_B$ be the motor's full load current. From Table 4D1A of IEE Regulation [Ref. 2], column 7, a 25 mm$^2$ cable with a current rating of 104 A is initially selected, and the line-to-line voltage drop is calculated as :

$$
\begin{aligned}
V_{drop,\ LL} &= \frac{\left(TVD_r \cos\theta + TVD_x \sin\theta\right) \times I_B \times \text{length}}{1000} \\
&= \frac{\left(1.5 \times 0.8 + 0.175 \times 0.6\right) \times 102 \times 75}{1000} \\
&= 9.983 \text{ V or } 2.496\% \text{ of } 400 \text{ V}
\end{aligned}
$$

The calculated $V_{drop,\ LL}$ is 2.496% that exceeds 2% of 400 V. Thus, the next higher size of 35 mm$^2$ is selected and $V_{drop,\ LL}$ is re-calculated :

$$
\begin{aligned}
V_{drop,LL} &= \frac{\left(1.1 \times 0.8 + 0.17 \times 0.6\right) \times 102 \times 75}{1000} \\
&= 7.512 \text{ V or } 1.88\%
\end{aligned}
$$

This calculated voltage drop is 1.88% of 400 V and thus, a 35 mm$^2$ cable is recommended.

**Example 3.5**

The circuit is the same as in Example 3.4, except that the full load current is reduced to 50 A and the cable selected is a 10 mm$^2$ cable for 30-metre run. Determine the voltage drop.

**Solution**

For the 10 mm$^2$ cable, as the reactance is very much less than the resistance, the tabulated reactive component $TVD_X$ is zero and the voltage drop can be calculated as :

$$V_{drop,\,LL} = \frac{(TVD_r\ \cos\theta + 0 \times \sin\theta) \times 50 \times 30}{1000}$$
$$= \frac{3.8 \times 0.8 \times 50 \times 30}{1000}$$
$$= 4.56\ \text{V}$$

Another approach of multiplying $TVD_r$ by the design current and the cable length is also acceptable. However, it may lead to a pessimistically higher calculated value, such as :

$$V_{drop,LL} = \frac{TVD_r \times I_B \times \text{length}}{1000}$$
$$= \frac{3.8 \times 50 \times 30}{1000}$$
$$= 5.7\ \text{V}$$

**Temperature Correction on Resistive Value**

The value of resistance of a conductor is usually given at a conductor temperature of $20^0C$ in the relevant standards or cable manufacturers. As the temperature of the conductor increases due to the load current, the value of resistance will also increase according to the resistance-temperature coefficient. This coefficient is approximately equal to 0.004 per $^0C$ at $20^0C$ for both copper and aluminium conductors [Ref. 2, P178]. Based on this coefficient and as shown in Figure 3.6, the value of resistance will be zero mathematically at a conductor temperature of $-230^0C$. Similarly, if the resistance value is given at $70^0C$, (denoted as $\Omega_{70}$), the resistance value at $160^0C$ ($\Omega_{160}$ ) can be calculated by :

$$\Omega_{160} = \Omega_{70}\left(\frac{230 + 160}{230 + 70}\right) = \Omega_{70} \times 1.3$$

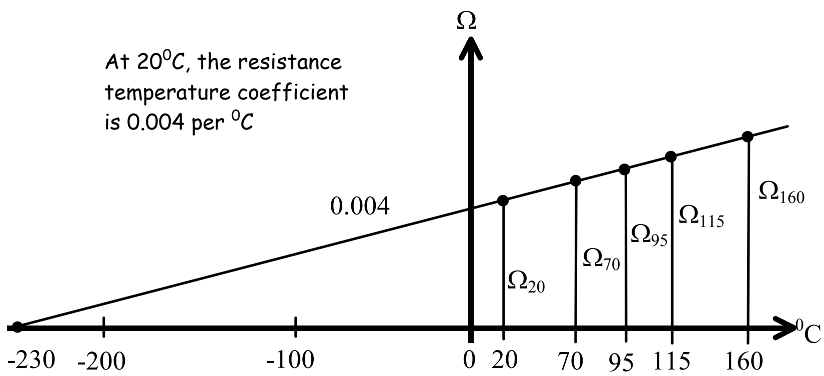



Figure 3.6 Calculation of Resistance Value at Various Temperatures

If the resistance value at a temperature of $20^0C$ is given, the resistance at the other temperatures such as $\Omega_{115}$ or $\Omega_{95}$ can also be calculated as :

$$\Omega_{115} = \Omega_{20}\left(\frac{230+115}{230+20}\right) = \Omega_{20} \times 1.38$$

$$\Omega_{95} = \Omega_{20}\left(\frac{230+95}{230+20}\right) = \Omega_{20} \times 1.3$$

**Conductor Temperature on Voltage Drop**

The resistive value $TVD_r$ is based on the resistance of the conductor at the rated temperature (e.g. $70^0C$ for pvc-insulated copper conductor) corresponding to the conductor carrying its rated current. Thus, if the design current is significantly less than the rated current of the cable, the actual value of the resistance will be lower than the tabulated value due to the lower conductor temperature. In this case, the direct use of $TVD_r$ may lead to pessimistically high-calculated values of voltage drop. As the value of reactance is not influenced by temperature, the temperature correction does not apply to the value of reactance.

**Example 3.6**

A three-phase circuit consisting of 4 x 10 mm$^2$ Cu/pvc/non-armoured single-core cables is selected to feed an electrical appliance which has a design current of 50 A at 0.8 power factor as shown in Figure 3.7. The circuit length is 30 m and the ambient temperature is $25^0C$. Determine the voltage drop by taking into consideration a lower conductor temperature.

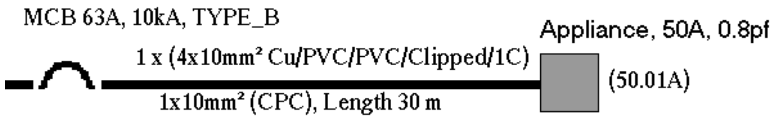



Figure 3.7 Circuit for Example 3.6

**Solution**

As the conductor temperature is proportional to the square of the current passing through the conductor, we can write:

$$\frac{t_{50A} - t_a}{t_p - t_r} = \frac{I_b^2}{I_t^2}$$

Where $t_{50A}$ is the conductor temperature when carrying a current of 50A, $t_a$ ($25^0C$) is the ambient temperature, $t_p$ ($70^0C$) is the conductor rated temperature when carrying the tabulated current($I_t$) of 59 A, $I_b$ (50 A) is the design current and $t_r$ (30$^0$C) is the reference ambient temperature. Thus, the conductor's actual operating temperature when carrying a current of 50 A, $t_{50A}$ is :

$$\begin{aligned} t_{50A} &= t_a + \frac{I_b^{\,2}}{I_t^{\,2}}\left(t_p - t_r\right) \\ &= 25 + \frac{50^2}{59^2}\left(70 - 30\right) \\ &= 53.73\ ^\circ C \end{aligned}$$

The corrected $TVD_r$ at 53.73$^0$C is :

$$\begin{aligned} \left(TVD_r\right)_{53.73} &= TVD_r\left(\frac{230 + 53.73}{230 + 70}\right) \\ &= 3.8 \times 0.9458 \\ &= 3.594 \end{aligned}$$

$$V_{drop,LL} = \frac{\left(\left(TVD_r\right)_{53.73}\ \cos\theta\right) \times I_B \times \text{length}}{1000}$$

$$= \frac{3.594 \times 0.8 \times 50 \times 30}{1000}$$

$$= 4.313\ V$$

The voltage drop of 4.313 V is actually 94.58% of the voltage drop obtained by directly multiplying the $TVD_r$ value. If the design current is 29.5 A which is half of the conductor rated current (i.e. the cable is 50% loaded), the conductor temperature at 29.5 A will be :

$$\begin{aligned} t_{29.5} &= 25 + \left(\frac{1}{2}\right)^2\left(70 - 30\right) \\ &= 35^\circ C \end{aligned}$$

The corrected $TVD_r$ at 35$^0$C is :

$$\left(TVD_r\right)_{35} = TVD_r\left(\frac{230 + 35}{230 + 70}\right) = 0.88\ TVD_r$$

Thus, the actual voltage drop is only 88% of the voltage drop obtained by directly multiplying the $TVD_r$ value.

### 3.5 PROTECTION AGAINST OVERLOAD

Overload currents may occur in various circuits in an installation. These overload circuits are electrically sound but are carrying more current than their rated capacity. These may be caused by a user deliberately or accidentally using more power than the circuit is designed for, or due to the design errors in estimating the maximum demand in some sections of the installation. The consequences of such an overload to the installation are that the temperature of the conductors and of their insulation will rise to the level where the effectiveness of the insulation and its expected life may be reduced. Circuit breakers or fuses are required to automatically detect overloads and to break the circuit if such overloads exceed a pre-determined value within a specified duration.

### 3.5.1 Required Conditions for Overload Protection

To provide an adequate protection for overload, IEE Regulation 433 [Ref. 2], requires the following conditions to be satisfied :

i) $I_N \leq I_Z$

ii) $I_2 \leq 1.45\ I_Z$

Where $I_Z$ is the current rating of the cable under the particular installation conditions, $I_N$ is the current rating of the protective device and $I_2$ is the current magnitude causing an effective operation of the protective device. The effective operating time is defined as 1, 2, 3 or 4 hours. For MCB, $I_2$ is 1.45 $I_N$. For MCCB and ACB, $I_2$ is 1.3 $I_N$. The effective operating time is 2 hours, except for breakers less than 63 A where the effective operating time is reduced to 1 hour. If the protective device is a fuse, $I_2$ is 1.6 $I_N$ and the effective operating time is in the range from 1 to 4 hours depending on the current rating of the fuse.

Since one of the prime functions of the protective device is to protect the cable from being overloaded, its current rating must not be greater than that of the cable to be protected, i.e. $I_N \leq I_Z$. The factor of 1.45 in condition (ii) is based on a combination of experience and investigation. Condition (ii) implies that the current in the circuit is allowed to increase to 145% of the cable rated capacity. In this loading condition, the temperature of the conductor will be higher than its rated temperature but is still below its critical temperature. For example, for pvc-insulated copper conductor cable, the rated conductor temperature is 70$^{0}$C, and the critical temperature is in the range from 140$^{0}$C to 160$^{0}$C. The loading at 145% is about 114$^{0}$C [Ref. 7, P 83]. The reduction of the factor from 1.45 downwards will result in the reduction of the overload capability of the circuit or even cause unnecessary tripping on minor overload.

Table 3.6 gives a sample of various rated conductor temperatures for two types of cables. It should be noted that operations at the overload temperature are acceptable provided that such operations shall not exceed 100 hrs per year and such 100-hr period shall not exceed five times [Ref. 6, P 559]. The critical temperature refers to the temperature that will cause insulation failure.

**Table 3.6 Rated Conductor Temperature**

| Cable Type | Rated Temperature ( $^oC$ ) | Overload Temperature ( $^oC$ ) | Critical Temperature ( $^oC$ ) |
|---|---|---|---|
| PVC-insulated | 75 | 95 | 150 |
| Cross-linked | 90 | 130 | 250 |

To assess whether there is an overload protection and how adequate it is, let us define the degree of overload protection as:

$$OL\_P\_Yes \equiv 100\% \times (1.45\, I_Z - I_2\,) \,/\, 1.45\, I_Z$$

A positive value of OL_P_Yes implies that the circuit is adequately protected against overload current, and a higher percentage means that the circuit is more unlikely to be overloaded. Obviously, a negative percentage indicates that the circuit is not provided with overload protection.

**Example 3.7**

The designed current of a circuit is 49 A and it is fed by a 4 x 10 mm$^2$ single-core copper conductor, pvc-insulated cables installed in trunking. This circuit is protected by a 50 A MCCB as shown in Figure 3.8.

a) Does this circuit satisfy the requirements for overload protection?
b) State the range of small overload that the circuit is not protected.
c) To eliminate the undesired small overload, the circuit is upgraded to 4 x 25 mm$^2$. Can this upgraded circuit be loaded up to 100% of its rated capacity? Why?

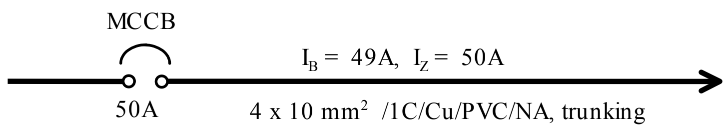



Figure 3.8 Circuit for Example 3.7

**Solution**

(a) This circuit satisfies the two overload requirements :

(i) From Table 4D1A of IEE Regulation [Ref. 2], $I_Z$ = 50 A. Since $I_N$ = 50 A, it satisfies $I_N \leq I_Z$.

(ii) Since $I_2$ = 1.30 x 50 = 65 A, and 1.45 $I_Z$ = 72.5 A, it satisfies $I_2 \leq 1.45\ I_Z$.

Thus, according to IEE Regulation 433 [Ref. 2], this circuit is provided with adequate protection against overload. We may also indicate by :

$$OL\_P\_Yes = 100\% \times (1.45\ I_Z - I_2\ ) / 1.45\ I_Z = 10.3\%$$

(b) In this particular case, there is a range of small overloads for which it is not protected. Since the breaker will only trip at a current higher than 65 A and the cable rating is 50 A, the range of unprotected overload is therefore, from a load current higher than 50 A to less than 65 A.

(c) The current rating of the 4 x 25 $mm^2$ cable is 89 A. As this circuit is protected by a 50 A MCCB, which will trip at any current higher than 65 A, this circuit can only load up to :

$$\frac{65}{89} \times 100\% = 73\%$$

**3.5.2 Small Overloads and Cable Utilisation**

In Example 3.7, it is illustrated that if the rated cable capacity, $I_Z$ is equal to or slightly higher than the rating of the protective device, $I_N$, it is possible to have a range of very small overloads which will not be detected by the protective device (i.e. at the range between $I_Z \leq I \leq I_2$). This condition exists even if the circuit is adequately protected against overload according to the IEE Regulations 433. Thus, in the general statement in IEE Regulation 433-01-01 [Ref. 2], it states that every circuit shall be designed so that a small overload of long duration is unlikely to occur. Similar to the definition of OL_P_Yes, we may define a percentage value to detect whether such small overload exists:

$$Sm\_OL\_No \equiv 100\% \times (I_Z - I_2\ ) / I_Z$$

A positive percentage in Sm_OL_No indicates that there is no un-detected small overload while a negative percentage means that such small overload range exists. Thus the designer should as far as possible minimize the negative percentage. Alternatively, the designer can simply increase the conductor size which will totally eliminate the occurrence of such small overloads. In fact, in Example 3.7, if the size of the conductor is increased from 4 x 10 mm$^2$ to 4 x 16 mm$^2$, the range of loading from 50 A to 65 A will not result in circuit overload since the current rating of the 4 x 16 mm$^2$ circuit is 68 A. We may also analyse using Sm_OL_No:

$$Sm\_OL\_No_{10\ mm} = 100\% \times (50-65) / 50 = -30\%$$

$$Sm\_OL\_No_{16\ mm} = 100\% \times (68-65) / 68 = 4.4\%$$

The margin between $I_N$ and $I_Z$ should be carefully determined. If the value of $I_Z$ is very close to $I_N$, the un-detected small overloads may occur. If the value of $I_Z$ is much higher than $I_N$, then it implies a larger size of cable has been selected which will obviously increase the installation cost. In such arrangements, the cable may not be able to be loaded up to its rated capacity and thus the cable rating will not be fully utilised.

### 3.5.3 Omission of Overload Protection

There are some circuits in which a break in current by the operation of protective devices can cause danger. For example, breaking the current of a lifting electromagnet could cause it to drop its load, or breaking the current in a current transformer could induce a very high e.m.f. In such situations, overload protection can be omitted, and if necessary, it can be replaced by an overload alarm.

To cater for starting condition in designing a circuit for a motor, the designer has to ensure that the protective device of the motor circuit will not trip during motor starting. Thus, if the starting current is large, the rating of the protective device, $I_N$, may have to be much higher than the design current, $I_B$. To provide adequate overload protection, the current rating $I_Z$ of the cable has to be equal to or larger than $I_N$. Thus, it will result in $I_N \gg I_B$ and $I_Z \gg I_B$. In this arrangement, the size of the circuit will be larger than necessary. However, if overload protection is not required, then even if $I_N \gg I_B$, the designer can select $I_Z$ to be independent of $I_N$, and $I_Z \geq I_B$.

As a circuit for a motor is always connected through a starter with overload release, any overload in the motor that may occur will always be interrupted by the built-in overload release. Thus, the protective device of the motor circuit will not be required to provide overload protection. The functions of the protective device are not for overload protection but for switching of the circuit and to provide protection for short circuit that may occur in the circuit.

If overload protection is required, the minimum tabulated current rating for the circuit is obtained by :

$$I_{t,min} = \frac{I_N}{C_a \times C_g \times C_i}$$

For motor circuit or any other circuit where overload protection is not required, the minimum tabulated current rating is [Ref. 2, P59, P177]:

$$I_{t,min} = \frac{I_B}{C_a \times C_g \times C_i}$$

Where the motor is intended for intermitted duty and for frequent stopping and starting, the conductor size shall be increased from 1.2 to 1.4 of the design current to cater for any cumulative effects of the starting periods upon the temperature rise in the circuit.

**Example 3.8**

A motor which has a full load current of 188 A is fed by a multi-core pvc-insulated copper conductor cable installed in trunking at an ambient temperature of 35$^{O}$C. This circuit is protected by a MCCB as shown in Figure 3.9. Due to the high starting current, the current rating of the MCCB is 350 A. Determine the size of the cable under the assumptions that

a) overload protection is not required,
b) adequate overload protection should be provided.

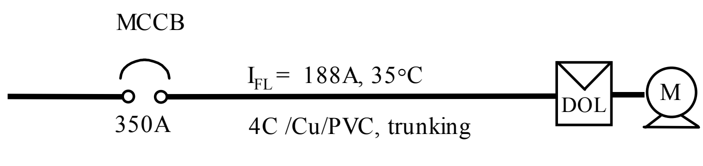



Figure 3.9 Circuit for Example 3.8

**Solution**

(a) For no overload protection, the minimum tabulated current rating is :

$$I_{t,min} = \frac{I_B}{C_a \times C_g \times C_i}$$
$$= \frac{188}{0.94 \times 1 \text{ x } 1} = 200 \text{ A}$$

From Table 4D2A of IEE Regulations [Ref. 2, P 190], column 5, a 120 mm$^2$/4C cable which has a tabulated current rating of 206 A is selected.

(b) To provide adequate protection against overload,

$$I_{t,min} = \frac{I_N}{C_a \times C_g \times C_i}$$
$$= \frac{350}{0.94 \times 1 \times 1} = 372 \text{ A}$$

From the same Table 4D2A, column 5, a 400 mm$^2$/4C cable which has a tabulated current rating of 402 A is selected. The current causing effective operation of the 350 A MCCB is :

$$I_2 = 1.30 \times 350 = 455 \text{ A}$$

$$1.45\ I_Z = 1.45 \times 402 \times 0.94 = 548 \text{ A}$$

Since $I_2 < 1.45\ I_Z$, this circuit satisfies the required overload protection.

It should be noted that under this condition, the conductor's cross-sectional area of the circuit is increased to more than 3 times to meet the additional requirement of overload protection.

## 3.6 PROTECTION AGAINST SHORT CIRCUIT

Calculations are necessary to ensure that the circuit conductors are protected adequately against the short-circuit current. Not only must the protective device open the circuit and interrupt the short-circuit current, it must do so quickly enough to prevent thermal damage to the cable.

### 3.6.1 Required Conditions for Short Circuit Protection

During fault conditions up to a duration of 5 s, the maximum time in seconds that the cable can withstand the fault current can be approximated by the following formula :

$$t_{cable,\,max} = \frac{k^2 S^2}{I_F^2}$$

The maximum time that the cable can withstand, $T_{cable,\ max}$ , is also known as critical time, which is the time taken in seconds for the temperature of the conductors to rise from the rated value $Q_1$ to the critical value $Q_F$. If the conductor temperature exceeds $Q_F$, the insulation material fails and the whole cable is thermally damaged.

Thus, at the maximum short circuit current, the operating time of the protective device should be shorter than $T_{cable,\ max}$ to isolate the fault current so that the conductor temperature will not exceed $Q_F$. The constant k represents the maximum thermal capacity of the conductor for the type of insulation being used, S is the cross-sectional area of the conductor in $mm^2$ and $I_F$ is the prospective short-circuit current in amperes. For a duration of more than 5 s, a more complicated formula has to be used. To assess whether short-circuit protection is provided and how adequate it is, let us define:

$$SC\_P\_Yes \equiv 100\% \times (t_{cable,\ max} - t_{bk,\ 3\text{-phase}\ F}) / t_{cable,\ max}$$

where $t_{bk,\ 3\text{-phase}\ F}$ is the operating time of the breaker corresponding to a current during a 3-phase fault at the cable. The largest current that may flow through the cable occurs during a 3-phase fault. A positive percentage in SC_P_Yes indicates that the circuit meets the requirement for short-circuit protection and a higher percentage implies a higher margin of short-circuit protection. Obviously, if SC_P_Yes is a negative value, the circuit is not protected against short-circuit current.

The value of k is a function of the conductor resistivity and its resistance-temperature coefficient, heat capacity of the conductor material, the rated conductor temperature $Q_1$, and the critical temperature $Q_F$. Some typical values of k are given in Table 3.7.

**Table 3.7 Values of k for calculation of the effects of fault current**

| Conductor | Insulation | $Q_1$, °C | $Q_F$, °C | k |
|---|---|---|---|---|
| Copper | PVC | 70 | 160 | 115 |
| | PVC * | 70 | 140 | 103 |
| | PVC | 30 | 160 | 143 |
| | PVC * | 30 | 140 | 133 |
| | Rubber | 85 | 220 | 134 |
| | XLPE | 90 | 250 | 143 |
| Aluminium | PVC | 70 | 160 | 76 |
| | PVC | 30 | 160 | 95 |
| Steel | PVC | 30 | 160 | 52 |
| Bare Copper | - | 30 | 200 | 159 |
| Bare Aluminium | - | 30 | 200 | 105 |

* for conductors larger than 300 $mm^2$

**Example 3.9**

A motor which has a full load current of 45 A, is fed by a four-core 10 mm$^2$ copper conductors, pvc-insulated cable installed in trunking and protected by a 100-A type B MCB which has a shortest operating time of 0.01 s. The three-phase short-circuit current is 5000 A as shown in Figure 3.10. Does this circuit provide adequate protection for overload? Does this circuit provide adequate protection for short-circuit? Why?

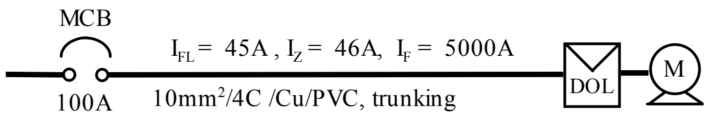



Figure 3.10 Circuit for Example 3.9

**Solution**

Since $I_B$ = 45 A, $I_N$ = 100 A, $I_Z$ = 46 A (from column 5 Table 4D2A of IEE Regulation), this circuit does not provide overload protection since $I_N$ is not $\leq I_Z$ and $I_2$ is not $\leq 1.45\ I_Z$.

For pvc-insulated cable, $Q_1$ = 70$^0$C, $Q_f$ = 160$^0$C and k = 115. To avoid thermal damage to the cable during fault condition, the MCB must operate and isolate the short-circuit current within the maximum time that the cable can withstand as follows :

$$t_{\text{cable, max}} = \frac{k^2S^2}{I_F^2} = \frac{115^2 \times 10^2}{5000^2} = 0.0529 \text{ s}$$

If the operating time of the MCB is specified as 0.01 s that is lower than the critical time of 0.0529 s, this circuit is therefore adequately protected for short circuit. Alternatively, we may verify by:

OL_P_Yes = 100% x (66.7 - 145 ) / 66.7 = -117%

SC_P_Yes = 100% x (0.0529 – 0.01 ) / 0.0529 = 81%

The negative value of -117% indicates that the circuit fails for overload protection but passes the short-circuit protection at a margin of 81%.

**Example 3.10**

A 4 x 10 mm$^2$ circuit clipped directly on a non-metallic surface is protected by a 60-A MCCB which has a maximum operating time of 0.15 s as shown in

Figure 3.11. The expected load current is 50 A while the short-circuit current is 4000 A.

a) Explain why this circuit is not fully protected by overload protection. State the appropriate modifications to provide adequate overload protection.

b) Explain why this circuit is not adequately protected against short-circuit and recommend the necessary remedial solution.

c) If both the conductor size and the breaker operating time remain unchanged, what is the maximum short-circuit current that this circuit can withstand?

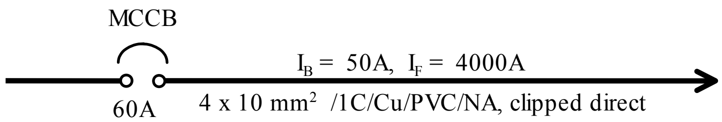



Figure 3.11 Circuit for Example 3.10

**Solution**

(a) (i) From Table 4D1A of IEE Regulation, column 7, the current rating of the 10 mm$^2$ circuit is 59 A. Since $I_N$ = 60 A and $I_Z$ = 59 A, thus $I_N$ is not $\leq I_Z$

(ii) Since $I_2$ = 1.30 x 60 = 78 A, and 1.45 $I_Z$ = 1.45 x 59 = 86 A, it satisfies $I_2 \leq 1.45\ I_Z$. This circuit is not considered fully protected by overload, as it does not satisfy condition (i), although it does satisfy condition (ii).

To provide adequate overload protection including small overloads, the minimum tabulated current rating of the circuit should be :

$$I_{t,min} = 1.3 \times 60 = 78A$$

From table 4D1A of IEE Regulations [Ref. 2, P 188], column 7, the conductor size should be 4 x 16 mm$^2$ which is rated at 79A.

(b) $$t_{cable,\,max} = \frac{k^2 s^2}{I^2} = \frac{115^2 \times 10^2}{4000^2} = 0.0827 \text{ second}$$

Since the maximum operating time of the MCCB is 0.15 s which is larger than the critical time of 0.0827 s, the circuit does not provide adequate protection for thermal damage during short-circuit conditions. The conductor size should be increased from 10 $mm^2$ to a larger cross section as follows :

$$s_{min} = \frac{I\sqrt{t_{bk,\,3\text{-phase},\,F}}}{k} = \frac{4000\sqrt{0.15}}{115} = 13.47\ mm^2$$

Thus, if adequate short-circuit protection is required, the conductor size should be equal to or greater than 13.47 $mm^2$ and thus 16 $mm^2$ is recommended.

(c) For both the conductor size and the breaker operating time to remain unchanged, the maximum short-circuit current that this circuit can withstand is :

$$I_{F,max} = \frac{kS}{\sqrt{t_{bk,\,3\text{-phase}\,F}}} \times \frac{115 \times 10}{\sqrt{0.15}} = 2969\ A$$

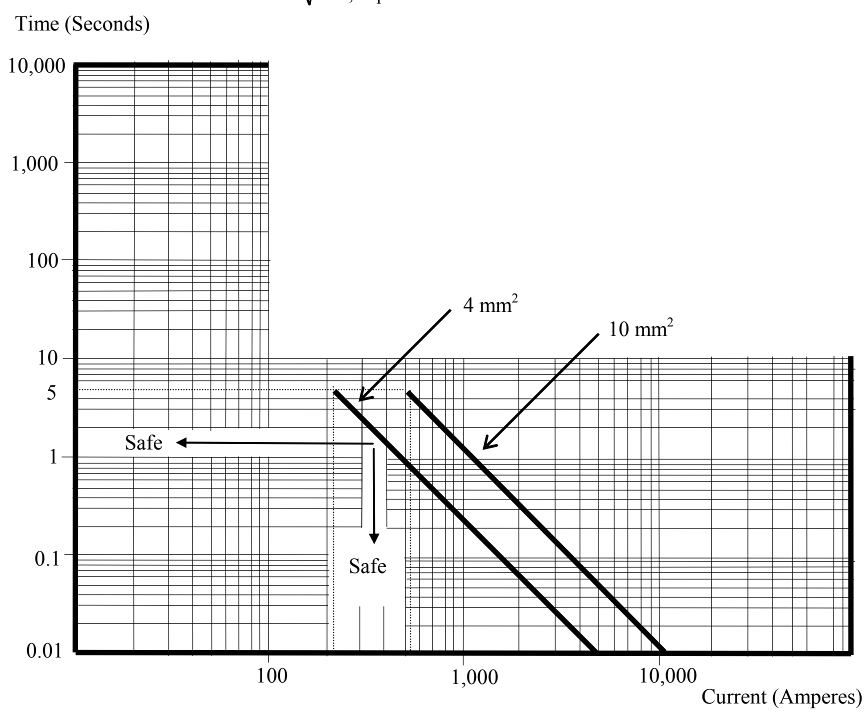



Figure 3.12 The adiabatic equations

### 3.6.2 Adiabatic Equation

The value of k is the same for cables that have the same type of conductor and insulation materials. If the cross-sectional area is also the same, then the product of $k^2S^2$ is a constant in the equation $t_{cable, max} = k^2S^2/I^2$. This equation can be rewritten as $t_{cable, max} = A_1 / I^2$ where $A_1$ is a constant which is equal to $k^2S^2$. Thus, a straight line known as adiabatic equation can be constructed on a log-log scale by substituting different values of I into the equation. The adiabatic equations of the 4 mm$^2$ and 10 mm$^2$ copper conductor, pvc-insulated cables are shown in Figure 3.12.

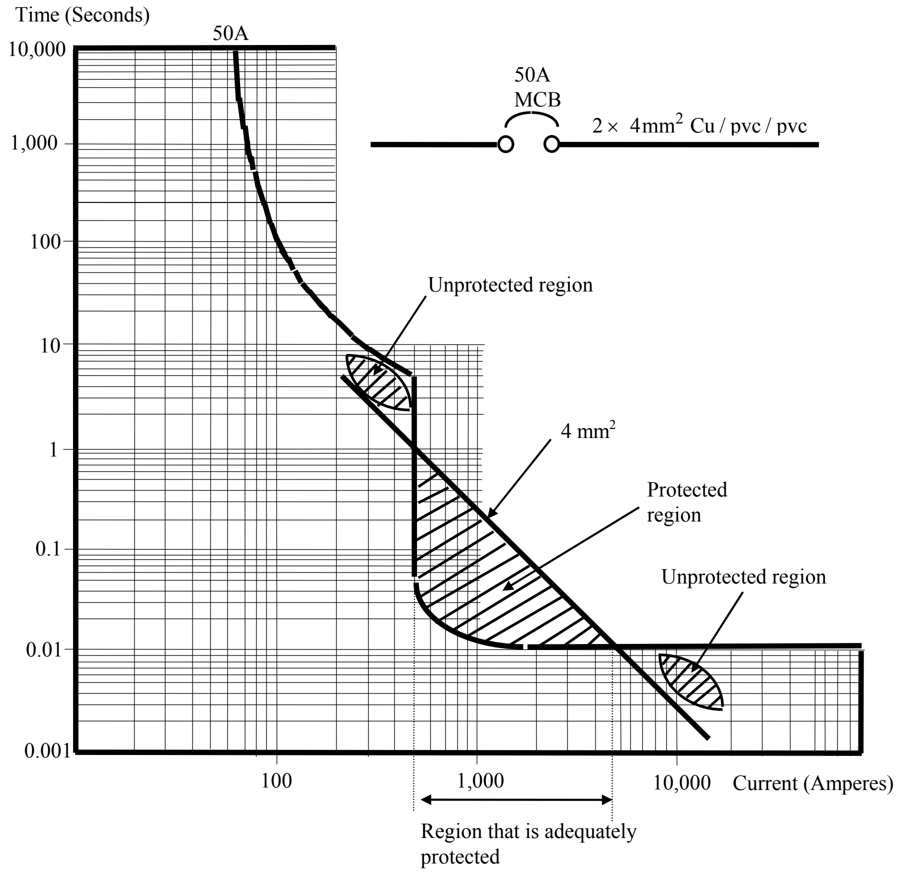



Figure 3.13 Region of short-circuit protection

This adiabatic equation can also be referred to as the time-current characteristic of the cable's withstand capability. The region to the left of the adiabatic equation as shown in Figure 3.12 can be considered as a safe or adequately protected region since any protective device operating in this region will always cut-off the short-circuit current before the cable exceeds its thermal limit. The adiabatic equation of a 4 mm$^2$ copper conductor, pvc-insulated cable is superimposed with the time-current characteristic of a type 3, 50-A MCB as shown in Figure 3.13.

It should be noted that for fault current from 500 A to 4600 A, the circuit is adequately protected since the operating time of the breaker is in the protected region, i.e. the breaker's operating time is less than the critical time of the 4 $mm^2$ cable. However, for current in the range from 206 A to 500 A or higher than 4600 A, the cable is not protected since the breaker's operating time exceeds the critical time of the cable. For current below 206 A, the formula given in Section 3.6.1 is not applicable and thus whether the cable is protected or not is un-defined. If the type 3 MCB is replaced by a type 1 MCB, will the region of protection cover the range from 206 A to 500 A? Why?

### 3.6.3 Formulae for Short-circuit Currents

Three-phase Fault. For 3-phase fault, the current magnitude in each phase is identical except that the angle is shifted by $120^0$ in each phase. Thus, the current in each phase during a 3-phase fault can be calculated by using an equivalent single phase approach as follows :

$$I_{F,3\phi} = \frac{V_{LL}/\sqrt{3}}{\sqrt{(R_S + R_1)^2 + (X_S + X_1)^2}}$$

where $R_S$ and $X_S$ are the per-phase values of the resistance and reactance of the supply source; $R_1$ and $X_1$ are the per-phase values of the resistance and reactance of the phase conductor and $V_{LL}$ is the line-to-line voltage.

Line-to Neutral Fault. By using the same single phase approach, the line-to-neutral short-circuit current can be calculated as follows :

$$I_{F,LN} = \frac{V_{LL}/\sqrt{3}}{\sqrt{(R_S + R_1 + R_n)^2 + (X_S + X_1 + X_n)^2}}$$

where $R_n$ and $X_n$ are the values of resistance and reactance of the neutral conductor.

Line-to-Line Fault. For a line-to-line fault, if the effect of the healthy phase is neglected, the fault current can be calculated as follows :

$$I_{F,LL} = \frac{V_{LL}}{\sqrt{(2R_S + 2R_1)^2 + (2X_S + 2X_1)^2}}$$

The values of the source resistance $R_S$ and reactance $X_S$ should be obtained from the supply utility or can be estimated from the impedance of the incoming transformer. The phase conductor's resistance, $R_1$ and reactance, $X_1$, can be referred to the tabulated voltage drop constant, TVD. If the value of TVD is read from the 2-cable, single phase column, the value of the resistance can be obtained by multiplying 0.5 to $TVD_r$ and the value of reactance by 0.5 to $TVD_X$. If the value of the TVD is read from the 3-or-4-cable, three phase column, the multiplication factor $1/\sqrt{3}$ is used instead of 0.5. The value of resistance obtained through TVD is based on a conductor temperature of $70^OC$. During fault condition, the conductor temperature is higher than $70^OC$ and for more accurate calculation, temperature correction on the resistive value is required. A typical conductor temperature during fault conditions is normally obtained by taking the average of the rated conductor temperature $Q_1$, and the critical conductor temperature $O_F$ i.e. $(Q_1+Q_f)/2$. If $Q_1 = 70^OC$, and $Q_f = 160^OC$, the average conductor temperature is $115^OC$. Thus, the value of resistance at $115^OC$ is :

$$\Omega_{115} = \Omega_{70}\left(\frac{230+115}{230+70}\right) = \Omega_{70} \times 1.15$$

**Example 3.11**

A 400 V, three-phase circuit is fed from a main distribution board where the source resistance $R_S$ is 0.02 $\Omega$ and the source reactance $X_S$ is 0.06 $\Omega$. The circuit is run in single-core, non-armoured, pvc-insulated cable having copper conductors of 95 mm$^2$ at a length of 15 m clipped direct and flat touching on a non-metallic surface as shown in Figure 3.14. Determine the three-phase short-circuit current and the line-to-neutral short circuit current.

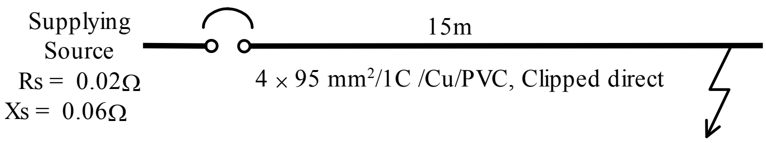



Figure 3.14 Circuit for Example 3.11

**Solution**

From Table 4D1B of IEE Regulation [Ref. 2, P 189] or Table 9D1 of CP5 [Ref. 4] column 8, the tabulated voltage-drop constant for the 95 mm$^2$ cable is $(mV/A/m)_r$ = 0.41 m$\Omega$ and $(mV/A/m)_X$ = 0.23 m$\Omega$. Thus,

$$R_1 = \frac{0.41 \times 15}{\sqrt{3}} \times 10^{-3} \times 1.15 = 0.0041\ \Omega \text{ at } 115\,^\circ\mathrm{C}$$

$$X_1 = \frac{0.23 \times 15}{\sqrt{3}} \times 10^{-3} = 0.00199\ \Omega$$

The three-phase short-circuit current is :

$$I_{F,3\,\text{phase}} = \frac{V_{LL}/\sqrt{3}}{\sqrt{(R_S + R_1)^2 + (X_S + X_1)^2}}$$

$$= \frac{400/\sqrt{3}}{\sqrt{(0.02 + 0.0041)^2 + (0.06 + 0.00199)^2}}$$

$$= \frac{230.9}{0.0665} = 3474.2\ \mathrm{A} \angle -69^\circ$$

The line-to-neutral short-circuit current is :

$$I_{F,LN} = \frac{V_{LL}/\sqrt{3}}{\sqrt{(R_S + R_1 + R_n)^2 + (X_S + X_1 + X_n)^2}}$$

$$= \frac{400/\sqrt{3}}{\sqrt{(0.02 + 0.0041 \times 2)^2 + (0.06 + 0.00199 \times 2)^2}}$$

$$= \frac{230.9}{0.0699} = 3303\ \mathrm{A} \angle -66^\circ$$

## 3.7 REFERENCES

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[4] CP5 : 1998, "Code of Practice for Electrical Installations", Singapore Productivity and Standards Board, 1998

[5] BS 6207 : 1991, "Mineral-insulated Copper-sheaths Cables with Copper Conductors", British Standard Institution, 1991.

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## CHAPTER 4

# EARTHING AND EARTH FAULT PROTECTION

The earth is a huge conductor which can be considered to be at reference or zero potential. Human beings are normally in direct contact with this earth. Any metal parts which become charged with respect to earth may cause a hazard or 'electric shock' if touched by a human body. The purpose of earthing is to link together all metalwork, except the live conductor, to the earth potential so that there is no excessive potential differences, either between different metal parts or between any metal parts and earth.

In a three-phase a.c. system, the best way to obtain the system neutral for earthing purposes is to use generators or source transformers with Y-connected windings. The neutral is readily available for connection to earth and the earth fault current can then return to this system neutral or system earth. If such a system neutral is not available in the delta-connected system, earthing transformers may be used to obtain the neutral.

## 4.1 EARTHING IN A UTILITY SYSTEM

Figure 4.1 shows the earthing arrangements in a typical 230-kV and 66-kV transmission system. In the 230-kV system, it is a solidly earthed system. The system earthing is implemented at the generating station C through the 13.2/230-kV generator step-up transformers and also at various locations in the main substations through the 230/66-kV transformers. Each generator step-up transformer has a delta-earthed wye connection and each 230/66-kV transformer has a earthed wye-delta-resistance earthed wye connection. Thus, during an earth fault in the 230-kV network, the fault current will have to return to the neutral of the 230-kV system at either the high-tension (HT) side of the generator step-up transformers or the HT side of the main 230/66-kV transformers. In this arrangement, the earth fault current will return to more than one location depending on the number of source transformers operated in parallel.

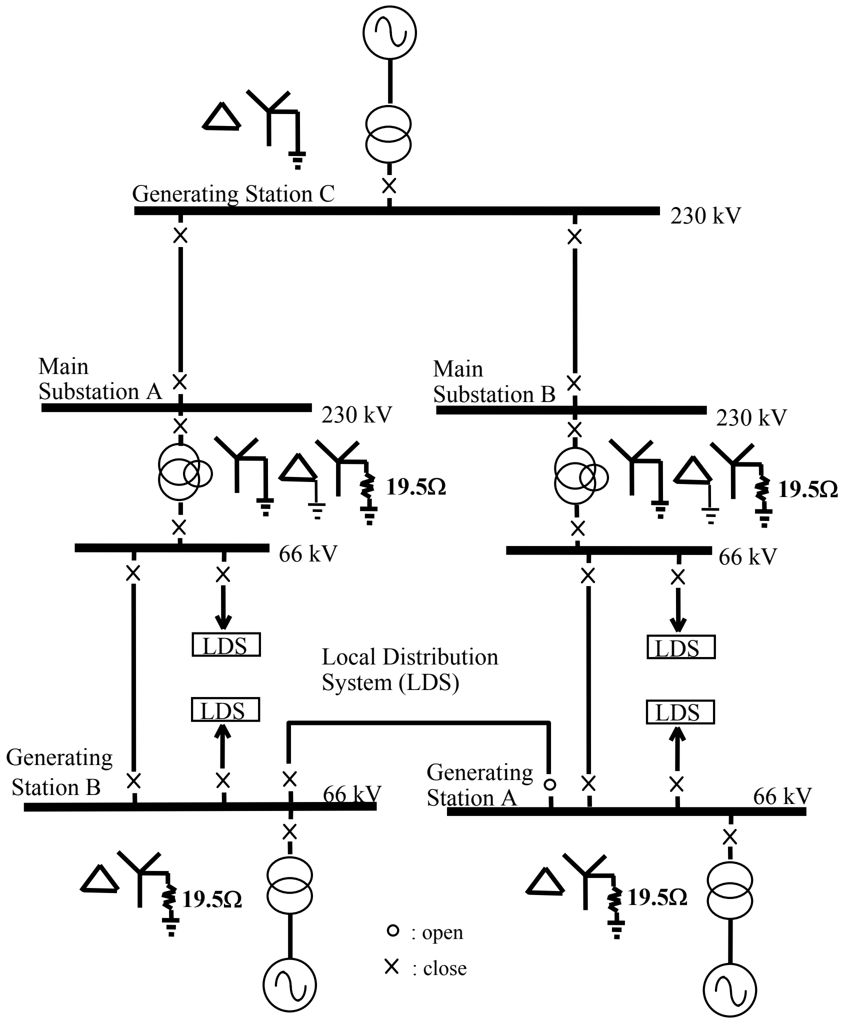



Figure 4.1 Transmission system earthing

In the 66-kV system, it is earthed through a 19.5 Ω resistor at either the low-tension (LT) side of one 230/66-kV transformer at each main substation and/or the HT side of the 11/66-kV generator step-up transformers at the generating stations A and B. The connection of the 66-kV network through the 19.5 Ω resistor to earth will limit the earth-fault current to within 2000 A per source transformer, ie. :

$$I_{EF} = \frac{(66 \times 1000)/\sqrt{3}}{19.5} = 1954 \text{ A}$$

To limit the earth fault current, it is a normal practice to earth through only one 19.5 $\Omega$ resistor within each generating station and also only one 19.5 $\Omega$ resistor within each main 230/66-kV substation, although there may be several 230/66-kV transformers operated in parallel within each main substation. If the main substation A is interconnected with generating station B, during an earth fault in the 66-kV network, the earth fault current will return to the neutral of the 66-kV system through one 19.5 $\Omega$ resistor at generating station B and another 19.5 $\Omega$ resistor at the main substation A. In this case, the earth fault current will be limited to 4000 A as there are two 19.5$\Omega$ resistors operating in parallel.

Figure 4.2 shows the earthing arrangement in a typical 22-kV distribution system. The neutral of the 22-kV system is earthed through one 6.5 $\Omega$ resistor at the 22-kV side of each 66/22-kV transformer. Each 66/22-kV distribution transformer is at an unearthed wye-delta-resistance earthed wye connection. Thus, during an earth fault in the 22-kV system, the earth-fault current will return through the resistance-earthed neutral. The connection of the 22-kV neutral through the 6.5 $\Omega$ resistor to earth will also limit the earth fault current to within 2000 A per source transformer:

$$I_{EF} = \frac{(22 \times 1000)/\sqrt{3}}{6.5} = 1954 \text{ A}$$

The 66/22-kV transformers are generally operated with two transformers in parallel at each substation. Thus the maximum earth fault current under this operating condition will be 4000 A, since there are two 6.5-$\Omega$ resistors operating in parallel. At substations C, D and E, the 22/0.4-kV transformer is at a delta-earthed wye connection. Thus, during an earth fault in the low-voltage (LV) system, the earth fault current will return to the respective earthed neutral. As the neutral is solidly earthed, the earth fault current in each LV system will be considerably higher.

It should be noted that by properly arranging the earthing system at each voltage level, the magnitude of the earth-fault current can be controlled to an acceptable level. Furthermore, the earth fault currents at various voltage levels would never 'mix-up' and they can always find their own paths and return to their designated 'homes' (i.e. their respective earthing neutrals). Thus, it makes sensitive and high-speed earth-fault protection possible based on the detection of the earth-current flow.

## 4.2 METHODS OF SYSTEM EARTHING

An electric system can also be designed as an unearthed system, i.e. with the neutral of the system isolated from earth. During a line-to-earth fault, as the neutral of the system is unearthed, no fault current will flow from the system. The advantage of such an unearthed system is its ability to continue operations during a line-to-ground fault. It will not result in the automatic tripping of the circuit. Thus, the unearthed system offers an added degree of service continuity.

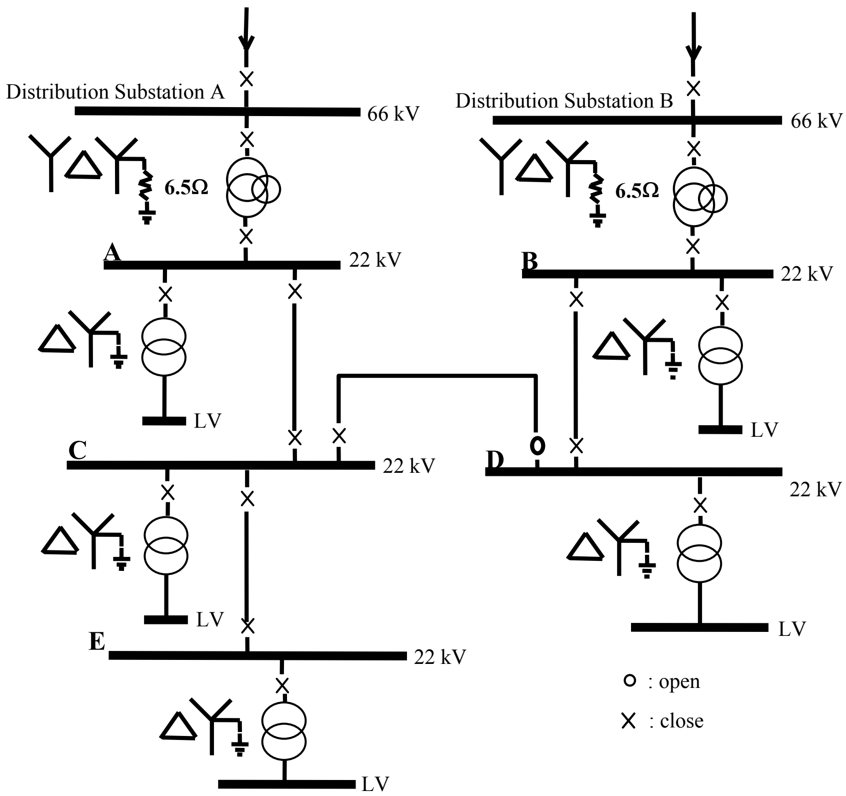



Figure 4.2 Distribution system earthing

However, as the system is unearthed and no fault current flows during a line-to-ground fault, the faulty phase will then take the earth voltage. As a result, the magnitude of the voltage between each healthy line to earth is equal to the line-to-line voltage. This causes a rise in voltage on the other two healthy phases of approximately $\sqrt{3}$ of the voltage between each phase to ground. In other words, the other two phase conductors throughout the entire system are subjected to 73% overvoltage. This additional voltage stress may produce insulation breakdown in the circuits, especially machine windings and other voltage sensitive equipment. Furthermore, due to the capacitance effect from the two healthy phases to ground, a capacitive current will flow from these two phases through their insulation to ground and return to the system neutral by way of the fault. This is, in fact, similar to a capacitance grounded system and it may have an intermittent arcing at the faulty location. As a result, the ungrounded system is subjected to a transient overvoltage which may cause a further fault to occur. Thus, most of the electrical systems employ some methods of earthing the system neutral at one or more points. The common methods are resistance earthing, reactance earthing or solid earthing [Ref 1].

Singapore's practice requires that one point of every system shall be earthed. This requirement is designed primarily to preserve the security of the system by ensuring that the potential on each conductor is restricted to such a value as is consistent with the level of insulation applied. From the safety point of view, it is equally important that earthing should ensure efficient and fast operation of protective gears in the case of earth faults [Ref 2, P 11].

**Resistance - Earthed Systems**

In a resistance-earthed system, the system neutral is connected to earth through one or more resistors. In this method, the resistance is actually in parallel with the system-to-ground capacitive reactance. The value of the resistance should be selected in such a way that this parallel circuit behaves more like a resistor than a capacitor.

Resistance earthing can be of high-resistance earthing or low-resistance earthing depending on the magnitude of the earth-fault current permitted to flow. Both methods are designed to limit the transient overvoltages due to the effect of the capacitive earthing during a line-to-earth short-circuit. In the high-resistance earthing, the earth fault current is limited to 5 A and it may not require the immediate clearing of a ground fault. For low resistance earthing, the earth fault current is in the range from 100 A to 2000 A. Due to the low resistance value, the line-to-earth voltage can be better controlled and sufficient earth fault current is available to operate the earth fault relay selectively.

**Reactance - Earthed Systems**

In a reactance-earthed system, the system neutral is connected to earth through a reactor. In terms of reducing the transient overvoltage, it is not as effective as resistance earthing. Thus, a reactance earthing system is not ordinarily employed in industrial power systems.

**Solidly Earthed Systems**

A solidly earthed system refers to the connection of the neutral of a generator or transformer directly to earth. Thus, it totally eliminates the overvoltage in the two healthy phases during a line-to-ground fault. However, it will result in the highest magnitudes of earth-fault current. Although each earthing system has its own advantages, solidly earthed systems are used extensively at all operating voltages.

## 4.3 EARTHING IN LOW-VOLTAGE SYSTEMS

For low-voltage system earthing, IEE Regulations [Ref 3] define an electrical system as consisting of a single source of supply and an installation. System earthing refers to the earthing arrangement at the source of energy and at the installation. There are five types of earthing systems classified by a combination of two to four letters namely TT, TN-S, TN-C, TN-C-S and IT. The first letter indicates the supply earthing arrangement:

- T: Earth, i.e. one or more points of the supply are directly connected to earth. The letter T is abbreviated from the French word Terre, which means earth.
- I: Impedance, i.e. supply system is not earthed, or one point is earthed through a fault-limiting impedance.

The second letter indicates the installation earthing arrangement:

- T: Earth, i.e. exposed conductive parts connected directly to earth.
- N: Neutral, i.e. exposed conductive part connected directly to the neutral point of the source of supply.

The optional third or fourth letter indicates the earthing conductor arrangement:

- S: Separate, i.e. separate neutral and protective conductors.
- C: Combined, i.e. neutral and protective conductor combined in a single conductor.

### 4.3.1 Installation Earthing

All metalwork of an electrical installation, other than parts which are normally live, should be connected to a main earthing terminal. The main earthing terminal shall be connected to earth by an appropriate earthing method [Ref 3, P 92]. Effective earthing of each exposed-conductive-part of the installation is essential for protection against electric shock. This type of earthing should be arranged to meet the following two objectives :

(a) to maintain, as close as practicable, the exposed-conductive-parts at earth potential.
(b) to ensure that any earth fault current will be returned safely to its source via a properly designed low-impedance path.

The earthing arrangements shall be co-ordinated so that during an earth fault, the voltages between simultaneously accessible exposed-conductive-parts and extraneous-conductive-parts occurring anywhere in the installation shall be of such magnitude and duration as not to cause danger [Ref 2, P 35]. A typical earthing arrangement of an installation is shown in Figure 4.3.

#### Exposed-Conductive-Part

The exposed-conductive-part refers to any metallic part of electrical equipment which can be touched and which is not a live part but may become live under fault conditions. These include the metallic enclosures of Class I current-using equipment, metallic cable sheaths, cable trays, trunkings and metallic conduits. Class I equipment refers to those equipment in which protection against electric shock does not rely on basic insulation only, but which includes means for the connection of exposed-conductive-parts to a protective conductor.

#### Extraneous-Conductive-Part

The extraneous-conductive-part is a conductive part liable to introduce a potential, generally earth potential and not forming part of the electrical installation. It includes non-electrical service pipes and ducting, such as water pipes, HVAC ducting, exposed metallic structural parts in buildings, and lightning protection system. It is quite likely that a person could be in simultaneous contact with an exposed-conductive-part (which may be made live by an earth fault) and a nearby extraneous-conductive-part.

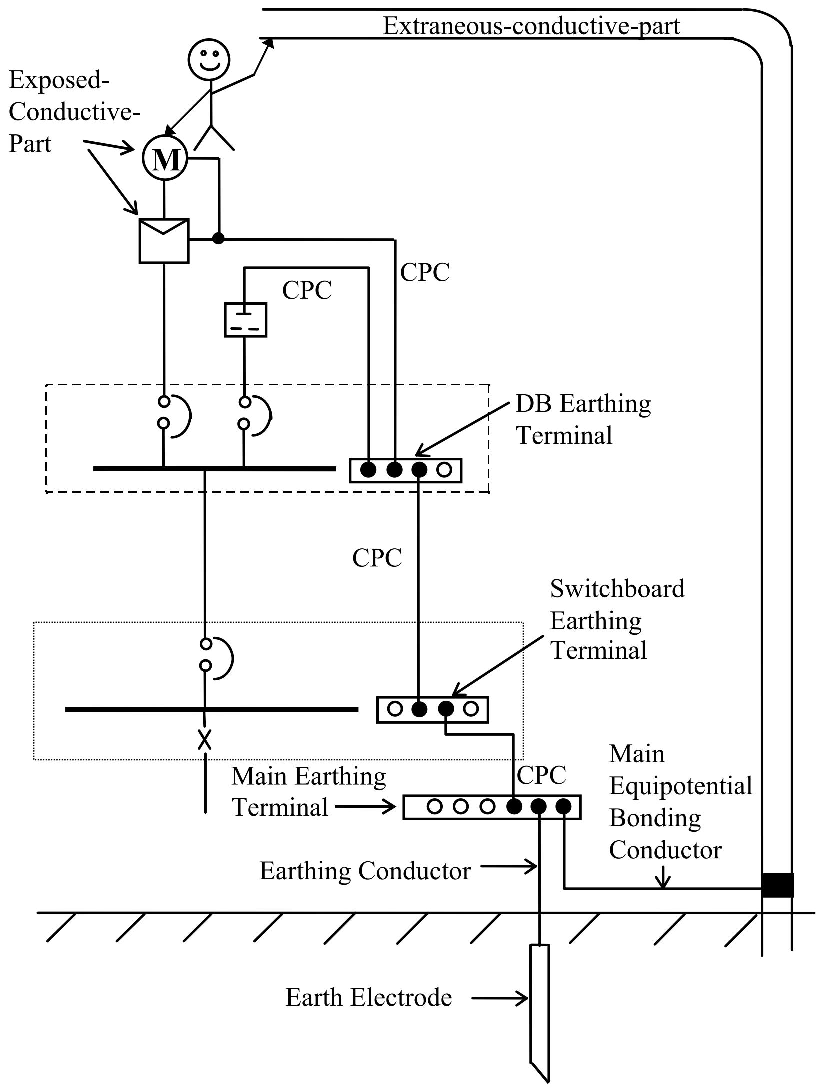



Figure 4.3 Earthing arrangement of an Installation

**Circuit Protective Conductor**

A circuit protective conductor (CPC) is usually known as earth continuity conductor or 'earth wire' which connects the exposed-conductive-parts of the current-using equipment to the respective distribution boards and from each distribution board to the main earthing terminal of an installation as shown in Figure 4.3. CPC forms part of the earth fault loop impedance and will carry the earth fault current in the event of an earth fault. The cross-sectional area of every protective conductor, other than an equipotential bonding conductor, shall be calculated in accordance with the following formula [Ref. 3, P 94], [Ref. 8, P 119] :

$$S \geq \frac{I_{EF}\sqrt{t_{bk,Ief}}}{k}$$

where : S is the minimum cross-sectional area of the protective conductor in $mm^2$, $I_{EF}$ is the earth fault current in amperes, $t_{bk,Ief}$ is the operating time of the protective device in seconds corresponding to the earth fault current $I_{EF}$ and k is the thermal capacity constant of the CPC. The values of k are given in Section 3.6.

Alternatively, the size of CPC can also be determined based on the size of the phase conductor in accordance with Table 4.1[Ref.3, P97].

**Table 4.1 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 |

**Equipotential Bonding Conductor**

Bonding refers to tying together the exposed-conductive-parts and the extraneous-conductive-parts. It is vital in order to minimise any potential differences that might exist between them during an earth-fault. The main equipotential bonding conductor refers to the conductor connecting from the extraneous-conductive-part to the main earthing terminal to create an earthed equipotential zone.

### 4.3.2 TT System

In the TT system, the source of supply is directly earthed (T) and the the installation's earthing terminal, which is connected to the exposed-conductive-parts, is also directly earthed (T) through its own earth electrode. The earthing at the source of supply is independent of the earthing at the installation. This arrangement is shown in Figure 4.4. The main feature of this system is that there is no continuous metallic path between the exposed-conductive-parts and the neutral of the source. The earth-fault current flows via two earth electrodes and the mass of the earth. The earth fault current is :

$$I_{EF,TT} = \frac{V_{LL}/\sqrt{3}}{Z_S + Z_E + R_1 + R_{CPC} + R_B + R_A} = \frac{V_{LL}/\sqrt{3}}{Z_{EFL,TT}}$$

Where : $Z_S$ is the source impedance (i.e. $R_S$ + $jX_S$ ), $Z_E$ is the phase conductor impedance external to the installation (i.e. $R_E$ +$jX_E$.), $R_1$ is the phase conductor resistance of the installation, $R_{CPC}$ is the resistance of the circuit protective conductor, and $R_B$ and $R_A$ are the resistances of the earthing conductor and the earth electrode at the installation and at the source of supply respectively. $Z_{EFL,TT}$ is the earth fault loop impedance in the TT system:

$$Z_{EFL,TT} = (R_S + R_E + R_1 + R_{CPC} + R_B + R_A) + j(X_S + X_E)$$

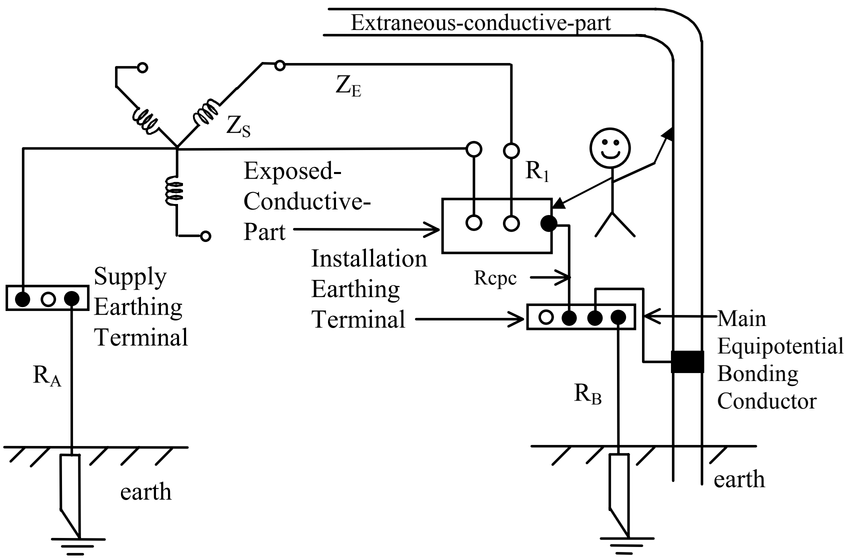



Figure 4.4 TT System

As shown in Figure 4.4, at the installation's earthing terminal, the exposed-conductive-parts and the extraneous-conductive-parts are connected together to provide an equipotential reference. Thus, during an earth fault, the voltage at the exposed-conductive-parts, with respect to earth (usually known as touch voltage or shock voltage), is:

$$V_{shock,\,TT,Yes} = I_{EF,TT} \times R_{CPC}$$

If, however, an equipotential zone is not created, i.e. without the main equipotential bonding, the touch voltage is:

$$V_{shock,\,TT,No} = I_{EF,TT} \times (R_{CPC} + R_B)$$

Obviously, the shock voltage without the equipotential zone, $V_{shock,\ TT,No}$, is much higher than the shock voltage with the equipotential zone $V_{shock,TT,Yes}$.

### 4.3.3 TN-S System

In the TN-S system, the source of supply is directly earthed (T) and the exposed-conductive-parts connected to the installation's earthing terminal is earthed at the neutral point (N) of the supply source through a separate (S) protective conductor as shown in Figure 4.5. The main feature of this system is that there is a continuous metallic path from the exposed-conductive-part to the neutral of the source and therefore, it usually results in a higher earth fault current. The earth fault current is also high enough to operate overcurrent protective devices. The earth fault current can be calculated by :

$$I_{EF,TN} = \frac{V_{LL}/\sqrt{3}}{Z_S + Z_E + Z_1 + Z_{cpc} + Z_{pc}} = \frac{V_{LL}/\sqrt{3}}{Z_{EFL,TN}}$$

where $Z_1$, $Z_{CPC}$ and $Z_{PC}$ are the impedances of the phase conductor, the CPC, and the protective conductor respectively. The impedance of the protective conductor depends on the distance from the installation to the source of supply, but in general, $Z_{EFL,TN}$ is very much lower than $Z_{EFL,TT}$ mainly due to the values of $R_A$ and $R_B$ associated with the TT system. As a result, the earth fault current in a TN system will be much higher.

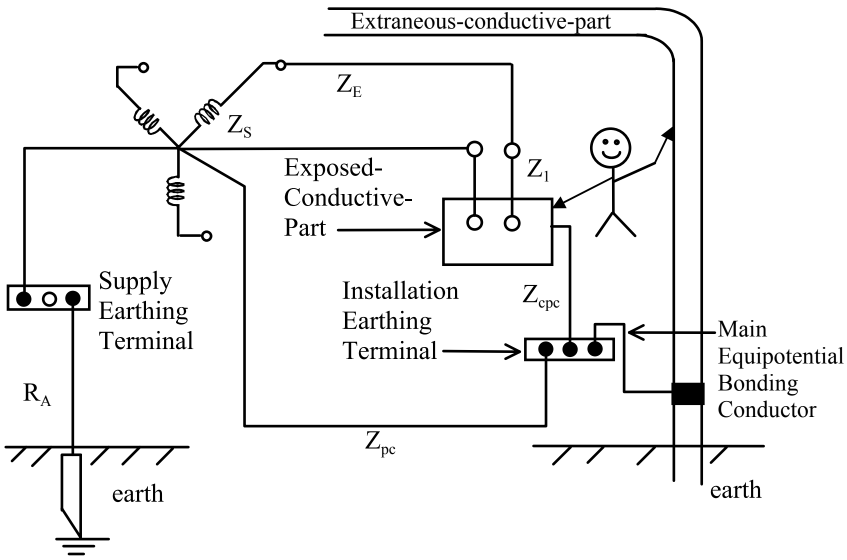



Figure 4.5 TN-S system

The shock voltages in the TN system with and without equipotential bonding are:

$$V_{shock,TN,Yes} = I_{EF,TN} \times Z_{CPC}$$

$$V_{shock,TN,No} = I_{EF,TN} \times (Z_{CPC} + Z_{PC}) \text{ for sustained fault, or}$$

$$= I_a \times (Z_{CPC} + Z_{PC}) \text{ if the breaker trips at a current of } I_a)$$

#### 4.3.4 TN-C-S System

The TN-C-S system is similar to the TN-S system, i.e. the source of supply is earthed (T) and the installation's earthing terminal is earthed at the neutral point (N) of the supply source. However, the separate (S) protective conductor is subsequently combined (C) with the neutral conductor at the installation's incoming supply terminal as shown in Figure 4.6. However, this type of system is not implemented in Singapore.

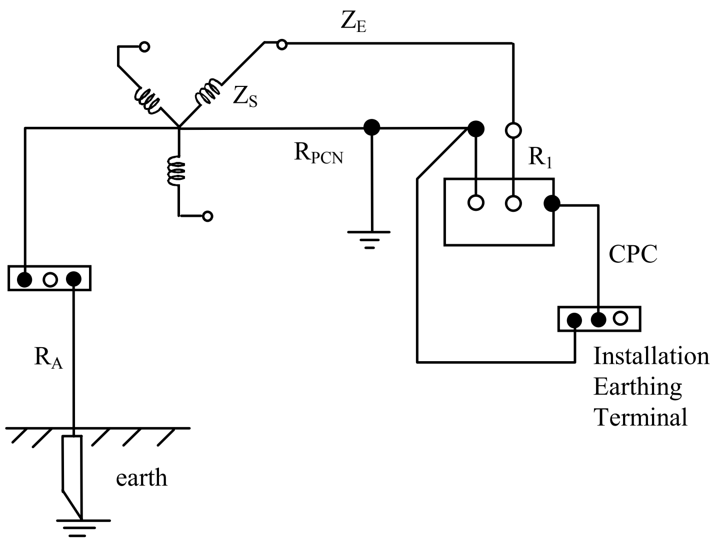



Figure 4.6 TN-C-S System

#### 4.3.5 TN-C and IT Systems

TN-C system is similar to the TN-S system except that the separate protective conductor that connects the installation's earthing terminal to the source's neutral (N) is combined (C) with neutral conductor. In this system, RCCBs cannot be used as they will not detect an earth fault. TN-C system is also not implemented in Singapore.

An IT system is normally not permitted on the low-voltage systems. The source of supply is either completely isolated (I) from earth, or is earthed through a high impedance. However, the installation's earthing terminal is directly earthed (T) through its own electrode. The IT system is also not implemented in Singapore.

## 4.4 EARTH FAULT PROTECTION

The earth fault protection for low-voltage systems is based on the protection against indirect contact for electric shock. It is dependent on the protection by earthed equipotential bonding and automatic disconnection of supply as stated in IEE Regulation 413-02 [Ref 3, P 31]. The disconnection of supply applies to any circuit including distribution circuits and final circuits in which an earth fault may occur. The characteristics of each protective device, the earthing arrangements and the relevant impedance of the circuit shall be co-ordinated so that during an earth fault, the touch voltage (i.e. the potential differences between simultaneously accessible exposed and extraneous-conductive-parts) occurring anywhere in the installation shall be of such magnitude and duration as not to cause danger[Ref. 2, P35].

The human body is composed largely of water and has very low resistance. The skin, however, if it is not wet or burnt, has a much higher resistance. Thus, most of the resistance to the passage of current through the body is at the points of entry and exit through the skin. The average values of body impedance are in the range from 1000 to 3000 ohms. [Ref. 4, P19]. Based on an average human impedance of 2000 ohms, the current that passes through the human body is 115 mA for a touch voltage of 230 V, or 25 mA for a touch voltage of 50 V. As reported by IEC [Ref. 4, P39], for an a.c. current from 15 to 100 Hz, the human body can withstand 30 mA for 5 s or 100 mA for 0.5 s. Thus, the criterion in determining the disconnection time of protective devices for protection against electric shock is usually based on a touch voltage of 230 V for 0.4 s or 50V for 5 s.

### 4.4.1 Protection on TN System

According to IEE Regulations 413-02-06 to 413-02-17 [Ref. 3, P31], for an installation which is part of a TN system, each exposed-conductive-part shall be connected to the main earthing terminal which shall be connected to the earth point of the supply source. One or both of the following two types of protective devices shall be used : (a) an overcurrent protective device, (b) a residual current device.

**Protection Provided by an Overcurrent Device**

During an earth fault, the characteristics of each protective device and the earth fault loop impedance, $Z_{EFL,TN}$, of each circuit protected by it should be such that automatic disconnection of the supply will occur within a specified time and should satisfy :

$$Z_{EFL,TN} \leq \frac{V_{LL}/\sqrt{3}}{I_a}$$

where : $Z_{EFL,TN}$ is the earth fault loop impedance, $V_{LL} / \sqrt{3}$ is the rated line-to-earth voltage and $I_a$ is the current causing the automatic operation of the protective device within the specified time.

**(i) Hand-held equipment at 0.4 s.** For final circuit which supplies socket outlets or hand-held Class I equipment (defined in the sub-heading: exposed-conductive-parts in Section 4.3.1), the maximum disconnection time should be specified according to the rated line-to-earth voltage as shown in Table 4.2 [Ref. 3, P 32].

**Table 4.2 Disconnection Time for TN Systems**

| Voltage (V) | Time in seconds |
|---|---|
| 220 - 277 | 0.4 |
| 400 | 0.2 |
| >400 | 0.1 |

The maximum earth fault loop impedances corresponding to a list of overcurrent protective devices which can achieve the required disconnection time of 0.4 s are stated in Tables 41B1 and 41B2 of the IEE Wiring Regulations [Ref 3, P 33]. The impedances, $Z_{EFL,TN,MAX}$, in these tables are obtained by :

$$Z_{EFL,TN,max} = \frac{\text{Rated line - to - earth Voltage}}{\text{Effective current operated at 0.4 s}}$$

For example, if the overcurrent protective device is a 32-A type C MCB, the operating time is 5 s for a current less than 320 A and 0.04 s for any current equal to or greater than 320 A. Thus, the current causing the MCB to operate at 0.4 s is 320 A and the corresponding maximum earth fault loop impedance is :

$$Z_{EFL,TN,max,\,32\,A,MCB,C} = \frac{240}{320} = 0.75\ \Omega$$

The value of 0.75 Ω is identical to those listed in Table 41B2(h) of IEE Regulations [Ref. 3, P 33]. For MCBs, as they are operated by the electromagnetic tripping, the operating time is in the range from 0.01 s to 0.1 s, although the required operating time is 0.4 s.

If the rated line-to-earth voltage is 230 V, then

$$Z_{EFL,TN,max,32A,MCB,C} = \frac{230}{320} = 0.719\ \Omega$$

**(ii) Fixed equipment at 5 s.** For a distribution circuit, or a final circuit supplying only stationary equipment, a disconnection time not exceeding 5 s is permitted. [Ref 3, P 35]

**(iii) Optional disconnection time at 5 s.** Irrespective of the value of the line-to-earth voltage for a final circuit which supplies a socket-outlet or portable hand-held class I equipment, and which is within the earthed equipotential zone, the disconnection time is permissible to increase to a value not exceeding 5 s, if the impedance of CPC is less than a value given in Table 41C of the IEE Regulations [Ref 3, P 34]. The maximum impedances of the CPC corresponding to a list of overcurrent protective devices listed in Table 41C are obtained by :

$$Z_{CPC,TN,max} = \frac{50\ \text{V}}{\text{Effective current operated at 5s}}$$

If the overcurrent protective device is a 32-A BS 88 fuse and the current causing the fuse to operate at 5 s is 125 A, the maximum impedance allowed of the CPC is :

$$Z_{CPC,TN,max,32A,fuse} = \frac{50\ \text{V}}{125} = 0.40\ \Omega$$

If the overcurrent protective device is a 32-A type 3 or type C MCB, and the current causing the MCB to operate at 5 s is 320 A, the maximum impedance allowed for the CPC is :

$$Z_{CPC,TN,max,32A,MCB,C} = \frac{50}{320} = 0.16\ \Omega$$

The values of 0.4 Ω and 0.16 Ω are identical to those values listed in Table 41C (a) and (h) of IEE Regulations [Ref. 3, P 34, 35] respectively.

**Protection Provided by a Residual Current Device**

If the protection is provided by a RCCB, the following condition shall be satisfied :

$$Z_{EFL,TN} \times I_{\Delta N} \leq 50\ \text{V}$$

where : $Z_{EFL,TN}$ is the earth fault loop impedance and $I_{\nabla N}$ is the rated residual operating current of the RCCB in amperes.

## 4.4.2 Protection on TT System

According to IEE Regulation 413-02-18 to 413-02-20, for an installation which is part of a TT system, every exposed-conductive-part shall be connected via the main earthing terminal to a common earth electrode. One or both of the following protective devices shall be used: (a) a residual current device, (b) an overcurrent protective device.

In the TT system, the earth fault loop impedance is usually higher than the TN system and thus, the earth fault current may not be high enough to operate the overcurrent protective device in time to disconnect the circuit. Thus, in this system, the use of RCCB is preferred. In addition, the shock voltage shall be limited to not more than 50 V by satisfying the following conditions :

$$R_a I_a \leq 50 \text{ V}$$

where : $R_a$ is the sum of the resistances of the earth electrode, earthing conductor and the CPC connecting to the exposed-conductive-part. $I_a$ is the current causing the automatic operation of the protective device within 5 s. If the protective device is a RCCB, $I_a$ is the rated residual operating current $I_{\Delta N}$.

As the value of $R_a$ includes the resistance of the earthing conductor and the earth electrode ( $R_B$), the calculated touch voltage is actually based on an installation without the main equipotential bonding. The shock voltage is calculated by :

$$V_{shock,TT,No} = I_{a,TT} \times R_a = I_{a,TT} \times (R_{CPC} + R_B)$$

If the main equipotential bonding has been installed, the shock voltage is:

$$V_{shock,TT,Yes} = I_{a,TT} \times (R_{CPC}), \text{ or}$$

$$= I_{EF,TT} \times (R_{CPC}) \text{ if protective device does not operate}$$

It is obvious that $V_{shock,TT,Yes} < V_{shock,TT,No}$ and thus, the shock voltage will be lower than 50 V if the calculation is based on $V_{shock,TT,No}$. However, it should be noted that although the value of $R_{CPC}$ is always within 1 Ω [Ref. 2, P 43], the earth electrode resistance may be as high as 5 Ω for most locations [Ref. 5, P 28]. A detailed calculation of earth fault current and shock voltage [Ref. 7] using a full three-phase representation for both TT and TN-S systems are given in Appendix C.

## 4.5 APPLICATION EXAMPLES

**Example 4.1**

In part of a TN-S system, the supply to a final DB is fed from a 22/0.4 kV transformer via a main DB as shown in Figure 4.7. The main circuit from the transformer to the main DB is a multicore, pvc-insulated, copper conductor cable of 120 mm$^2$ with a separate protective conductor of 70 mm$^2$, pvc-insulated copper conductor cable. The sub-circuit from the main DB to the final DB is a twin-core, pvc-insulated, copper conductor cable of 35 mm$^2$ with a separate CPC of 6 mm$^2$, pvc-insulated copper conductor cable. The transformer has a resistance of 0.002 Ω and a reactance of 0.008 Ω with respect to the voltage of 400V. During fault condition, it is assumed that the temperatures of the 35 mm$^2$ phase conductor and the 6 mm$^2$ CPC are 115$^0$C and 95$^0$C respectively, and that the 120 mm$^2$ phase conductor and the 70 mm$^2$ CPC are 70$^0$C and 30$^0$C respectively.

(a) Determine the earth fault loop impedance at the final DB and the earth fault current for a line-to-earth short circuit inside the final DB.

(b) Is the CPC size of 6 mm$^2$ appropriate? Why?

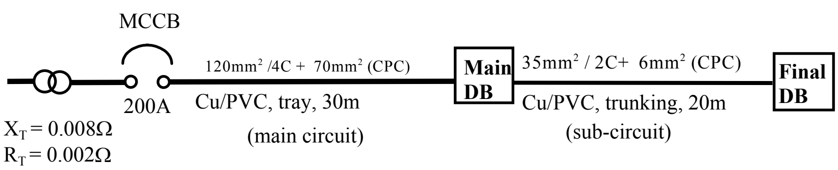



Figure 4.7 Installation for Example 4.1

**Solution**

(a) From Table 4D2B(columns 3, 4) of IEE Regulations [Ref. 3, P 191]:

| | | | |
|---|---|---|---|
| 120 mm$^2$ | : | $(mV/A/m)_r$ = 0.33 mΩ, | $(mV/A/m)_x$ = 0.135 mΩ |
| 70 mm$^2$ | : | $(mV/A/m)_r$=0.63 mΩ, | $(mV/A/m)_x$ = 0.160 mΩ |
| 35 mm$^2$ | : | $(mV/A/m)_r$ = 1.25 mΩ, | $(mV/A/m)_x$ = 0.165 mΩ |
| 6 mm$^2$ | : | $(mV/A/m)_r$ = 7.3 mΩ, | $(mV/A/m)_x$ = 0 Ω |

$$R_{120} = \frac{0.33 \times 30}{\sqrt{3} \times 1000} = 0.0057\Omega \qquad X_{120} = \frac{0.135 \times 30}{\sqrt{3} \times 1000} = 0.0023\Omega$$

$$R_{70} = \frac{0.63 \times 30(230+30)}{2 \times 1000(230+70)} = 0.0082\Omega \qquad X_{70} = \frac{0.16 \times 30}{2 \times 1000} = 0.0024\Omega$$

$$R_{35} = \frac{1.25 \times 20(230+115)}{2 \times 1000(230+70)} = 0.0144\Omega \qquad X_{35} = \frac{0.165 \times 20}{2 \times 1000} = 0.0017\Omega$$

$$R_{6} = \frac{7.3 \times 20(230+95)}{2 \times 1000(230+70)} = 0.079\Omega \qquad X_{6} = 0$$

$$Z_{EFL,TN} = \sqrt{(R_{120} + R_{70} + R_{35} + R_6 + R_T)^2 + (X_{120} + X_{70} + X_{35} + X_T)^2}$$
$$= 0.1102\ \Omega$$

The line-to-earth short-circuit current is :

$$I_{EF,TN} = \frac{230}{0.1102} = 2087\ \text{A}$$

(b) For an earth fault current of 2087 A, the operating time of the MCB in the final DB is estimated at 0.1 s . Thus the minimum size of CPC is:

$$S_{min} \geq \frac{\sqrt{I_{EF,TN}^2\, t}}{k} = \frac{\sqrt{2087^2 \times 0.1}}{143} = 4.62\ \text{mm}^2$$

The CPC size of 6 mm$^2$ is appropriate since it is greater than the minimum required size of 4.62 mm$^2$.

**Example 4.2**

An installation which is part of a TT system has a final circuit with a length of 20 m for socket-outlets. This circuit is a single-core, pvc-insulated copper conductor cable of 4 mm$^2$ with a separate CPC of the same size as shown in Figure 4.8. The CPC from the final DB to the main earthing terminal is 16 mm$^2$ at 30 m and the earthing conductor from the earthing terminal to the earth electrode is 25 mm$^2$ at 10 m. All the CPCs are single-core pvc-insulated copper conductors and the earth electrode resistance is 0.9 Ω. The protective device for the final circuit can be selected from a 32-A type 1 MCB, a 32-A type C MCB or a 63-A RCCB with a residual operating current of 0.03 A. Temperature correction on cable resistive value is not required.

(a) To satisfy the protection for electric shock, suggest the appropriate type of protective devices for the final circuit to the socket outlets.

(b) State the differences if the same installation is part of a TN-S system in which the external earth fault loop impedance $R_E + jX_E$ from the final DB and the earthing terminal to the source of supply is (0.3 +j0.6) Ω.

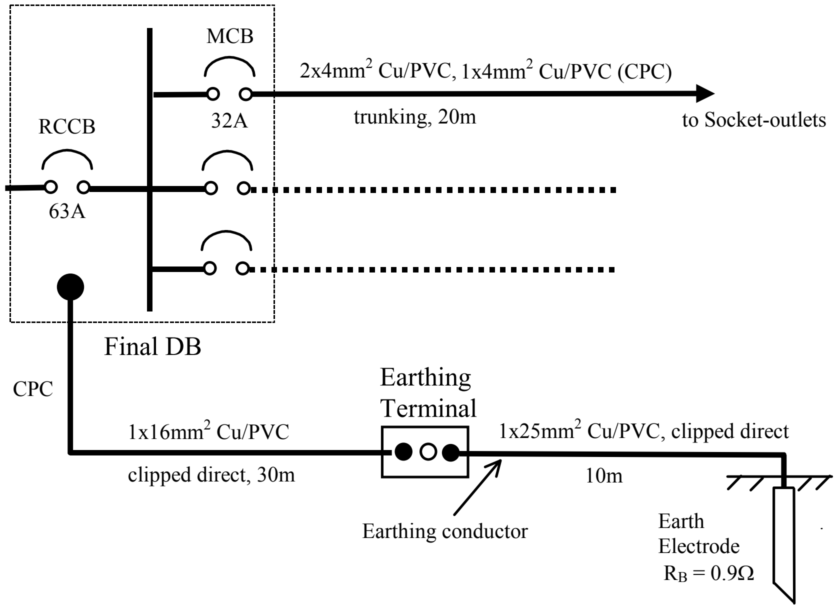



Figure 4.8 Installation for Example 4.2

**Solution**

(a) From Table 4D1B (columns 3,4) of IEE Regulations [Ref. 3, P 189],

| | | |
|---|---|---|
| 4 $mm^2$ | : | $(mV/A/m)_r$ = 11 mΩ |
| 16 $mm^2$ | : | $(mV/A/m)_r$ = 2.8 mΩ |
| 25 $mm^2$ | : | $(mV/A/m)_r$ = 1.75 mΩ |

$$R_4 = \frac{11 \times 20}{2 \times 1000} = 0.11\ \Omega \qquad R_{4,CPC} = R_4$$

$$R_{16,cpc} = \frac{2.8 \times 30}{2 \times 1000} = 0.042\ \Omega$$

$$R_{25} = \frac{1.75 \times 10}{2 \times 1000} = 0.009\ \Omega \qquad R_B = 0.9\ \Omega$$

For TT system, the condition to satisfy the requirement for the protection against electric shock is to limit the shock voltage to not more than 50 V as follows :

$$R_a\, I_a \leq 50\ \text{V}$$

where $I_a$ is the current causing the automatic operation of the protection device within 5 s.

$$R_a = R_{4,cpc} + R_{16,cpc} + R_{25} + R_B = 1.061\ \Omega$$

$$I_a = \frac{50}{1.061} = 47.1\ \text{A}$$

The operating times of the 32-A MCB for both type 1 and type C are 1000 s for a current of 47.1 A. As this disconnection time exceeds 5 s, both type 1 and type C MCBs do not provide adequate protection against electric shock. However, as the operating time of the RCCB is 0.04 s for a current of 47.1 A, it gives adequate protection for electric shock.

(b) If the same installation is part of a TN-S system, the earth fault loop impedance is :

$$\begin{aligned} Z_{EFL,TN} &= \sqrt{(R_4 + R_{4,cpc} + R_{16,cpc} + R_E)^2 + (X_E)^2} \\ &= \sqrt{(0.11 + 0.11 + 0.042 + 0.3)^2 + 0.6^2} \\ &= 0.822\ \Omega \end{aligned}$$

The line-to-earth fault current is :

$$I_{EF,TN} = \frac{230}{0.822} = 280\ \text{A}$$

The operating time of the 32-A type 1 MCB is within 0.1 s but for the type C MCB, it is slightly more than 5 s. Thus, only type 1 MCB and the RCCB can satisfy the requirements for protection against electric shock if the same installation is part of a TN-S system.

**Example 4.3**

A 230-V supply to an electric heater utilises a circuit of pvc-insulated copper conductor cable of 6 mm$^2$, protected by a 40-A MCB with a CPC size of 4 mm$^2$. The length of the cable is 18 m and the CPC is bundled together with the phase conductors as shown in Figure 4.9. It is assumed that a type B MCB is first installed and then it may be replaced by a type C MCB subsequently during maintenance. If the external earth fault loop impedance $R_E + jX_E$ is $(0.12 + j0.8)\Omega$, determine whether the size of 4 mm$^2$ CPC can satisfy the electric shock protection as well as the thermal constraint. Temperature correction on cable resistive value is required.

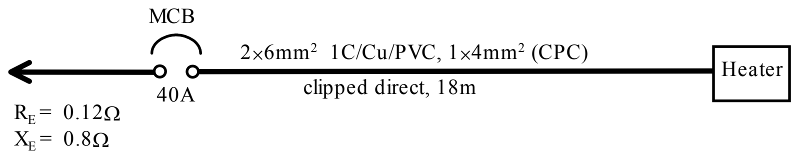



Figure 4.9 Circuit for Example 4.3

**Solution**

Assume that the average temperature for both phase conductors and the CPC during the fault is (70+160)/2 = 115$^0$C. From Table 4D1B column 4) of IEE Regulations [Ref 3, P 189],

$$6\text{ mm}^2 \quad : \quad (\text{mV/A/m})r \;=\; 7.3\text{ m}\Omega$$
$$4\text{ mm}^2 \quad : \quad (\text{mV/A/m})r \;=\; 11\text{ m}\Omega$$

The resistive values for the 6 mm$^2$ cable and the 4 mm$^2$ cable at an assumed conductor temperature of 115$^0$C are :

$$R_6 = \frac{7.3}{2} \times \left( \frac{230 + 115}{230 + 70} \right) \times \frac{18}{1000} = 0.0756\ \Omega$$

$$R_4 = \frac{11}{2} \times \left( \frac{230 + 115}{230 + 70} \right) \times \frac{18}{1000} = 0.1139\ \Omega$$

The earth fault loop impedance is :

$$\begin{aligned} Z_{EFL,TN} &= \sqrt{(R_6 + R_4 + R_E)^2 + X_E{}^2} \\ &= \sqrt{(0.0756 + 0.1139 + 0.12)^2 + 0.8^2} \\ &= 0.858\ \Omega \end{aligned}$$

The line-to-earth fault current is :

$$I_{EF,TN} = \frac{230}{0.858} = 268\ \text{A}$$

As the disconnection time for heater (fixed equipment) is within 5s and from Table 2.2, the current causing the type B 40-A MCB to operate within 5 s is 200 A and for type C, is 400 A. Thus, the corresponding maximum earth fault loop impedances are :

$$Z_{EFL,TN,max,40\ A,type\ B} = \frac{230}{200} = 1.15\ \Omega$$

$$Z_{EFL,TN,max,40\ A,type\ C} = \frac{230}{400} = 0.575\ \Omega$$

Since $Z_{EFL,TN}$ is 0.858Ω, which is lower than $Z_{EFL,TN,max,40A,typeB}$ (1.15 Ω), it satisfies the requirements for protection against electric shock. However, since $Z_{EFL,TN}$ is higher than $Z_{EFL,TN,max,40A,typeC}$ (0.575 Ω), the type C MCB fails to meet the requirements. In other words, the disconnection time of the 40-A type C MCB exceeds 5 s.

For an earth fault current of 268 A, the operating time of the type B MCB is 0.1 s (from Table 2.2), and for type C, 8 s (from Figure 2.9). To satisfy the thermal constraint, the minimum cross-sectional areas of the CPCs for type B and type C MCBs are :

$$S_{min,\, type\ B} = \frac{\sqrt{I^2 t}}{k} = \frac{\sqrt{268^2 \times 0.1}}{115} = 0.737\ \text{mm}^2$$

$$S_{min,\, type\ C} = \frac{\sqrt{I^2 t}}{k} = \frac{\sqrt{268^2 \times 8}}{115} = 6.59\ \text{mm}^2$$

Thus, by using type B MCB, the CPC of 4 $mm^2$ satisfies the thermal constraint since it only requires a minimum size of 0.737 $mm^2$. For type C MCB, however, the CPC size of 4 $mm^2$ is not adequate since the required minimum size is 6.59 $mm^2$.

This application example illustrates that the design engineer should not select CPC according to the minimum requirement of the type B MCB, as type C MCB may be replaced during maintenance.

**Example 4.4**

Use the same details as for Example 4.3, except that the CPC is separated with the phase conductors and the protective device is a 63-A RCCB with a rated residual current of $I_{\Delta N}$ at 0.03 A. This RCCB operates at 0.04 s at a residual current of 5 $I_{\Delta N}$.

(a) Is the size of CPC acceptable based on the thermal constraint and the electric shock constraint?

(b) If an intentional time delay is introduced, determine the maximum time delay which can satisfy both the thermal constraint and electric shock constraint.

**Solution**

(a) Since the operating current of the RCCB is 5 x 0.03 = 0.15 A at 0.04 s and the line-to-earth fault current $I_{EF,TN}$ is 268 A (calculated in Example 4.3), the RCCB will operate within 0.04 s which satisfies the requirements for electric shock protection.

The maximum disconnection time based on the thermal limit of the CPC of 4 $mm^2$ is :

$$t_{cable,\,max} = \frac{k^2 S^2}{I^2_{EF,TN}} = \frac{143^2 \times 4^2}{268^2} = 4.56 \text{ s}$$

As the CPC is separated with the phase conductor, the temperature before the fault is $30^0$C and thus the value of k is 143 instead of 115 as in Example 4.3 where the temperature before the fault is $70^0$C. Since the operating time of the RCCB is 0.04 s which is lower than 4.56 s, it satisfies the requirement for the thermal constraint.

(b) Based on the thermal limit of the CPC of 4 $mm^2$, the maximum time delay for the RCCB is :

4.56 - 0.04 = 4.52 s

Based on the requirement for electric shock protection, the maximum time delay is :

5 - 0.04 = 4.96 s

**Example 4.5**

For a 3-phase 4-wire system, draw a schematic diagram of an earth fault protection scheme for a 500-A MCCB using one IDMT relay. It is required to isolate an earth fault current of 50 A within 3 seconds. Determine the number of current transformers (CT), CT ratio and the relay's plug setting (PS) and the time multiplier setting (TMS). The maximum earth fault current of the installation is 400 A.

**Solution**

The schematic diagram for earth fault protection for a MCCB is shown in Figure 4.10. The earth fault relay operates by detecting the vector sum of the red, yellow, blue and neutral currents. Thus, four CTs are required. The CT ratio is 500/5 since the MCCB is rated at 500 A. As it is required to detect an earth fault current of 50 A, the plug setting should be 10% since the CT ratio is 500/5. The relay constant M corresponding to a maximum earth fault current of 400 A can be calculated by :

$$M = \frac{I_{EF} \times 100}{CT \times PS} = \frac{400 \times 100}{500 \times 10} = 8$$

The operating time of the relay [Ref. 6, P 139] is :

$$t = \frac{0.14}{M^{0.02} - 1} \times TMS$$

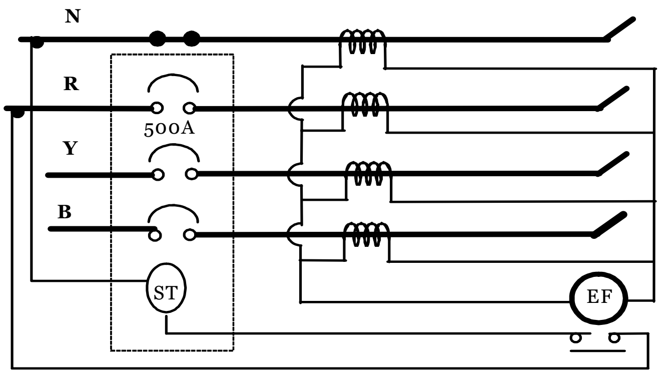



Figure 4.10 Schematic diagram for earth fault protection

If this relay has to operate within 3 seconds, the value of t is 3 in the above equation, and thus :

$$3 = \frac{0.14}{8^{0.02} - 1} \times \mathrm{TMS}$$

$$\mathrm{TMS} = \frac{3 \times \left(8^{0.02} - 1\right)}{0.14} = \frac{3 \times (1.042 - 1)}{0.14} = 0.9$$

In other words, for a CT ratio of 500/5 and for a 10% plug setting, the earth fault relay will activate at an earth fault current of 500 x 0.1 = 50 A. If the relay's TMS setting is 0.9, the relay will operate at 3 seconds for an earth fault current of 400 A.

## 4.6 REFERENCES


[1] IEEE Std 142-1991, "IEEE Recommended Practice for Grounding of Industrial and Commercial Power System", IEEE, 1991.

[2] CP16 : 1991, "Code of Practice for Earthing", SISIR, 1991.

[3] "IEE Regulations for Electrical Installations", 16th Edition, IEE, UK, 1991.

[4] IEC 479-1 Technical Report, " Effects of Current on Human Beings and Livestock, Part 1", International Electrotechnical Commision, 1994.

[5] IEE Guidance Notes No.5, "Guidance Notes on Protection against Electric Shock", IEE, UK, 1992

[6] GEC, "Protective Relays Application Guide", GEC Measurements, UK, 1987.

[7] Teo C Y, He W X, Chan T W," A Phase Co-ordinate Approach to Calculate Earth-fault Current and Shock Voltage", IEE proceedings on Electric Power Applications, Vol. 144, No. 6, PP 441 – 115,1997.

[8] CP5: 1998. "Code of Practice for Electrical Installations", Singapore Productivity and Standards Board, 1998.

**CHAPTER 5**

**FUSES**

According to BS 88 [Ref. 1], a fuse refers to a device that by the fusing of one or more of its specially designed and proportioned components opens the circuit in which it is inserted by breaking the current when the current exceeds a given value for a sufficient time. The fuse comprises all the parts that form the complete device. The complete device consists of a fuse-holder and a fuse-base. Each fuse-holder has a fuse-carrier and a fuse-link as shown in Figure 5.1

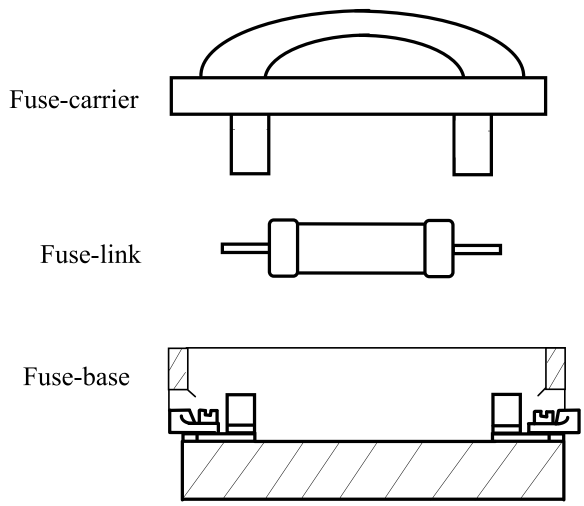



Figure 5.1 Component parts of a fuse

BS 88 [Ref. 1] also defines a fuse-link as a device comprising a fuse element enclosed in a cartridge, usually filled with an arc-extinguishing medium and connected to terminations. The fuse-link is the part of a fuse that requires replacing after the fuse has operated. The arc-extinguishing medium consists of high purity sand or powdered quartz and the material for the fuse-element is either silver or copper. Once a fuse-element operates (i.e. melts), the arc with its high instantaneous power creates a tube of melted sand around it which withdraws energy from the arc and extinguishes it. The spray of metal from the arc root is also entrapped in the filler.

Fuses are still used extensively in the utility's LV network for cable protection; as backup protection in the industrial installation for a circuit-breaker that has inadequate breaking capacity, and for protection in various types of electrical appliances. The main advantage of the fuse is its ability to interrupt very large short-circuit currents safely within its breaking capacity and in a much shorter time than that of a circuit breaker. The other advantage is its lower capital cost as compared to a circuit breaker of a similar rating and breaking capacity. The disadvantages of using fuses are obviously that once a fuse has operated, it has to be replaced by the correct type; and that fuses generates heat, dissipates power and may also result in a voltage drop.

## 5.1 CHARACTERISTIC OF FUSES

A fuse rated at 50 A does not operate when a current of more than 50 A, say 60 A passes through it during a slight overload condition. A fuse with a specified breaking capacity of 80 kA does not 'see' the 80 kA at all when the prospective current of 80 kA passes through it. The current of 80 kA is actually 'cut-off' by the specially designed fuse-element.

### 5.1.1 Current Rating and Fusing Current

The rated current of a fuse is a current stated by the manufacturer as the current that the fuse-link, fuse-carrier and fuse-base will carry continuously without deterioration in accordance with the specified conditions. The conventional non-fusing current ($I_{nf}$) is a value of current specified as that which the fuse-link is capable of carrying for a specified time (conventional time) without melting. The conventional time can be 1 hr (for $I_N \leq 63$ A), 2 hr (for $I_N \leq 160$ A), 3 hr (for $I_N \leq 400$ A) or 4 hr (for $I_N > 400$ A). The conventional fusing current ($I_f$) is a value of current specified as that which causes operation of the fuse-link within the conventional time. For "*gG*" fuse-links, $I_{nf} = 1.25\ I_N$, and $I_f = 1.6\ I_N$ where $I_N$ is the current rating of the fuse. Based on the range of breaking capacity and utilisation category, BS 88 [Ref. 1] defines fuses by two letters as follows:

- gG : full-range breaking capacity (g) for general applications (G).
- gM : full-range breaking capacity (g) for protection of motor circuits (M).
- aM : partial range breaking capacity (a) for protection of motor (M). The partial range refers to the high current range for short circuit protection. This type of fuse is not designed to interrupt small overcurrent.

### 5.1.2 $I^2t$ and Cut-off Current

A conductor will generate heat by the passage of current through it. The heat generated in the conductor which has a resistance value of R, in the time dt for a current I, is $I^2R$ dt. In other words, $I^2dt$ Joules are generated for every ohm of conductor. If the current is changing over a time interval, the integral of $I^2dt$ (i.e. $\int I^2dt$) Joules will be generated for every ohm of resistance. If a fuse-link is tested on a very high prospective current, there is no time for the heat to be lost into the surrounding and thus $I^2t$ required to melt the fuse-element is constant and independent of the injected current. However, the pre-arcing $I^2t$ is proportional to the square of the cross-sectional area of the section melted [Ref. 2, P 327]. For silver to be used as the fuse-element, the value of $I^2t$ is 66,000 $S^2A^2s$, and for copper, it is 90,000 $S^2A^2s$ where S is the cross-sectional area of the fuse-element at the narrowest point in $mm^2$, A is the current in amperes and s is the time in seconds. Limits on the minimum and maximum values of the pre-arcing $I^2t$ at 0.01 s specified by BS 88 [Ref.1, P 22] are given in Table 5.1.

Typical values of the pre-arcing $I^2t$ and the total $I^2t$ for a range of fuses from 2 A to 1250 A under short-circuit conditions on prospective current up to 80 kA are given in Figure 5.2 and Figure 5.3. The operating $I^2t$ is the sum of the pre-arcing $I^2t$ and the arcing $I^2t$. For a particular fuse rating, as the $I^2t$ is at a constant value, the prospective current that passes through the fuse will be limited to a value called the cut-off current. For example, for a prospective current of 80 kA (r.m.s. symmetrical) passing through a fuse-link rated at 400 A, this current will be cut-off at 40 kA peak which is equal to 28 kA r.m.s. For the same fuse link, if the prospective current is 30 kA (r.m.s. symmetrical), this current will be cut-off at 30 kA peak which is equal to 21 kA r.m.s. The prospective current is defined as the current that would flow in the same circuit if the fuse had been replaced by a copper link of negligible resistance. The value of the cut-off current is a function of the normal rating of the fuse, the prospective current and the degree of asymmetry of the short-circuit current. Figure 5.4 shows the values of cut-off current of a particular fuse-link for ratings from 2 A to 1250 A.

An indication of the speed of operation and current limiting ability of a 400-A fuse-link is given in Figure 5.5 which shows the oscillogram of the fuse interrupting a prospective current of 80 kA r.m.s. at 400 V. The cut-off current is 39.5 kA and the instantaneous power absorbed by the melting sand is 36,700 kW. The pre-arcing time is 0.0016 s and the arcing time is 0.0034 s.

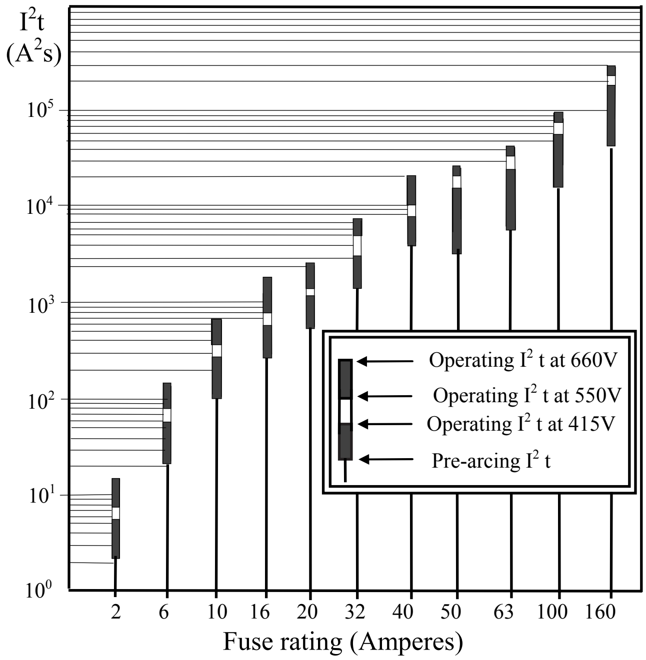



Fig 5.2 $I^2t$ characteristics for fuse-link from 2 to 160 A

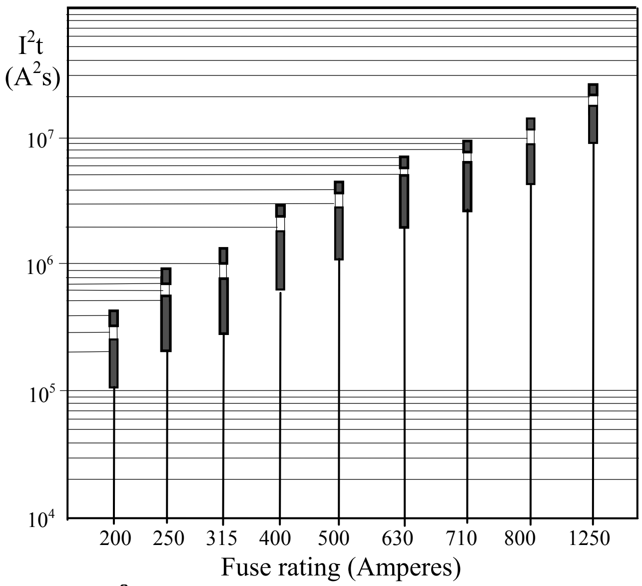



Fig 5.3 $I^2t$ characteristics for fuse-link from 200 to 1250 A

**Table 5.1 Pre-arcing $I^2t$ at 0.01 s for 'gG' fuse-links**

| Fuse rating | $I^2t$, ($10^3$ x $A^2s$) | |
|---|---|---|
| | min | max |
| 16 | 0.3 | 1.0 |
| 32 | 1.8 | 5.0 |
| 40 | 3.0 | 9.0 |
| 63 | 9.0 | 27.0 |
| 100 | 27.0 | 86.0 |
| 125 | 46.0 | 140.0 |
| 200 | 140.0 | 400.0 |
| 400 | 760.0 | 2250.0 |
| 630 | 2250.0 | 7500.0 |

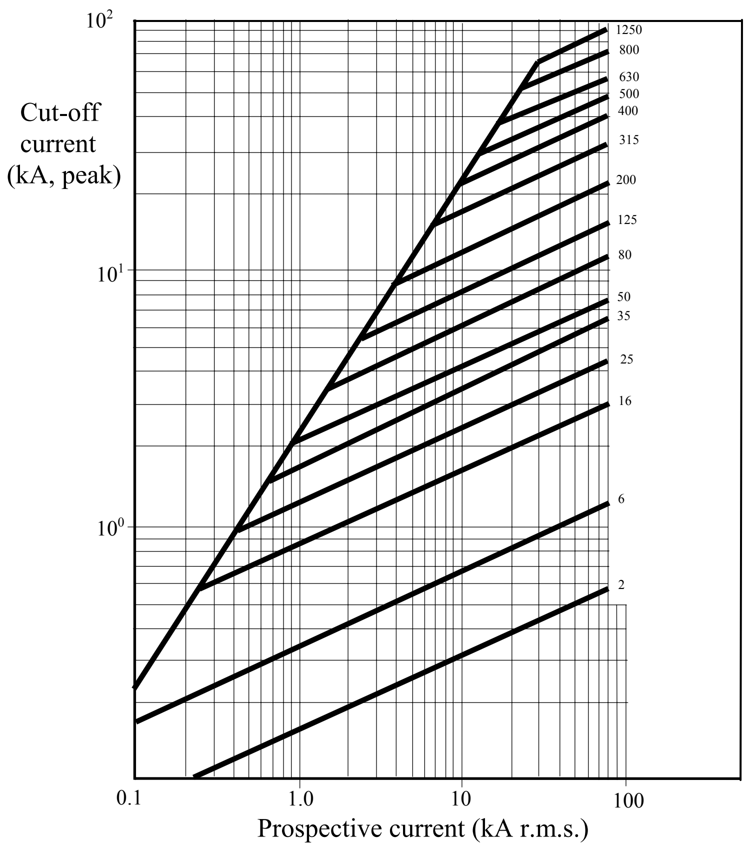



Fig 5.4 Cut-off current characteristics for fuse-link from 2 to 1250 A

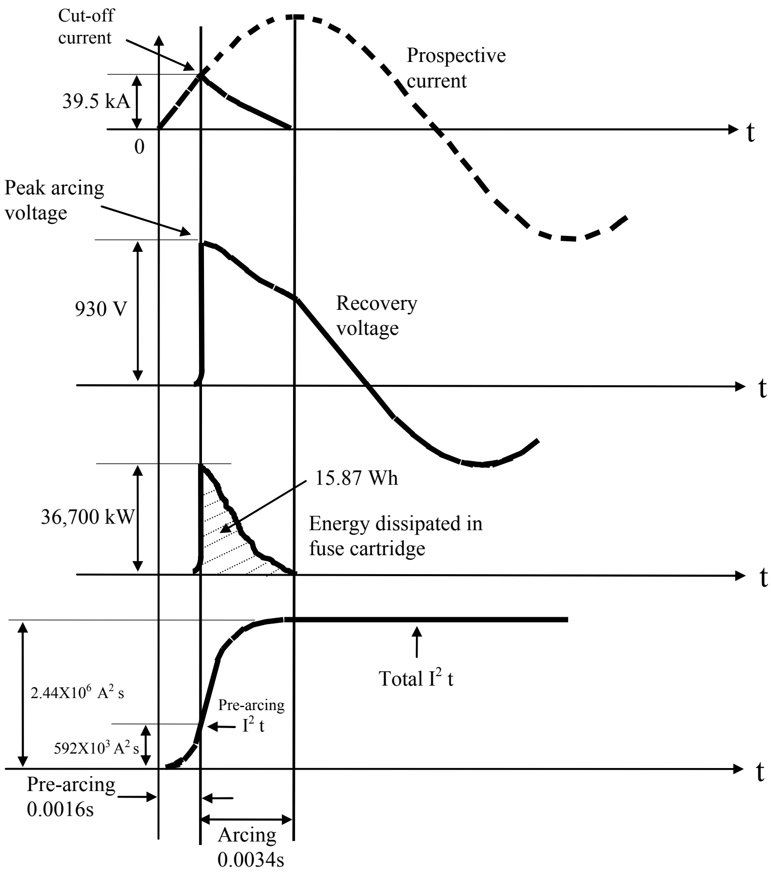



Fig 5.5 The operation of a 400-A fuse-link at 80 kA

### 5.1.3 Time-current Zone

The time-current characteristic of a fuse-link is a curve giving the pre-arcing time or the operating time (the sum of pre-arcing time and arcing time) as a function of the prospective current under the stated conditions of operation. For a time longer than 0.1 s for practical purposes, the difference between pre-arcing time and operating time is negligible. This time-current characteristic similar to the time-current characteristic of MCB, can be used to determine the operating time of a fuse-link for a particular prospective current if the operating time is above 0.1 s. For operating times less than 0.1 s, the arcing time becomes a significant part and the asymmetric currents may vary considerably and thus the operating time below 0.1 s cannot be obtained accurately.

Instead of specifying the time-current characteristic, many standards specify a time-current zone. The time-current zone indicates the range contained by the minimum pre-arcing time-current characteristic and the maximum operating time-current characteristic under specified conditions. Four points known as gates in the time-current zone are specified. These gates are the maximum and minimum levels between which the manufacturer's time-current characteristics for individual fuse-links must lie. The values of the four gates are: the minimum value of current corresponding to the pre-arching time of 0.1 s, $I_{min}$ (0.1 s), the maximum value of current corresponding to the pre-arcing time of 0.1 s, $I_{max}$ (0.1 s), the minimum value of current corresponding to the pre-arcing time of 10 s, $I_{min}$ (10 s), and the maximum value of current corresponding to the pre-arcing time of 5 s, $I_{max}$ (5 s). Typical time-current zones [Ref. 3] for 'gG' fuse-link are given in Figure 5.6 together with the four gates for the 63-A fuse-link.

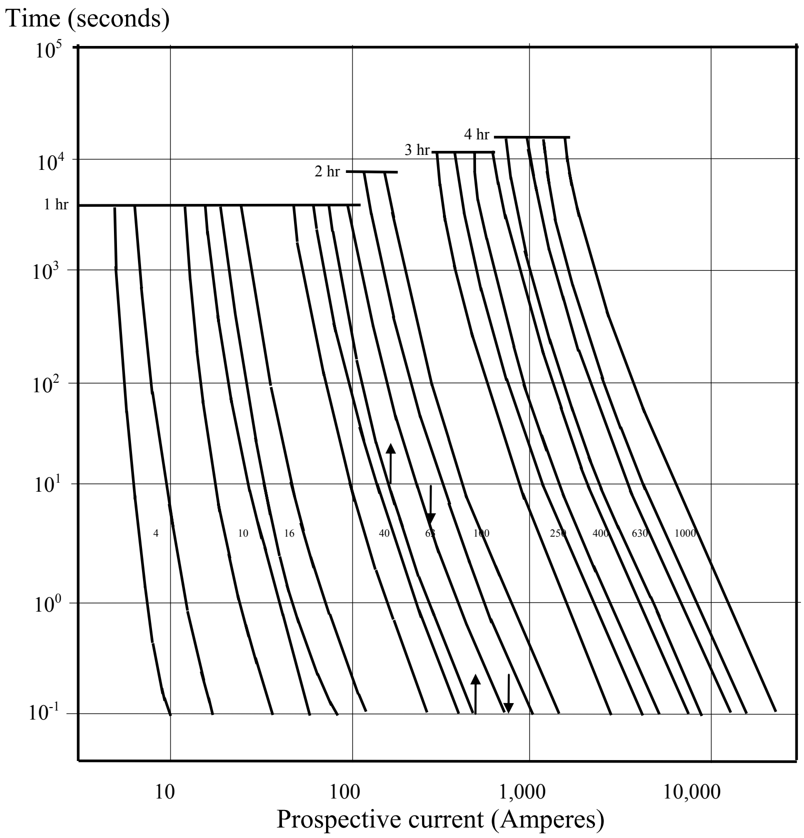


Fig 5.6 Time-current zones for "gG" fuse-link

## 5.2 MINIATURE FUSES

Miniature fuses are fuses with dimensions of 5 mm x 20 mm and 6.3·mm·x·32 mm. They are used for the protection of electric appliances, electronic equipment and the relevant components. These fuses are rated at 250 V with a current rating from 32 mA to 6.3 A. Fuses in this category normally have a resistance value in the range from 1 Ω to 200 Ω. Thus, the voltage drop at rated current can vary from 1 V to as high as 10V. Typical values of the maximum sustained power dissipation for miniature fuses are 1.6 W, 2.5 W and 4 W.

**High and Low Breaking Capacity**

There are two types of miniature fuse-links, namely low breaking capacity and high breaking capacity. The low breaking capacity types have cylindrical glass bodies and the fuse-element breaks the current in the air within the glass body. The rated breaking capacity is 35 A or 10 $I_N$, whichever is greater. This breaking capacity is adequate for clearing short-circuit currents at component level. However, at the incoming supply to the equipment, a fuse-link of higher breaking capacity is required. A miniature fuse-link with high breaking capacity is rated at 1.5 kA. These fuse-links have ceramic barrels and are filled with sand.

**Quick-Acting and Time-Lag**

To satisfy the operation requirements for various applications, the speeds of operation of the miniature fuse-links are made in five different types, ranging from very quick acting type to long time-lag which may take up to 5 s for four times the rated current. According to BS EN 60127-1 [Ref. 4], the symbols denoting the speed of operation are to be marked on the fuse as follows:

FF : denoting very quick acting
F : denoting quick acting
M : denoting medium time-lag
T : denoting time-lag
TAT: denoting long time lag

The pre-arcing time/current characteristic of the high breaking capacity fuses are summarised in Table 5.2 and for the low breaking capacity fuses in Table 5.3. In some applications, surge-proof time-lag fuse-links are required. This fuse-link is able to absorb the transient inrush current when switching on capacitors or motors. Each fuse-link shall be marked with its type of operation, rated current, type of breaking capacity and the rated voltage.

Examples of markings are:

T315L 250 V : time lag, 315 mA, low breaking capacity, 250 V
F4H 250 V : quick-acting, 4 A, high breaking capacity, 250 V

**Table 5.2 Time/current characteristic of high breaking fuses**

| Injected Current | | $2.1\ I_N$ | $2.75\ I_N$ | $4\ I_N$ | $10\ I_N$ |
|---|---|---|---|---|---|
| Pre-arcing time | Quick-acting | 30 min | 2 s | 0.3 s | 0.02 s |
| | Time-lag | 30 min | 80 s | 5 s | 0.1 s |

**Table 5.3 Time/current characteristic of low breaking fuses**

| Injected Current | | $2.1\ I_N$ | $2.75\ I_N$ | $4\ I_N$ | $10\ I_N$ |
|---|---|---|---|---|---|
| Pre-arcing time | Quick-acting | 30 min | 2 s | 0.3 s | 0.02 s |
| | Time-lag | 2 min | 10 s | 3 s | 0.3 s |

**Miniature Fuse Standards**

The main industrial standards for miniature fuses are BS EN 60127-1 [Ref. 4] and BS EN 60127-2 [Ref. 5]. These two standards define the requirements, standard ratings, markings and methods of testing.

**Standard Rating**

Voltage : 60, 150, 250 V
Current : 50, 63, 80, 100, 125, 160, 200, 250, 315, 400, 500, 630, 800 mA
1, 1.25, 1.6, 2, 2.5, 3.15, 4, 5, 6.3 A
Breaking capacity : 35 A, 1.5 kA
Power dissipation : 1.6, 2.5, 4 W

## 5.3 LOW VOLTAGE FUSES

The low-voltage fuses cover a large range of fuses incorporating enclosed current-limiting fuse-links with rated breaking capacity of not less than 6 kA. They are used for protection of a.c. circuits of nominal voltages not exceeding 1000 V or d.c. circuits of nominal voltages, not exceeding 1500 V. The low-voltage fuses have three major groups, namely the BS 88 [Ref. 1] of a high breaking capacity up to 80 kA for industrial and utility applications, the BS 1361 [Ref. 6] with a breaking capacity up to 33 kA for use in domestic and office buildings, and the BS 1362 [Ref. 7] with a breaking capacity of 6 kA for use in plugs.

**80-kA Fuse**

Fuses for industrial applications with breaking capacity up to 80 kA are specified in BS 88: Part 2 [Ref. 1] and in IEC 269-2-1 [Ref. 3]. The preferred current ratings for fuse-links are: 2, 4, 6, 8, 10, 12, 16, 20, 25, 32, 40, 50, 63, 80, 100, 125, 160, 200, 250, 315, 400, 500, 630, 800, 1000, 1250 A. The values of the maximum power dissipation are in the range from 3 W for a 20-A fuse, 40 W for a 400-A fuse to 100 W for a 1250-A fuse. Fuse-links are also classified according to their fusing factors. A class P fuse-link shall have a fusing factor not exceeding 1.25 and a class Q1 fuse-link not exceeding 1.5 [Ref. 8].

Typical time/current characteristics for fuses to BS 88: Part 2 and Part 6 are given in Figure 5.7. BS 88: Part 5 [Ref. 9] specifies the fuse link ratings from 100 A to 630 A for use in utility's low-voltage supply network. BS 88: Part 6 [Ref. 10] specifies the fuse-link for use in industrial and commercial installations which have current ratings of 2, 4, 6, 10, 16, 20, 25, 32, 40, 50 and 63 A.

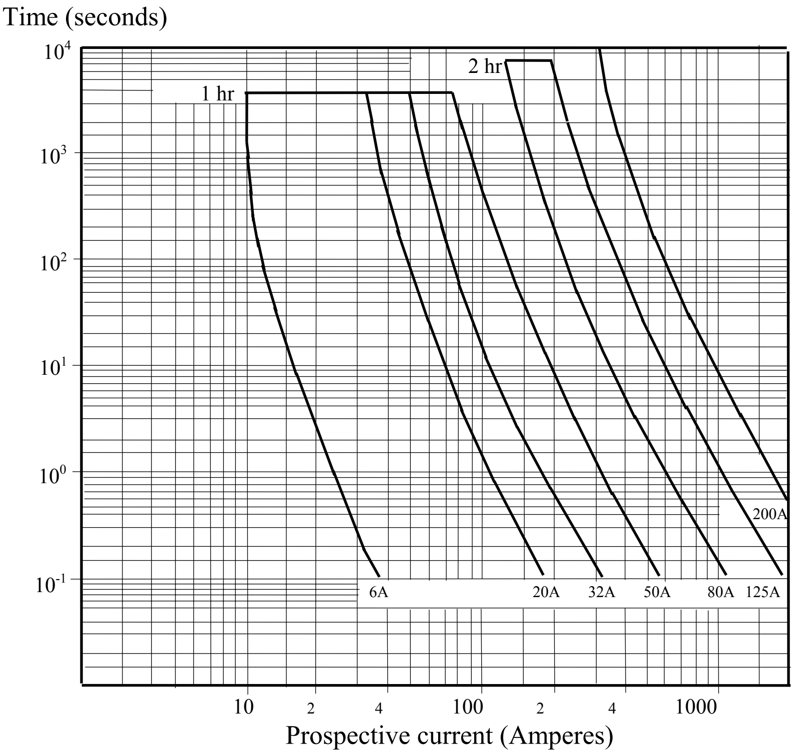



Figure 5.7 Time-current characteristic for fuse to BS 88

**33-kA and 16.5-kA Fuses**

BS 1361 [Ref. 6] specifies the requirements for fuses for a.c. circuits of 240 V with a breaking capacity of 16.5 kA for use in consumer's DBs in dwelling houses, blocks of flats and office buildings. It also covers fuses of 415 V with a breaking capacity of 33 kA for use by the supply utility in the incoming service units of such premises. The current ratings are 5, 15, 20, 30 and 45 A for the 16.5-kA fuse, and 60, 80 and 100 A for the 33-kA fuse. The values of maximum power dissipation are in the range of 1 W to 8 W. Typical time/current characteristics are given in Figure 5.8.

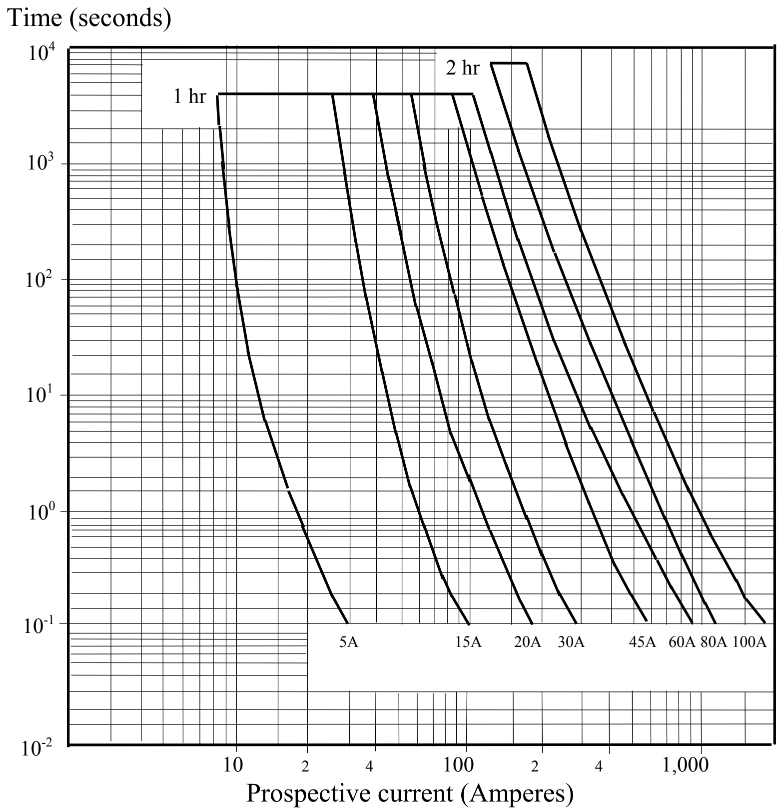



Fig 5.8 Time-current characteristics for fuse to BS 1361

**6-kA Fuse**

BS 1362 [Ref. 7] specifies the dimensions and performance requirements for general purpose cartridge fuse-links of a current rating not exceeding

13 A, primarily for use in plugs at a voltage not exceeding 250 V. The rated breaking capacity is 6 kA and the preferred current ratings are 3 A (coloured red) and 13 A (coloured brown). Other current ratings may be used for special applications and are coloured black. Standard time/current zones for 3-A and 13-A fuse-links are shown in Figure 5.9.

## 5.4 APPLICATION GUIDES

Almost the whole LV cable network of an urban utility uses fuses as the only protective devices for overload and short-circuit protection. Although MCCBs and MCBs are popular and the cost margin between circuit breakers and fuses is small, there are still many existing industrial installations which utilise fuses as the only means of protection except for the incoming circuit which is protected by an ACB. Fuses are also used intensively in plugs, appliances and at various component levels in electronic equipment. Therefore, a guide on the selection of fuses is still essential.

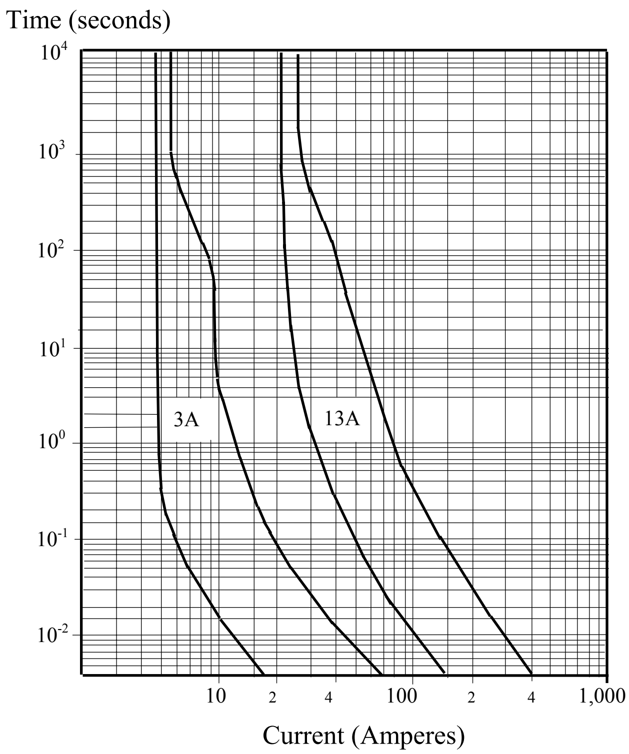



Fig 5.9 Time-current zone for fuse to BS 1362

The single-line diagram of a typical low-voltage (LV) board feeding by a 1-MVA 6.6/0.4-kV transformer for utility services is shown in Figure 1.14. All the outgoing circuits are four-core 300 mm$^2$ copper conductors XLPE cables protected by BS 88 fuses rated at 500 A. Each outgoing circuit from the LV board is connected to a number of over-ground (OG) boxes. The single-line diagram of a typical OG box is shown in Figure 1.15. Each outgoing circuit from the OG box is a four-core or two-core copper conductors XLPE cable protected by a BS 88 fuse rated at 200 A. The outgoing circuits from OG boxes feed the consumers directly.

### **5.4.1 *Cable Protection***

In section 3.5, the conditions for adequate protection of cables for overload are specified. They are:

$$\text{(i)}\ I_N \leq I_Z$$
$$\text{(ii)}\ I_2 \leq 1.45\ I_Z$$

IEE Regulation 433-02-02 [Ref. 11, P 45] states that where the protective device is a general purpose type (gG) fuse to BS 88 Part 2, a fuse to BS88 Part 6, or a fuse to BS 1361, compliance with condition (i) also results in compliance with condition (ii).

Based on BS 88 Part 2 [Ref. 8], class Q1 fuse-links have a fusing factor not exceeding 1.5. In other words, the fuse will operate at 1.5 $I_N$, i.e. $I_2$= 1.5 $I_N$. BS 88 Part 1 [Ref. 1, P 14] has considered a conventional fusing current of 1.6 $I_N$, i.e. $I_2$ = 1.6 $I_N$. Thus, if the cable size is so selected that $I_Z$ is equal to or slightly higher than $I_N$, condition (ii) may not be fully satisfied. Let us consider the following case:

$$I_N = 100\ A,\ I_Z = 100\ A \text{ and } 1.45\ I_Z = 145\ A$$

Based on a fusing factor of 1.5, the value of $I_2$ is 150 A and based on a conventional fusing current of 1.6 $I_N$, the value of $I_2$ is 160 A. In either case, $I_2$ is not $\leq$ 1.45 $I_Z$ and condition (ii) is not satisfied. Thus, to provide adequate protection for small overloads, it is suggested that the value of $I_Z$ should not be too close to $I_N$.

For short-circuit protection to prevent thermal damage to the cable, IEE Regulation 434-03-03 [Ref. 11, P 46] requires the operating time of the protective device to be less or equal to $t_{cable,max}$ as follows :

$$t_{cable,max} = \frac{k^2 S^2}{I_F^2}$$

where k, S and $I_F$ are specified in Section 3.6. This formula can be used to check for short-circuit protection by fuses in the same way as by breakers. However, during short-circuit conditions for which the short-circuit current would result in the fuse to operate within 0.1 s, the requirement for short-circuit protection can be stated as:

$$I^2t \le k^2S^2$$

where the $I^2t$ is the let-through operating $I^2t$ of the fuse (not equal to the square of the prospective current times the operating time of the protective device). As long as $I^2t$ is less than $k^2S^2$, it ensures that the fuse-links selected will not allow the cable to exceed its critical (maximum) temperature if a short-circuit fault occurs. You may consider a fuse as a weak link in a circuit and it has much smaller cross-sectional area than the cable it protects. During short circuit, the fuse-element will reach its melting point before the cable reaches its critical temperature. Thus, as long as the let-through operating $I^2t$ of the fuse is lower than the $k^2S^2$ of the cable, it is always safe. The larger the current, the quicker the fuse-element melts. If deterioration should occur, it operates even faster. Therefore, a fuse is a device that 'fails safe'.

**Example 5.1**

The same details for Example 3.10 are used, except that the protective device is a BS 88 fuse rated at 63 A as shown in Figure 5.10.

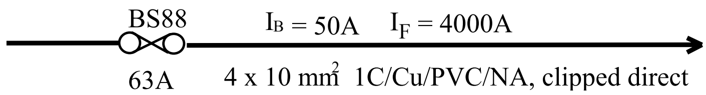



Figure 5.10 Circuit for Example 5.1

**Solution**

(a) $I_N$ = 63 A, $I_Z$ = 59 A
$I_2$ = 1.5 x 63 = 94.5 A based on a fusing factor of 1.5 or
$I_2$ = 1.6 x 63 = 100.8 A based on a conventional fusing current of 1.6 $I_N$
1.45 $I_Z$ = 1.45 x 59 = 85.6 A

Since $I_N$ is not $\le I_Z$ and $I_2$ is not $\le$ 1.45 $I_Z$, this circuit does not provide adequate overload protection. The designer should select the next higher size of conductor such as 16 mm$^2$ so that this circuit can be fully protected by overload.

(b) In Example 3.10, since the operating time of the MCCB is 0.15 s, which is larger than the critical time of 0.0827 s, this circuit could not provide adequate protection for thermal damage during short-circuit conditions. In this example, we have replaced the 60-A MCCB by a BS 88 63-A fuse. The operating $I^2t$ of the 63-A fuse obtained from Figure 5.2 is 22 x $10^3$ $A^2s$ and the $k^2S^2$ of the cable is:

$$k^2S^2 = 115^2 \times 10^2 = 1{,}322{,}500 \ A^2s$$
$$= 1{,}323 \times 10^3 \ A^2s$$

It is obvious that the $k^2S^2$ of the cable is much larger than the $I^2t$ of the fuse, and thus, it provides very good protection from short-circuit currents. In this particular application, a MCCB fails and a fuse passes.

The value of $I^2t$ of the 63-A fuse obtained from Figure 5.2 is based on a prospective current of 80 kA but in this example, the prospective current is only 4 kA. Thus, the value of $I^2t$ for the 63-A fuse may not be 22 x $10^3$ $A^2s$. However, the referred value of 22 x $10^3$ $A^2s$ is much lesser than the $k^2S^2$ of the cable of 1323 x $10^3$ $A^2s$.

### 5.4.2 Motor Circuit

In a motor circuit, the starter overload relay protects the associated cable against overload current, and the fuse-link in the circuit provides the required degree of short-circuit protection. Therefore, the selection of fuse-link is based on the requirement for short-circuit protection only, i.e.:

$$I^2t < k^2S^2$$

where $I^2t$ is the operating $I^2t$ of the fuse-link.

In addition to the ability to interrupt fault current and protect the associated contractor and cable, the fuse-link must also be capable of withstanding the motor starting current for the starting period. The general methods of determining the capability of a fuse to withstand motor starting conditions is to refer to the 10-s withstand current. Usually it is assumed that the starting current is approximately seven times the motor full load current and that such a current would exist for up to 10 s.

Most of the fuse manufacturers give recommended sizes of fuse-links for standard sizes of motors in their catalogues. BS 88 also specifies the value of current for each rating of fuse-links to withstand for 10 s [Ref. 1, P 15].

If the manufacturer's data is not available, the starting conditions are suggested in Table 5.4.

**Table 5.4 Typical starting condition**

| Motor Rating | DOL Starter | Assisted Starters |
|---|---|---|
| up to 1 kW | 5 x $I_{FL}$ for 5 sec | 2.5 x $I_{FL}$ for 20 sec |
| 1.1 kW to 75 kW | 7 x $I_{FL}$ for 10 sec | 4 x $I_{FL}$ for 15 sec |
| Above 75 kW | 6 x $I_{FL}$ for 15 sec | 3.5 x $I_{FL}$ for 10 sec |

For a fuse-link in a motor circuit, a dual rating such as 32M63 may be used. The first rating denotes the continuous current rating of the fuse-holder in which the fuse-link can be fitted and the second rating (after the letter M) indicates the time/current characteristic of the fuse-link. Therefore, the 32M63 fuse-link has a continuous rating of 32 A because of the limitation of the fuse-holder in which it is installed, and has the same time/current characteristic as the standard 63-A fuse-link.

**Example 5.2**

The same details as in Example 2.2 are used, except that the protective device is a BS 88 fuse instead of an MCCB as shown in Figure 5.11.

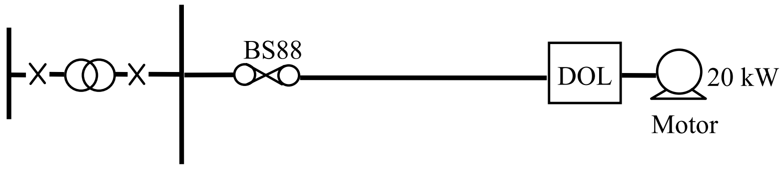



Figure 5.11 Selection of the current rating of a fuse

**Solution**

As calculated in Example 2.2, the 3-phase short-circuit current at the main switchboard is 28.86 kA. A BS 88 fuse with a breaking capacity of 80 kA or a BS 1361 fuse with a breaking capacity of 33 kA will be adequate to provide protection for short circuit.

As the full load current is 35.75 A, the current rating of the fuse should be at least equal to 35.75 A and a standard size of 50 A will be adequate. For an ambient temperature of $20^{0}C$ and a starting current of 250 A for 10 s, the operating time of the 50-A fuse obtained from Figure 5.7 is 4 s. If the current rating of the fuse is 80 A, the operating time is 60 s. Thus, a BS 88 fuse with a current rating of 80 A is selected. In Example 2.2, the current rating of the MCCB is 63 A which has an operating time of 18 s for the starting current of 250 A.

BS 88 Part 2 [Ref. 8] requires fuse-links be suitable for use in ambient air temperature not exceeding 35$^{0}$C and it is recognised that derating may be necessary at higher ambient air temperatures. Thus, for an ambient temperature of 40$^{0}$C, the current rating of the fuse may have to be higher than 80 A. The designer must check for the relevant derating factor from the fuse manufacturers or their publications.

### 5.4.3 Electric Shock

Fuses normally do not operate fast enough to protect against electric shock, as the earth leakage current is usually not high enough for the fuse to operate within the required time. For example, based on Figure 5.7, for an earth fault current of 100 A, the operating time of a 20-A fuse is 1.5 s and for a 32-A fuse, 15 s. As discussed in Section 4.5, protection against electric shock requires the protective device to operate in either 0.4 s or 5 s. Therefore, for installation that is protected by fuse, an RCCB is always recommended especially for a TT system. However, if protection for electric shock has to be provided by a fuse, the earth fault loop impedance for the circuit has to be reduced to a value such that the earth fault current is high enough to operate the fuse within the required time of either 0.4 s or 5 s.

Table 41B1 of IEE Regulations [Ref. 11, P 33] specifies the maximum earth fault loop impedance for fuses to operate within 0.4 s, Table 41C(a) of the IEE Regulations [Ref. 11, P 34] specifies the maximum impedance of the CPC for a disconnection time not exceeding 5 s and Table 41D(a) of IEE Regulations [Ref. 10, P 35] specifies the maximum earth fault impedance for a 5 s disconnection time.

As discussed in Section 4.4.1, the values of the maximum earth fault loop impedance are obtained by:

$$Z_{EFL,TN,max} = \frac{\text{Rated line - to - earth voltage}}{\text{Effective current causing operation within the required time}}$$

If the overcurrent protective device is a BS 88 32-A fuse, and based on Figure 5.7, the current causing the 32-A fuse to be operated at 0.4 s is 220 A, and at 5 s is 125 A. Thus, the maximum earth fault loop impedance for a line-to-earth voltage of 240 V at 0.4 s disconnection time is:

$$Z_{\mathrm{EFL,TN,max,0.4}} = \frac{240}{220} = 1.09\ \Omega$$

The value of 1.09 Ω is identical to the value given in Table 41B1 of the IEE Regulations. The maximum earth fault loop impedance for a line-to-earth voltage of 240 V at 5 s disconnection time is:

$$Z_{\mathrm{EFL,TN,max,5}} = \frac{240}{125} = 1.92\ \Omega$$

The value of 1.92 Ω is also identical to the value given in Table 41D of IEE Regulations. If the line-to-earth voltage is 230 V, the maximum earth fault loop impedance is:

$$Z_{\mathrm{EFL,TN,max,0.4,230}} = 1.09 \times \frac{230}{240} = 1.045\ \Omega$$

or it can be calculated by:

$$\frac{230}{220} = 1.045\ \Omega$$

### 5.4.4 Discrimination

For a simple network as shown in Figure 5.12, if there is a short-circuit or excess overload in one of the outgoing circuits, the respective fuse (called minor fuse) should operate first to isolate the fault. If, however, the incoming fuse (called major fuse) operates faster than the minor fuse, it will result in the loss of supply to all the outgoing circuits. This un-coordinated operation is known as loss of discrimination.

Positive discrimination under short-circuit conditions is achieved when the major fuse-link is unaffected by the fault current which causes the smaller or minor fuse-link to operate. The total operating $I^2t$ let through by the minor fuse-link must, therefore, be less than the pre-arcing $I^2t$ of the major fuse-link. Typical $I^2t$ characteristics for a range of fuse-links are shown in Figures 5.2 and 5.3. They were derived from tests taken under maximum arc energy conditions and can be used to assess discrimination at 415 V, 550 V or 660 V. For 415 V or 400 V applications, a current rating ratio of 2: 1 between major and minor fuse-links will ensure discrimination at all fault levels. However, the $I^2t$ characteristics can be used to assess discrimination where it is necessary to resort to the use of a smaller ratio to overcome a particular problem. At 550 V and 660 V, it may not always be possible to assume a general discrimination ratio of 2:1 if large fault levels are encountered. In such cases, the $I^2t$ characteristics must be used to achieve a satisfactorily graded installation.

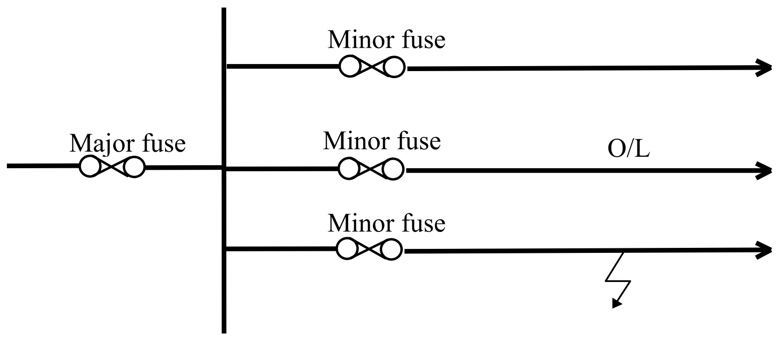



Figure 5.12 Illustration for discrimination

### 5.4.5 Back-up for Circuit-breakers

Both MCCBs and MCBs have limited breaking capacity in the range from 6 kA to 35 kA but the breaking capacity of a BS 88 fuse is 80 kA. Final circuits at a reasonably long distance from the incoming supply normally have a fault level in the range from 4 kA to 10 kA. However, if MCBs or MCCBs are installed very close to the incoming transformer, the fault level may reach values of 20 to 25 kA which may exceed the breaker's breaking capacity. A short-circuit would be likely to cause the circuit-breaker to fail or explode in the absence of suitable back up protection.

A fuse, with its high breaking capacity and its very short operating time during a high prospective current, is therefore an ideal candidate to provide stand-by back-up for a circuit breaker that has an inadequate breaking capacity. The criteria for selecting fuses for such back-up protection is illustrated in Figure 5.13 and as follows:

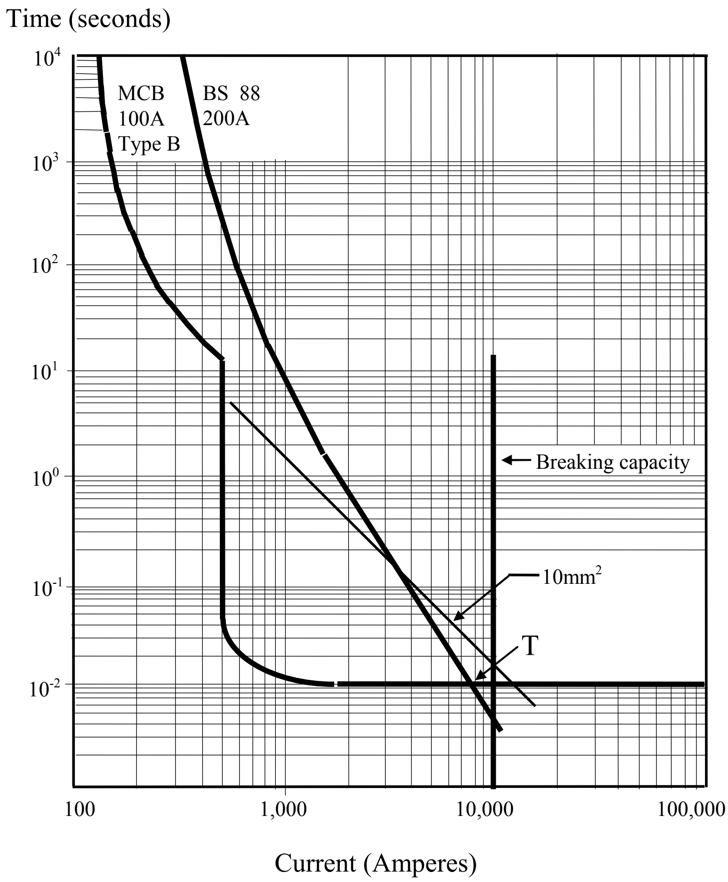



Fig 5.13 Back-up of MCB by fuse

(i) The time-current characteristic of the fuse-link should be such that the operating time of the fuse is significantly greater (i.e. higher than the curve of the circuit breaker) than the operating time of the circuit-breaker at all currents up to the takeover current T as shown in Figure 5.13. In other words, for all fault currents below point 'T', the breaker should operate faster than the fuse since the fault current is below the level corresponding to the pre-arcing $I^2t$ of the fuse and also within the breaker's breaking capacity.

(ii) The take-over current T is chosen to be not exceeding the breaking capacity of the breaker so that the fuse can take over at a current just before it exceeds the breaking capacity of 10 kA as shown in Figure 5.13.

(iii) The current rating of the fuse is selected in such a way that the operating $I^2t$ of the fuse-link will also provide protection against thermal damage of the associated cable in the region exceeding 11 kA where the breaker fails to provide such protection.

## 5.5 REFERENCES


[1] BS 88: Part 1: 1988, "Cartridge Fuses for Voltages up to and including 1000 V a.c. and 1500 V d.c. Part 1: General Requirements", British Standard Institution, 1988/1991 (identical to IEC 269-1 : 1986).

[2] Electricity Council, "Power System Protection I", Peter Petegrinus, UK, 1981.

[3] IEC 269-2-1, "Low-voltage Fuses, Part 2: Supplementary Requirements for Fuses for use by Authorised Persons (fuses mainly for industrial applications)", International Electrotechnical Commission, 1987/1994.

[4] BSEN 60127-1: 1991, "Miniature Fuses, Part 1, Definitions for Miniature Fuses and General Requirements for Miniature Fuse-links", British Standard Institution, 1991.

[5] BSEN 60127-2: 1991, "Miniature Fuses, Part 2, Specifications for Cartridge Fuse-Links", British Standard Institution, 1991.

[6] BS 1361 : 1971, "Cartridge Fuses for A.C. Circuits in Domestic and Similar Premises", British Standard Institution, 1971/1991.

[7] BS 1362 : 1973, "General Purpose Fuse-Links for Domestic and Similar Purposes (primarily for use in plugs)", British Standard Institution, 1973/1991.

[8] BS 88 : Part 2 : 1975, "Supplementary Requirements for Fuses of Standardised Dimensions and Performance for Industrial Purposes", British Standard Institution, 1975/1991.

[9] BS 88 : Part 5 : 1988, "Supplementary Requirements for Fuse-links for use in a.c. Electricity Supply Networks", British Standard Institution, 1988.

[10] BS 88 : Part 6 : 1988, "Supplementary Requirements for Fuses of Compact Dimension for use in 240/415 V a.c. Industrial and Commercial Electrical Installations", British Standard Institution, 1988/1991.

[11] "Regulations for Electrical Installation", 16th Edition, IEE, 1991.

# CHAPTER 6

# DESIGN PROCEDURES AND EXAMPLES

Safety of life and preservation of property are the first two important factors to be considered in the design of low-voltage systems in buildings. Safety to personnel should not be compromised at all and only the safest system can be considered. The safety requirements should follow the established codes such as the IEE Wiring Regulations [Ref 1], CP5 [Ref 2] or NEC [Ref 3]. Most of the established codes require the installations to be properly earthed and the whole electric system should be protected adequately against electric shock. Such electric shock can be due to a direct contact to any live conducting parts, or due to an indirect contact to the exposed-conductive-parts which are maintained normally at the earth potential, but may become live during an earth fault. In addition, every electric circuit should be designed to be adequately protected against overcurrent as a result of overload or short circuit.

Although overloaded circuits are electrically sound, sustained overload for a long duration will result in the conductor temperature exceeding their rated limit and the effectiveness of the insulation and their expected lifetime will be reduced. The designer must also ensure that appropriate protective devices are provided to interrupt any short-circuit current in the conductor of every circuit before such current causes danger or damage to the system due to thermal effects and mechanical forces produced in conductors and connections.

The designer must provide a reliable system and keep the supply interruption to a minimum. There should be no nuisance tripping of breakers and no loss of discrimination in the automatic disconnection of supply during any fault conditions. The estimated demand in each area of the building should be met adequately over a long period and the designed system must also be provided with some overload capability for contingency. The designer must also provide flexibility for future expansion and to meet varied requirements during the life of the plant.

While first costs are important, safety, reliability, voltage regulation, and the potential for expansion must also be considered in the design of low-voltage systems. On one hand, the designer should not provide unnecessary increase in the circuit capacity to avoid over-design. On the other hand, the system should meet all the safety requirements as well as reliability and flexibility, so that the installed system is robust enough and the designer has nothing to worry and can always 'sleep well' over 20 to 30 years after the system has been commissioned and tested.

## 6.1 DESIGN CURRENTS

Since a good designer has to provide adequate and reliable supply at minimum cost, the estimation of the design currents in each circuit in the installation is a major factor that the designer has to decide. Any error in the estimation of load current in the circuits would result in either over-design which will increase the installation cost or under-design which will result in more circuits being overloaded and frequent breaker tripping. The design current which is the expected load current in a circuit can be determined by the power demand (i.e. the rated wattage), power factor and efficiency of the connected load. However, the design current of an incoming circuit may not necessarily be equal to the current drawn by the total connected load. For example, if a circuit has to supply 10 appliances, each drawing up to 10 A, a 100 A circuit would presumably be required to supply all appliances. In actual implementation, it is unlikely that each appliance will be loaded up to the specified value of 10 A all the time and that all the appliances would be used at the same time. Based on past experiences, the designer may provide only an 85-A circuit. In other words, we recognise that while the total connected load (TCL) may be 100 A, the maximum demand (MD) or the design current of the circuit will only be 85 A.

### 6.1.1 Design Currents in a Final DB

Let us define a final DB as a DB that has appliances connected directly to it, and each outgoing circuit from the final DB to the appliance as a final circuit. Each final circuit has to carry the full load current of its connected appliance and thus, the design current of each final circuit should be equal to the full load current of the appliance. This full load current is normally calculated from the wattage and power factor of the connected load. However, the design current of the incoming circuit of the final DB, also known as the maximum demand of the DB, should be less than the summation of all the design currents in each outgoing circuit. The current reduction in the incoming circuit is due to three reasons. First of all, it is unlikely that all the final circuits will be turned on at the same time. Secondly, if all the final circuits are turned on, it is unlikely that they will all carry their full load currents simultaneously. The third reason is that the rating of many appliances, especially motors, are of standard rating such as 500 W or 1000 W, and the actual required power (i.e. the mechanical power in the case of a motor) is actually less than the standard size. For example, for any required power in the range from 451 W to 499 W, a standard size 500 W motor will be used. Thus, the appropriate design current of a DB can be obtained by defining a demand factor as follows:

$$DF = \frac{MD}{TCL}$$

where: DF is the demand factor, MD is the maximum demand or the design demand of a DB and TCL is the total connected load of the DB.

The value of the demand factor depends on the number of circuits and the types of load connected to the DB. A typical value is in the range from 0.8 to 0.95.

**6.1.2 Design Currents in a Distribution DB**

Several final DBs may be connected to a main DB that will then be connected to the incoming switchboard. Let us define all the interconnected DBs except the final DBs as distribution DBs and all the circuits connected between the various DBs as distribution circuits. As there is no appliance connected directly to the distribution DB, the estimation of load current or the design current will be slightly different from the method for final DBs.

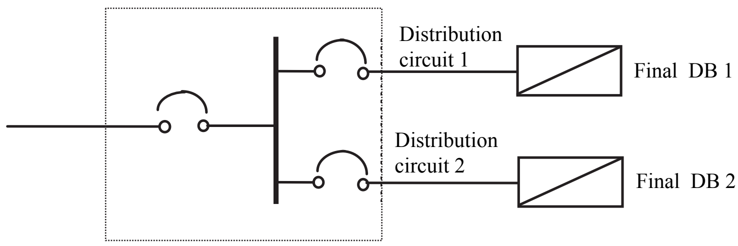



Figure 6.1 Design current for distribution DB

If a distribution DB is connected to two final DBs, DB1 and DB2, as shown in Figure 6.1, the design current of distribution circuit 1 will be equal to the maximum demand of the final DB1, and similarly, the design current of distribution circuit 2 will be equal to the maximum demand of the final DB2.

Let us examine the variation of maximum demand over a 24-hour period in distribution circuits 1 and 2 as shown in Figure 6.2. Circuit 1 has a maximum demand of 50 kW occurring at 4:00 p.m. Circuit 2 also has the same value of maximum demand but occurs at 7:30 p.m. The hourly summation of the maximum demand of circuits 1 and 2 should be equal to the hourly maximum demand of the incoming circuit of the main DB as shown in Figure 6.2.

It is noted that the maximum demand of the main DB is 72.5 kW occurring at 6:00 p.m. You may install a chart recorder at the incoming and the two outgoing circuits, and you will find that although the maximum power of both circuits are 50 kW, the maximum power at the incoming circuit is not 100 kW but 72.5 kW. The value of the maximum demand of the incoming circuit depends on how coincident are the maximum demands of the two outgoing circuits. It can, of course, be equal to 100 kW if the maximum demands of the two outgoing circuits coincide.

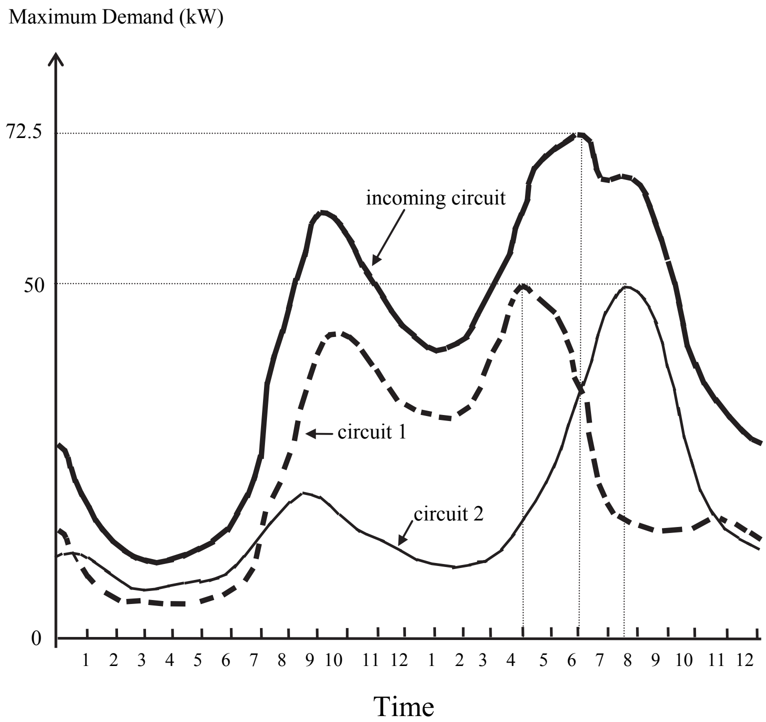



Figure 6.2 Maximum demand coincides at 6:00 p.m.

For the estimation of design current in any distribution DB or at any switchboard, if the values of the maximum demand of all the outgoing circuits are given or have been estimated in the upstream calculation, the maximum demand of the incoming circuit can be calculated by defining a coincidence factor as follows:

$$CF = \frac{MD_I}{\sum_{k=1}^{n} MD_K}$$

where: CF is the coincidence factor, $MD_I$ is the maximum demand of the incoming circuit, n is the number of outgoing circuits and $MD_K$ is the maximum demand of the kth outgoing circuit

The value of CF depends mainly on the number of outgoing circuits and has a typical value from 0.75 to 0.95. In some other guides [Ref 4, P 66], a diversity factor which is the reciprocal of CF is referred.

### 6.1.3 Procedure for Load Estimation

A suggested procedure for determining the design currents in various sections of a building is given in the following steps.

- Determine the quantity of each type of load and the power requirements. Estimate the design current in each final circuit based on the rating of the connected load. Apply an appropriate demand factor to obtain the maximum demand of each final DB.
- Determine the type of connection from the final DB to the main DB and continue up to the incoming switchboard. Estimate the design current in each distribution circuit using an appropriate coincidence factor.
- Determine the spare capacity to be provided for load growth.

In the preliminary design stage of the project, the types of connected loads and their exact number may not be available. Some typical data given in Table 6.1 [Ref 4, P 57] can be referred to determine the total estimated load in a building, if exact loads are not available.

**Example 6.1**

Calculate the partial load requirement of general purpose lighting, general purpose socket outlets and air-conditioning of a new office building consisting of 20 levels, each having a floor area of 1200 $m^2$.

**Solution**

Based on NEC [Ref 3, P 100], Table 220-3 (b), the general lighting load is 3.5 VA per $ft^2$ and 1 VA per $ft^2$ for general-purpose socket outlets. Based on a conversion factor of 1 $m^2$ to 10.8 $ft^2$ and a power factor of 0.8, the total general purpose lighting load is estimated to be:

$$\begin{aligned} LL &= (3.5 \times 0.8 \times 10.8 \times 1200 \times 20)\,\mathrm{kW} \\ &= 726\ \mathrm{kW} \end{aligned}$$

The total load for general-purpose socket outlets is:

$$\begin{aligned} LS &= (1 \times 0.8 \times 10.8 \times 1200 \times 20)\,\mathrm{kW} \\ &= 207\ \mathrm{kW} \end{aligned}$$

Based on an approximate air-conditioning load of 6 VA per $ft^2$ that might occur in the average office building [Ref 4, P 59], the total air-conditioning load is:

$$\begin{aligned} LA &= (6 \times 0.8 \times 10.8 \times 1200 \times 20)\,\mathrm{kW} \\ &= 1244\ \mathrm{kW} \end{aligned}$$

The partial load requirement of the building is:

$$\begin{aligned} PL &= (726 + 207 + 1244)\,\mathrm{kW} \\ &= 2177\ \mathrm{kW} \end{aligned}$$

**Table 6.1 Load Demand for Preliminary Analysis**

| Type of Load | Average Demand |
|---|---|
| Lighting in Building | 10 to 35 $W/m^2$ |
| General Purpose Socket Outlets | 6 to 12 $W/m^2$ |
| Air Conditioning in Commercial Building | 30 to 80 $W/m^2$ |
| Typical Textile Factory | 120 $W/m^2$ |
| Small Device Manufacturing | 35 to 75 $W/m^2$ |
| Typical Electronics Manufacturing | 100 $W/m^2$ |
| Industrial Lighting | 10 to 80 $W/m^2$ |
| Water Pump (10-storey) | 10 to 45 kW |
| Fire Pump (10-storey) | 65 to 100 kW |

### 6.1.4 Standard Code for Diversity

Both CP5 [Ref 2] and the 15th Edition of the IEE Wiring Regulations have 17 appendices providing a great deal of data such as Appendix 4 on maximum demand and diversity, and Appendix 5 on the standard circuit arrangements. The 16th Edition [Ref 1] has only 6 appendices and Appendices 4 and 5 of the 15th Edition have been removed. The philosophy is that the IEE Wiring Regulations [Ref 1] are now more general in their requirements, giving the designer only the basic requirements and leaving it to him to decide precisely what is needed.

Referring to the estimation of maximum demands, IEE Regulation 311-01-01 only states that the maximum demand of an installation, expressed in amperes, shall be assessed and that in determining the maximum demand of an installation or part thereof, diversity may be taken into account. Table 4A and Table 4B of Appendix 4 of the 15th Edition of the IEE Wiring Regulations regarding maximum demand and diversity are still available in the form of 'Guidance Notes' [Ref 5, P 101]. However, it should be understood that the contents of the Guidance Notes will not form part of the IEE Wiring Regulations for legal purposes.

## 6.2 DESIGN PROCEDURES

Whether it is a final circuit for lighting, socket outlets or motor, or a distribution circuit connecting DBs, the basic design procedure is the same. The recommended design procedures in eight steps given in Table 6.2 are based on the requirements of the IEE Wiring Regulations [Ref 1].

### 6.2.1 Lighting Circuit

For lighting circuit, the running current of luminaries is not necessarily the major consideration especially where discharge fittings are used. In estimating the design current in step 1, the effects of the associated control gear and harmonics must be considered. Where the circuit is for discharge lighting and in the absence of more exact information from the manufacturers, the design current [Ref 5, P 34] can be taken as:

$$I_B = \frac{1.8 \times \text{lamp rated wattage}}{\text{nominal voltage of circuit}}$$

The multiplier of 1.8 is based on the assumption that the circuit is corrected to a power factor of not less than 0.85 lagging, and it takes into account control gear losses and harmonic currents. The typical power factor of an uncorrected discharge lamps may vary between 0.5 lead and 0.3 lag [Ref 5, P 35]. Lighting installations should be classified as fixed systems. The disconnection time (in Step 7) is 5 s for installations within the equipotential zone.

**Table 6.2 Basic Design Procedure**

| Procedure | Design Task | Factors under consideration |
|---|---|---|
| Step 1 | Determine design current, $I_B$. | Connected load, demand factor and coincidence factor. |
| Step 2 | Select the type and current rating of protective device, $I_N$. | $I_B$, $I_F$ such that :<br>$I_N \geq I_B$, $I_{BC} \geq I_F$ |
| Step 3 | Determine the minimum tabulated current rating, $I_{t,min}$. | $I_{t,min} = I_N / (C_a \times C_g \times C_I)$ or<br>$I_{t,min} = I_B / (C_a \times C_g \times C_I)$ |
| Step 4 | Select the type of cable and the current rating such that<br>$I_{t,min} \leq I_t$<br>$I_t$ : tabulated current rating | Conductor material, insulation material, single-or multi-core and installation methods. |
| Step 5 | Check voltage drop within 4% from supply intake to individual appliances. If the voltage drop exceeds 4%, repeat step 4. | $I_B$, circuit length, power factor, $TVD_r$, $TVD_x$,and conductor temperature. |
| Step 6 | Check thermal limit of cable such that<br>$T_{bk,3\text{-}Phase\ F} \leq t_{cable,max}$<br>$t_{cable,max} = (k^2 S^2) / I_{F,3\text{-}Phase}^2$ | Cable thermal constant k, 3-Phase short-circuit current, time-current characteristic of protective device. |
| Step 7 | For TN system, check for earth fault loop impedance $Z_{EFL,TN}$, such that during an earth fault, the protective device will disconnect supply within the specified time of either 0.4 s or 5 s. | Time current characteristic of protection device, source impedance, cable resistance, cable reactance and average conductor temperature during fault condition. |
| Step 8 | Select the size of CPC such that $S_{min} \geq \dfrac{I_{EF}\sqrt{t_{bk,Ief}}}{k}$<br>For TT system check for:<br>$R_a \times I_a \leq 50$ V.<br>$I_a$: the current causing the automatic disconnection of the protective device within 5s.<br>$R_a$ : resistances of the earth electrode and the CPC. | Earth fault current $I_{EF}$, operating time of protective device.<br>Thermal limit constant k of CPC.<br>Resistance of earth electrode.<br>$S_{min}$ can also be obtained from Table 4.1 given in Section 4.3.1. |

### 6.2.2 Socket-outlet Circuit

Socket-outlet circuits can be fed by either radial or ring circuits. Figure 6.3a shows a radial circuit arrangement and in Figure 6.3b, a ring circuit utilises one additional conductor to loop back to the sending end. In other words, the socket outlets in the ring circuit are fed by two parallel conductors. The sharing of the load between the two parallel conductors will depend on the load distribution within the ring. For overcurrent protection, it is assumed that not more than 67% of the total current will be carried by any part of the ring. Such an assumption is based partly on experience and partly on a consideration of the likely load distribution in domestic circuits [Ref 6, P 25]. For other situations, such an assumption may need to be reviewed.

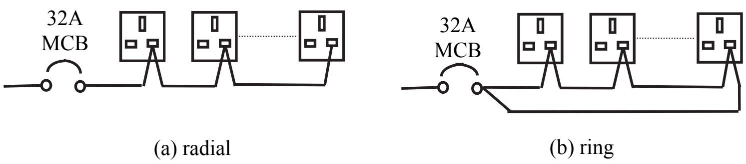



Figure 6.3 Radial and ring circuits

Prior to the release of the 15th Edition of the IEE Wiring Regulations in 1981, there were three standard circuit arrangements for socket outlets and each circuit can only supply to a fixed number of socket outlets. For example, a radial circuit using an overcurrent protective device of 32 A with a 4 $mm^2$ copper conductor pvc-insulated cable was allowed to supply to only six socket outlets. In the 15th Edition of the IEE Regulations, for the same 32 A standard circuit, it was allowed to supply an unlimited number of socket outlets but within a floor area of 75 $m^2$. In 1991, the standard circuit arrangements for socket outlets have been removed from the 16th Edition of the IEE Wiring Regulations [Ref 1] and the designer has to decide precisely what is needed.

**Example 6.2**

Determine the type and current rating of the protective device and the size of conductors of the circuit feeding a group of ten socket outlets as shown in Figure 6.4. The length of the cable from the protective device to the group of the socket outlets is 17 m and the ambient temperature is $35^0C$. The circuit is a single-core, copper conductor, pvc-insulated cable, clipped direct on a non-metallic surface. The expected average connected load of each socket outlet is 300 W at 0.9 power factor and the voltage drop limits in the final circuit are:

(a) 1%, (b) 1.5%.

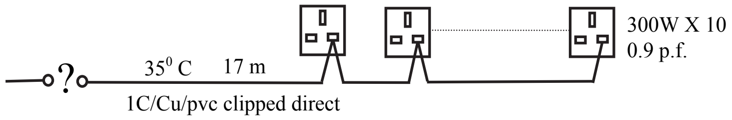



Figure 6.4 Circuit for Example 6.2

**Solution**

(a)

Step 1 : $I_B = \dfrac{\text{Connected load}}{\text{rated voltage} \times \cos\theta}$

$$= \frac{300 \times 10}{230 \times 0.9} = 14.49 \text{ A}$$

Step 2 : Assume the 3-phase fault current is within 9 kA and thus, an MCB with a current rating of 16 A is selected.

Step 3 : $I_{t,min} = \dfrac{I_N}{C_a \times C_g \times C_i} = \dfrac{16}{0.94 \times 1 \times 1} = 17.02 \text{ A}$

Step 4 : From Table 4D1A of the IEE Wiring Regulation [Ref 1, P 188], a 2 x 1.5 mm$^2$ cable with $I_t$ = 20 A is selected.

Step 5 : $V_{drop} = \dfrac{TVD_r \cos\theta \times I_B \times \text{length}}{1000}$

$$= \frac{29 \times 0.9 \times 14.49 \times 17}{1000} = 6.43 \text{ V}$$

Since $V_{drop}$ of 6.43 V (2.8%) is higher than 1%, the next higher rating of 2.5 mm$^2$ is selected.

$$V_{drop,2.5} = \frac{18 \times 0.9 \times 14.49 \times 17}{1000} = 3.99 \text{ V}$$

Since $V_{drop}$ of 3.99 V (1.74%) is again higher than 1%, the next higher rating of 4 mm$^2$ is selected.

$$V_{drop,4.0} = \frac{11 \times 0.9 \times 14.49 \times 17}{1000} = 2.44 \text{ V}$$

Since $V_{drop}$ of 2.44 V (1.06%) is still higher than the required 1%, a 6 mm$^2$ cable should be considered. However, the size of 6 mm$^2$ cable will be too large to terminate inside the socket outlet. Thus, the group of 10 socket outlets will be separated into two groups and to be fed by two separate circuits. Each circuit is protected by a 16 A MCB but the design current is only half of the previous value. By using a 2.5 mm cable, the voltage drop will be half of 3.99 V or 1.995 V (0.87%) which is less than the voltage drop limit of 1%. The recommended circuit arrangement is shown in Figure 6.5(a).

(b) Since the voltage drop limit is 1.5%, the 4 mm$^2$ cable with a voltage drop of 2.44 V (1.06%) is within the required limit, and thus a 4 mm$^2$ cable is recommended as shown in Figure 6.5(b).

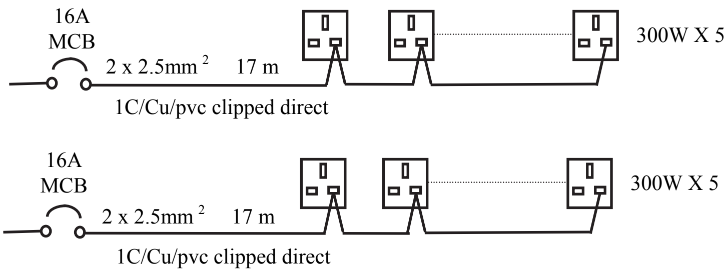



Figure 6.5(a) Recommended circuit for 1- % voltage drop

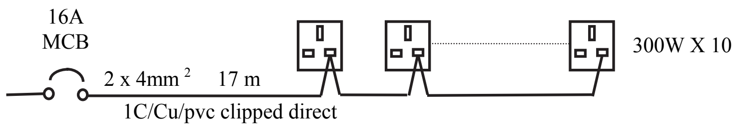



Figure 6.5(b) Recommended circuit for 1.5% voltage drop

### 6.2.3 Motor Circuit

For motor circuit, the rating of the breaker and cable should be greater than or equal to the full load current of the motor. Where the motor is intended for intermittent duty and for frequent stopping and starting, the conductor size shall be increased to cater for any cumulative effects of the rise in circuit temperature during the starting periods.

The IEE Regulation 552 states that for every electric motor having a rating exceeding 0.37 kW shall be provided with a starter incorporating means of protection against overload of the motor [Ref 1, 552-01-02]. For a motor circuit, the breaker is installed mainly for switching/isolation purpose and for short-circuit protection. Thus, it is not necessary for the breaker to provide overload protection for the cable since built-in overload protection is provided in the starter [Ref 2, 473-01-04]. Furthermore, the designer should consider the starting current to ensure that the breaker will not trip during motor starting.

### 6.3 EXAMPLES OF A TWO-LEVEL BUILDING

A two-level building which has two shops on each floor is shown in Figure 6.6 and a pump room which has a 55 kW water pump and a 80-kW sprinkler pump operated by the utility. Each shop has a final DB serving a floor area of 15 m x 10 m. On each floor, there is a main DB connecting to two final DBs as shown in Figure 6.6. The connected loads of each shop are as follows:

- 20 units of 40-W fluorescent lighting.
- 28 units of 13-A socket outlets with an average connected load of 300 W for each socket outlet at a power factor of 0.9.
- One 3-Phase 10-kW compressor motor.
- One 3-Phase 15-kW direct-on-line motor.

The power supply to the building is fed from a 22 / 0.4 kV transformer. The voltage drop limit from the supply intake to the main DB is specified as 1%, from main DB to final DB is 0.5% and from the final DB to each appliance is 1%. The ambient temperature is $35^{O}C$. All cables are installed in trunking and every two circuits are grouped together.

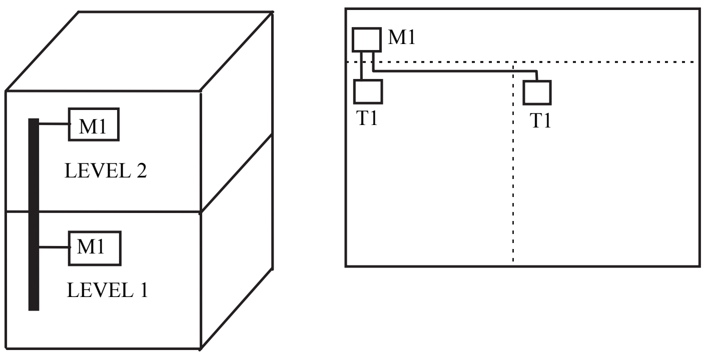



Figure 6.6 The two-level building

### 6.3.1 Final DB

The circuit arrangement and phase connection of the appliances connected to the final DB in each shop are shown in Figure 6.7.

**Socket-outlet Circuits**

Red Phase :

$$I_B = \frac{300 \times 8}{230 \times 0.9} = 11.59 \text{ A} \quad I_N = 16 \text{ A}$$

$$I_{t.\min} = \frac{16}{0.94 \times 0.8 \times 1} = 21.28 \text{ A}$$

Select a circuit using a 16-A MCB with a 2.5 mm$^2$ copper conductor multi-core pvc-insulated non-armoured cable.

Cable length: L = 4.5 m

Voltage drop: $V_{drop}$ = 0.8418 V or 0.36%

Circuit loading: LD = $I_B/I_Z = 11.59/(23 \times 0.94 \times 0.8)$ = 67%, $I_Z$ = 17.3 A.

Active connected load: $CL_a$ = 2.4 kW

Reactive connected load: $CL_r$ = 2.4 x (tan (cos$^{-1}$ 0.9)) = 1.16 kVAr.

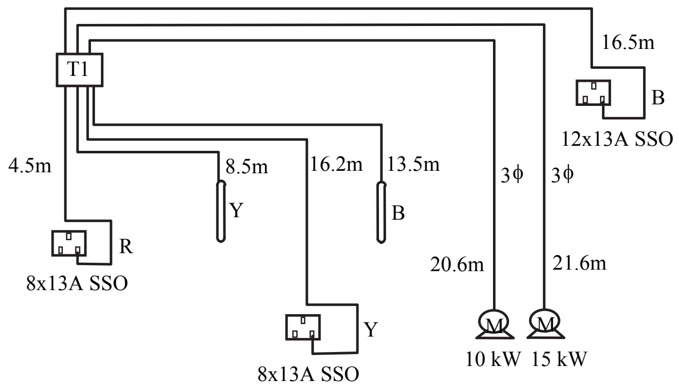



Figure 6.7 Final DB connection and circuit

Yellow phase :

$$I_B = 11.59 \text{ A}, \quad I_N = 16 \text{ A}, \quad I_{t,\min} = 21.28 \text{ A}, \quad L = 16.2 \text{ m}$$

To meet the required voltage drop limit of not exceeding 1%, a higher rating circuit of 16-A MCB and a 4 mm$^2$ copper conductor multi-core cable is selected.

$V_{drop} = 0.8\%$, LD = $\dfrac{11.59}{30\text{x}0.94\text{x}0.8} = 51.2\%$, $CL_a$ = 2.4 kW, $CL_r$ = 1.16 kVAr

Blue Phase :

$$I_B = 17.32\text{ A} \quad I_N = 20\text{ A} \quad \text{I}_{\text{t,min}} = 26.6\text{ A} \quad \text{L} = 16.5\text{ m}$$

To meet the required voltage drop limit of not exceeding 1%, the required conductor size exceeds 4 mm$^2$. Thus, we can use a ring circuit of 20-A MCB and a 4 mm$^2$ copper conductor multi-core cable.

$I_B$ = 17.32 A $I_N$ = 20 A L = 16.5 m $I_z$ = 45.12 A

$V_{drop}$ = 1.415 V or 0.6% LD = 38.4% $CL_a$ = 3.6 kW $CL_r$ = 1.74 kVAr

**Lighting Circuit**

Yellow/Blue phase :

$$\text{I}_\text{B} = \frac{40 \times 10 \times 1.8}{230} = 3.13\text{ A}, \quad \text{I}_\text{N} = 6\text{ A}, \quad \text{I}_{\text{t,min}} = \frac{6}{0.94 \times 0.8 \times 1} = 7.98\text{ A}$$

Select a circuit using a 6-A MCB and a 1.5 mm$^2$ copper conductor cable.

L=8.5 m, 13.5m $V_{drop}$=0.28%, 0.45% LD=25.2 %, 25.2 %

$CL_a$=40 x 1.8 x 10 x 0.85 = 612 W

$CL_r$ = 40 x 1.8 x 10 x 0.85 x tan (cos$^{-1}$0.85) = 379 VAr

For lighting and socket-outlet circuits, it is assumed that the selected cables can withstand the short-circuit currents. An illustration of checking whether the cable can withstand the thermal limit during short-circuit condition is given in the design of the motor circuit.

**10 kW Motor**

$$\text{I}_\text{B} = \frac{\text{Net output of Motor}}{\sqrt{3} \times 400 \times \text{Eff} \times \text{Pf}} = \frac{10 \times 10^3}{\sqrt{3} \times 400 \times 0.9 \times 0.8} = 20.05\text{ A}$$

$$\text{I}_\text{N} = 25\text{ A} \quad \text{I}_{\text{t,min}} = \frac{20.05}{0.94 \times 0.8 \times 1} = 26.67\text{ A}$$

Select a circuit using a 25-A MCB and a 4 mm$^2$ copper conductor cable.

L = 20.6 m $V_d$ = 3.139 V or 0.78% LD = 98.7%

$CL_a$ = 10/0.9 = 11.11 kW

$CL_r$ = 11.11 tan (cos$^{-1}$0.8) = 8.33 kVAr

The motor starting current is assumed to be four times the full load current which is 80 A during the first 15 s. As the operating time of the

25-A type C MCB is 50 s, this circuit satisfies the requirement for motor starting. Based on the estimated 3-phase short circuit current of 1889 A, the calculated critical time ($t_{cable,max}$) is 0.06 s. Since the operating time ($t_{bk,3\text{-}Phase,F}$) of the 25-A MCB is 0.01 s, this circuit satisfies the requirement in Step 6. This circuit does not satisfy the requirement in Step 4, since the 25-A MCB will not operate for a current of 1.45 $I_z$ (i.e. 29 A). However, this is acceptable. Why?

**15-kW Motor**

$$I_B = 30.07\ \text{A} \quad I_N = 32\text{A} \quad I_{t,min} = 39.99\ \text{A}$$

The motor starting current is assumed to be seven times the full load current which is 210 A during the first 10 s. As the operating time of the 32 A type C MCB is 9 s, the next higher MCB rating which is 40 A is selected. The operating time of the 40-A MCB is 11 s which is longer than the required 10 s and is thus acceptable.

L = 21.6 m $V_{drop}$ = 1.975 V or 0.5% LD = 87% $CL_a$ = 15/0.9 = 16.67 kW

$CL_r$ = 12.5 kVAr $T_{cable,max}$ = 0.09 s $t_{bk,3\text{-}Phase,F}$ = 0.01 s $I_f$ = 3810 A

Since $t_{cable,max}$ is greater than $t_{bk,3\text{-}Phase,F}$, it satisfies the requirement in Step 6. However, it does not satisfy the requirement in Step 4 since the 40-A MCB will not operate at a current of 1.45 $I_z$ (50 A).

**DB Incoming Circuit**

Total active connected load :

$TCL_a$ = (2.4+2.4+3.6+0.612+0.612+11.11+16.67) kW = 37.4 kW

Total reactive connected load:

$TCL_r$ = (1.16+1.16+1.74+0.38+0.38+8.33+12.5) kW = 25.65 kVAr

Power factor = $\cos\left(\tan^{-1}\dfrac{Q}{P}\right) = \cos\left(\tan^{-1}\dfrac{25.65}{37.4}\right) = 0.825$

Step 1 : Select a demand factor of 0.8. The maximum demand or the design current of the incoming circuit is

$$I_B = \frac{TCL_a}{\sqrt{3}\times 400\times\cos\theta}\times DF$$
$$= \frac{37.4\times 10^3}{\sqrt{3}\times 400\times 0.825}\times 0.8 = 52.35\ \text{A}$$

Step 2 : Select both MCCB and RCCB with $I_N$ = 63 A

Step 3 : $I_{t,min}$ = 63/(0.94 × 0.8) = 83.78 A

Step 4 : Select a 35 mm$^2$ copper conductor, pvc-insulated multi-core cable in trunking at a length of 18 m.

$I_z$ = 99 × 0.94 × 0.8 = 74.45 A. LD = 70.4%

Step 5 : L = 16.4 m, $I_B$ = 52.35 A $V_{drop}$ = 0.93 V or 0.23%

Step 6 : At an assumed fault current of 9 kA, $t_{bk,3\text{-}Phase,F}$ = 0.01 s and $t_{cable,max}$ = 0.09 s and thus $t_{bk,3\text{-}Phase,F} < t_{cable,max}$

The single-line diagram for the final DB is shown in Figure 6.8 and the single-line diagram for the main DB connected to the two final DBs is shown in Figure 6.9.

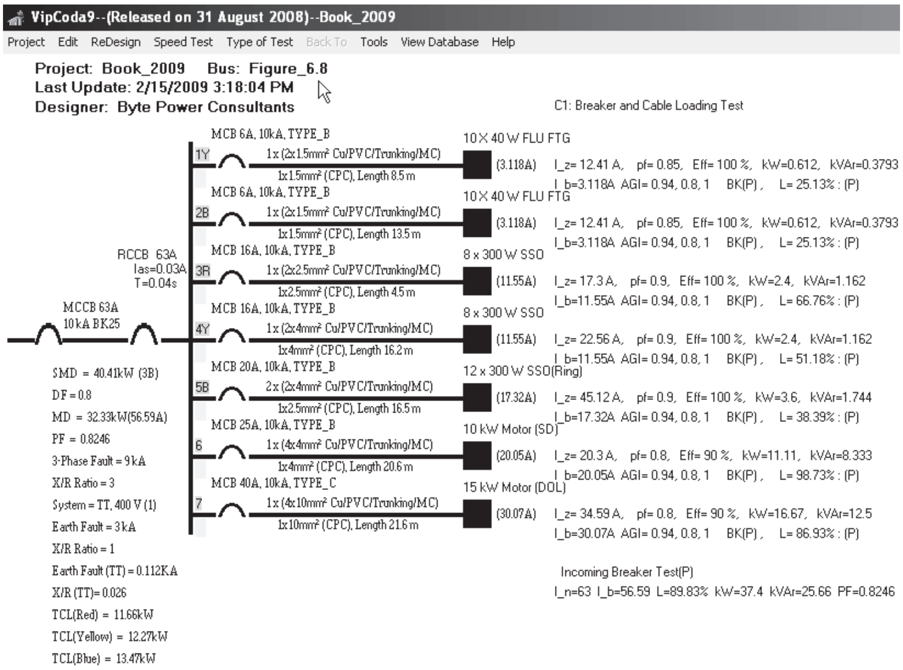



Figure 6.8 Single-line diagram of the Final DB T1

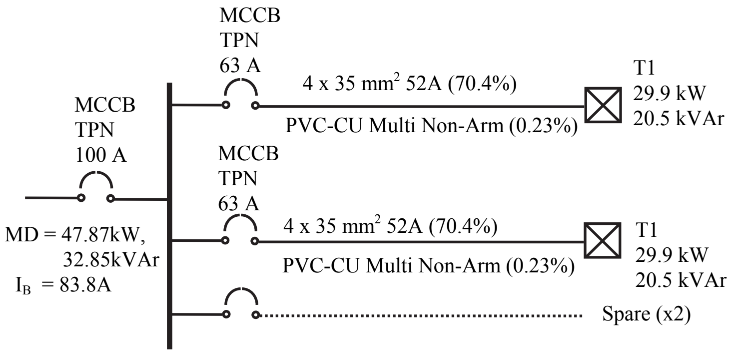



Fig 6.9 Single-line diagram of the main DB M1

### 6.3.2 Main switchboard

Only three outgoing circuits are required in the main switchboard. The first circuit is a cable riser connecting the main DB in level 1 and the other main DB in level 2. The second and third circuits are connected to the 55-kW water pump and the 80-kW sprinkler pump respectively in the pump room.

**Cable Riser**

Using a coincidence factor of 0.9, the maximum demand of the riser is:

$$MD_a = (47.87 \text{ x } 2) \text{ x } 0.9 = 86.17 \text{ kW}$$
$$MD_r = (32.85 \text{ x } 2) \text{ x } 0.9 = 59.13 \text{ kVAR}$$
$$I_B = \frac{\sqrt{86.17^2 + 59.2^2}}{\sqrt{3} \times 400} \times 1000 = 150.8 \text{ A}$$

Use a MCCB with $I_N = 160$ A, and $I_{BC} = 20$ kA

$$I_{t,min} = \frac{160}{0.94 \times 1 \times 1} = 170.2 \text{ A}$$

Select a 4 x 50 mm$^2$ single-core, pvc-insulated, copper conductor cable, installed on cable tray. This circuit has a tabulated current carrying capacity of 172 A. The voltage drop can be calculated by:

$$V_{drop} = \frac{(TVD_r \cos\theta + TVD_x \sin\theta) \times I_B \times \text{length}}{1000}$$
$$= \frac{(0.8 \times 0.825 + 0.165 \times 0.565) \times 150.8 \times 9}{1000}$$
$$= 1.02 \text{ V or } 0.26\% \text{ of } 400 \text{ V}$$

**Water Pump**

The design current of the 55-kW water pump is 110.3 A and a MCCB is selected. Using the same design procedure, we obtain:

$$I_N = 160\ \text{A} \quad CL_a = 55/0.9 = 61.11\ \text{kW}$$
$$I_{t,min} = 117.3\ \text{A} \quad CL_r = 45.83\ \text{kVAr}$$

Select a 4 x 35 mm$^2$ single-core, pvc-insulated, copper conductor cable which has a tabulated current carrying capacity of 129 A. Based on a circuit length of 19.5 m, the voltage drop is 2.11 V which is less than the specified voltage drop tolerance of 1%. Based on the motor starting current of 441 A, the operating time of the 160 A MCCB is higher than the required limit of 15 s.

**Sprinkler Pump**

The design current of the 80-kW sprinkler pump is 160.4 A and a MCCB rated at 200 A is selected. Based on the $I_{t,min}$ of 170.6 A, a 4 x 70 mm$^2$ copper conductor cable is suggested. This cable has a tabulated current rating of 214 A and the voltage drop is 0.63% at an estimated circuit length of 29.5 m. Based on the motor starting current of 642 A, the operating time of the 200-A MCCB is slightly greater than the required limit of 15 s.
\

**Main Incoming Circuit**

Select a MCCB as the protective device and based on the coincidence factor of 0.9, the maximum demand at the main incoming circuit is:

$$MD_a = (86.18 + 61.11 + 88.89) \times 0.9 = 212.56\ \text{kW}$$
$$MD_r = (59.12 + 45.83 + 66.67) \times 0.9 = 154.46\ \text{kVAr}$$
$$I_B = \frac{\sqrt{212.56^2 + 154.46^2}}{\sqrt{3} \times 400} \times 1000 = 379.3\ \text{A}$$
$$I_N = 400\ \text{A}$$

The single line diagram of the main switchboard is shown in Figure 6.10.

**6.3.3 Short-circuit Protection**

It is assumed that the main switchboard is fed by a 300 mm$^2$ copper conductor XLPE multi-core cable from a LV board at a distance of 30 m. The LV board is fed by a 22/0.4-kV transformer that has a reactance of 0.009 Ω and a resistance of 0.002 Ω. It is also assumed that the 22-kV source impedance is negligible and the 300 mm$^2$ XLPE cable has a reactance of 0.07 mΩ per m and a resistance of 0.08 mΩ per m. The three-phase short-circuit current at the main switchboard is:

$$
\begin{aligned}
I_{F,3\phi} &= \frac{V_{LL}/\sqrt{3}}{\sqrt{(R_T + R_1)^2 + (X_T + X_1)^2}} \\
&= \frac{230}{\sqrt{(0.002 + 0.00008 \times 30)^2 + (0.009 + 0.00007 \times 30)^2}} \\
&= \frac{230}{0.012} = 19{,}166 \text{ A}
\end{aligned}
$$

Thus, all the MCCBs at the main switchboard are recommended to have a breaking capacity of 20 kA. To verify the thermal limit of cable as stated in Step 6, the critical operating time of the three outgoing circuits are calculated as follows:

$$\text{Riser } t_{\text{cable, max}} = \frac{k^2S^2}{I_F^{\,2}} = \frac{115^2 \times 50^2}{19166^2} = 0.09 \text{ s}$$

$$\text{Water pump } t_{\text{cable, max}} = \frac{115^2 \times 35^2}{19166^2} = 0.04 \text{ s}$$

$$\text{Sprinkler pump } t_{\text{cable, max}} = \frac{115^2 \times 70^2}{19166^2} = 0.18 \text{ s}$$

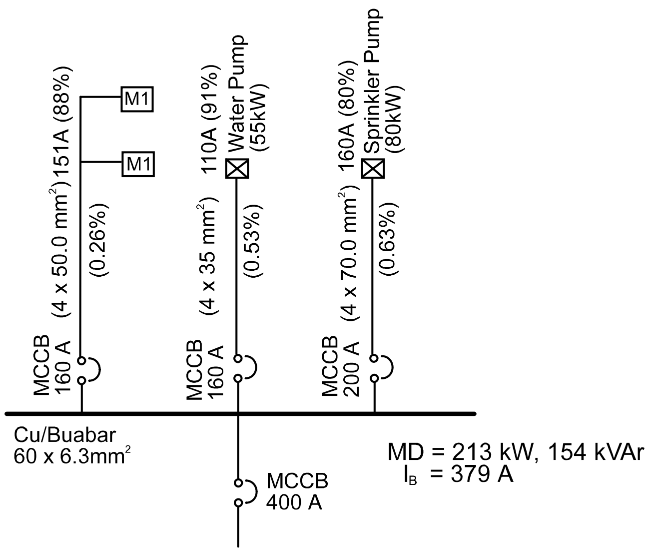



Figure 6.10 The main switchboard of the two-level building

The operating time of each of the three MCCBs at a short-circuit current of 19 kA is 0.01 s which is within the three critical operating times calculated above. However, if the operating time of the breaker is 0.1 s, the first and second circuits will not meet the requirement for protection against short-circuit current.

### 6.4 EXAMPLE OF A SEVEN-STOREY FACTORY

A seven-storey flatted factory which has four tenants on each floor is shown in Figure 6.11 and its basic single-line diagram is shown in Figure 6.12. The first busbar which provides supply to all the tenants is fed by a 22/0.4-kV transformer, the second busbar which provides supply to all the common services for the whole building such as lighting in the common area, ventilation fans and exhaust fans, etc. is fed by another 22/0.4-kV transformer. The third busbar which provides supply to all the emergency loads such as emergency lighting, fire-fighting equipment, etc. is fed from either the second busbar or the standby generator when the supply from the utility fails.

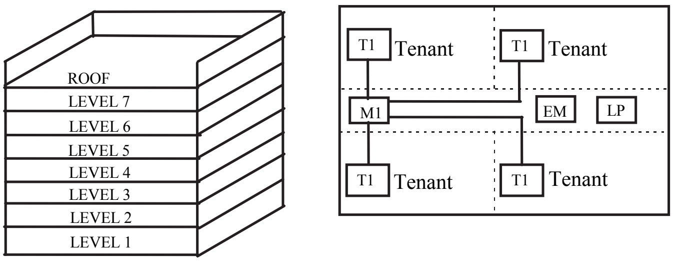



Figure 6.11 The seven-storey

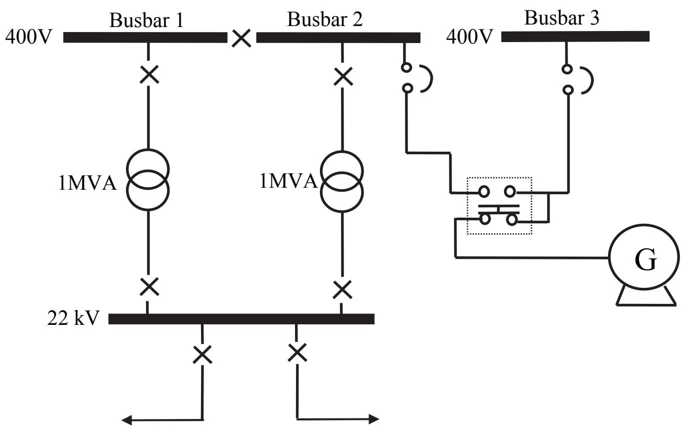



Figure 6.12 The basic single-line diagram

On each floor, there is one distribution board M1 connecting to the four tenants DBs, T1, and another distribution board LP which provides supply to all the common services in the building, and an emergency distribution board EM for emergency loads as shown in Figure 6.11. The area of each floor is 1000 $m^2$ and each tenant occupies a floor area of 200 $m^2$. The average floor height is 4.5 m. The maximum demand of each DB is shown in Table 6.3. All the single loads connected directly to the main busbars are given in Table 6.4.

**Table 6.3 The maximum demand of DB on each floor**

| DB | Maximum Demand | | | Source of Supply |
|---|---|---|---|---|
| | (kW) | (kVAr) | (Ampere) | |
| M1 | 134.6 | 94.2 | 237 | Busbar 1 |
| LP | 32.1 | 20.4 | 55 | Busbar 2 |
| EM | 20.1 | 12.8 | 34 | Busbar 3 |
| AHU | 16.67 | 12.5 | 30 | Busbar 2 |

**Table 6.4 Single loads connected directly to the busbars**

| **Single Load** | **Maximum Demand** | | | **Floor located** | **Source of Supply** |
|---|---|---|---|---|---|
| | (kW) | (kVAr) | (Ampere) | | |
| Lift Motor 1 | 33.3 | 25.0 | 60.1 | 8 | busbar 2 |
| Lift Motor 2 | 33.3 | 25.0 | 60.1 | 8 | busbar 2 |
| Chiller | 44.4 | 33.3 | 80.1 | 8 | busbar 2 |
| Condense Pump | 16.7 | 12.5 | 30.1 | 8 | busbar 2 |
| Lift Motor 3 | 33.3 | 25.0 | 60.1 | 8 | busbar 3 |
| Lift Motor 4 | 33.3 | 25.0 | 60.1 | 8 | busbar 3 |
| Water Pump 1 | 22.2 | 16.7 | 40.1 | 1 | busbar 2 |
| Water Pump 2 | 22.2 | 16.7 | 40.1 | 1 | busbar 3 |
| Sprinkler Pump | 57.88 | 43.3 | 104.3 | 1 | busbar 3 |

### 6.4.1 Busbar 1

Cable or busway riser can be used to connect from busbar 1 to the main distribution board M1 at each floor. It is assumed that each riser has a minimum rating of 225 A and a maximum rating of 800 A. The specified voltage drop limit is 1% from busbar 1 to each main DB. The designer may select one riser for each main DB since the maximum demand of each main DB is 237 A which is higher than the minimum riser size of 225 A. In this case, it will require seven outgoing circuits which implies seven breakers with the associated protective devices from busbar 1. On the other hand, the designer may select one riser connecting to as many main DBs as possible. As the maximum demand of each main DB is 237 A and the maximum riser rating is 800 A, the maximum number of main DBs which can be connected to one riser is three, subjected to the voltage drop constraints. In this example, three risers are recommended: the first riser is a cable riser connected to two main DBs at levels 7 and 6, the second riser is also a cable riser connected to two main DBs at levels 5 and 4 and the last riser is a busway riser connecting to three main DBs at levels 3, 2 and 1. The completed design of busbar 1 is shown in Figure 6.13.

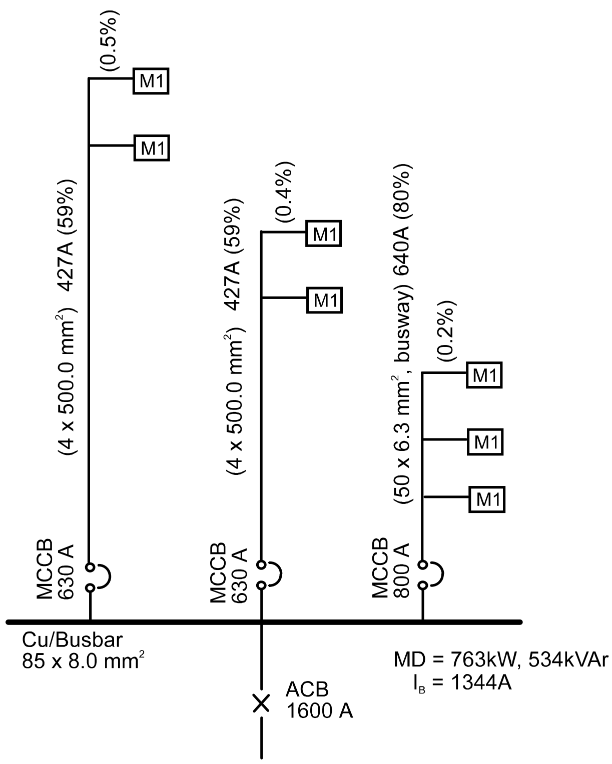



Figure 6.13 The design of busbar 1

#### 6.4.2 Busbar 2

There are five single loads, namely one 20-kW water pump, two 30-kW lift motors, one 40 kW chiller and one 15 kW condenser pump to be connected directly from busbar 2. In addition, one distribution board LP and one tap-off supply for the air handling unit (AHU) are required at each floor to be fed from busbar 2. It is also required that the supply for LP and the AHU should be on two separate risers. As the maximum demand for LP is 55 A, the designer can supply all the DBs by one riser. Alternatively, the designer can also provide the supply by using two risers. However, if it is supplied by more than two risers, each riser will be loaded less than 50% of the rated capacity and thus, it is not recommended. The maximum demand of each AHU is 30 A and for the same reason, only one riser is recommended to supply all the AHUs. The completed design of busbar 2 including the associated protective device for the incoming circuit is shown in Figure 6.14.

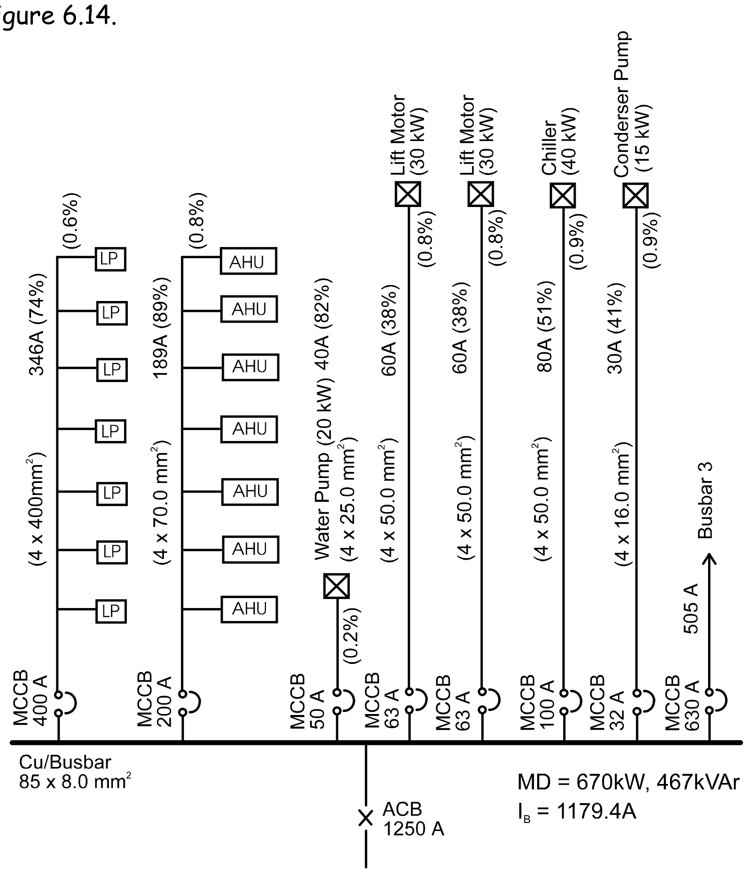



Figure 6.14 The design of busbar 2

### 6.4.3. Busbar 3

There are four single loads, namely two 30-kW lift motors at the roof, one 20-kW water pump and one 52-kW sprinkler pump at level 1 to be connected directly from busbar 3. The emergency distribution board EM, which has a maximum demand of 34 A on each floor should also be fed from busbar 3. As the demand of EM is low, the designer should select only one riser from busbar 3. Due to the voltage drop requirement, the current ratings of the two lift motor circuits are actually much larger than those required for the full load current only. For emergency loads, as all the appliances will be required to operate simultaneously, the coincidence factor of 1.0 is selected. The completed design of busbar 3 is given in Figure 6.15.

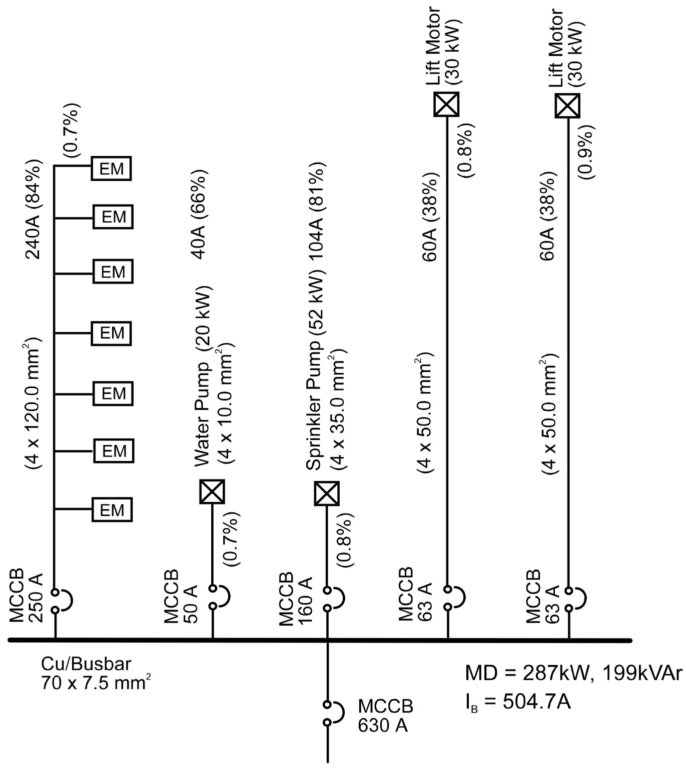



Figure 6.15 The design of busbar 3

## 6.4.4 Short-Circuit Protection

The impedance of the 22/0.4-kV transformer is normally 5% on 1 MVA base. The three-phase short-circuit current in per unit of 1 MVA and 0.4 kV base is:

$$I_{F,3\phi} = \frac{1}{0.05} = 20 \text{ p.u. current}$$

$$1 \text{ p.u. current} = \frac{1 \times 10^6}{\sqrt{3} \times 4 \times 10^3} = 1443 \text{ A}$$

$$I_{F,3\phi} = 20 \times 1.443 \text{ kA} = 28.86 \text{ kA}$$

It is also assumed that proper interlocking facility is implemented and thus, the two 22/0.4-kV transformers will never be operated in parallel. Under this assumption, the breaking capacity of the two ACBs and all the other MCCBs at busbar 1, busbar 2 and busbar 3 can be 30 kA which is higher than the critical limit of 28.86 kA.

To verify the thermal limit of cable as stated in Step 6, the critical time of the first riser from busbar 1 is calculated:

$$t_c = \frac{k^2 S^2}{I_F^2} = \frac{115^2 \times 500^2}{28860^2} = 3.97 \text{ s}$$

The value of 3.97 s is much larger than the breaker operating time of 0.01 s and thus, the cable is well protected. However, at busbar 2, the 4 x 16 mm$^2$ circuit to the condenser pump fails to meet this requirement, as the critical time is less than the breaker's operating time of 0.01s.

$$t_c = \frac{k^2 S^2}{I_F^2} = \frac{115^2 \times 16^2}{28860^2} = 0.004 \text{ s}$$

In actual case, the three-phase short circuit current at the roof will be much lower than 28 kA, and the critical time should be closer to the breaker operating time of 0.01 s if the impedance of the 4 x 16 mm$^2$ circuit is considered.

### 6.4.5 Earth Fault Protection

As the impedance of the 22/0.4-kV transformer is 5% and the typical X/R ratio of the transformer is 5, the value of the resistance and reactance of the transformer can be obtained by:

$$Z_T = \sqrt{R_T^2 + X_T^2}$$

$$R_T = \frac{Z_T}{\sqrt{1 + 5^2}} = \frac{5\%}{\sqrt{26}} = 0.98\%$$

$$X_T = 5 \times R_T = 5 \times 0.98\% = 4.9\%$$

The resistance and reactance in ohms can be obtained by multiplying the per unit value by the base impedance of 0.16 Ω.

$$R_T = 0.16 \times 0.0098 = 0.0016\ \Omega$$
$$X_T = 0.16 \times 0.049 = 0.0078\ \Omega$$

Let us assume that the earthing of the installation is a TN-S system and the protective conductor from the transformer neutral to the earthing terminal of busbar 2 is a 300 mm$^2$ pvc-insulated, copper conductor cable of 25 m length, and the CPC from busbar 2 to the distribution board LP at level 1 is a 120 mm$^2$ pvc-insulated copper conductor of 5 m length. The cable riser from busbar 2 to each LP is a 4 x 240 mm$^2$ pvc-insulated, copper conductor cable as shown in Figure 6.16. The earth fault loop impedance at DB LP at level 1 is:

$$Z_{EFL} = \sqrt{\left(R_T + R_{500} + R_{240} + R_{120} + R_{300}\right)^2 + \left(X_T + X_{500} + X_{240} + X_{120} + X_{300}\right)^2}$$

where

$$R_{500} = \frac{0.086 \times 25}{\sqrt{3} \times 1000 \times 2} = 0.00062\ \Omega \quad R_{240} = \frac{0.16 \times 5}{\sqrt{3} \times 1000} = 0.00046\ \Omega$$

$$R_{120} = \frac{0.32 \times 5}{\sqrt{3} \times 1000} = 0.00092\ \Omega \quad R_{300} = \frac{0.13 \times 25}{\sqrt{3} \times 1000} = 0.0019\ \Omega$$

$$X_{500} = \frac{0.135 \times 25}{\sqrt{3} \times 1000 \times 2} = 0.00098\ \Omega \quad X_{240} = \frac{0.22 \times 5}{\sqrt{3} \times 1000} = 0.00064\ \Omega$$

$$X_{120} = \frac{0.23 \times 5}{\sqrt{3} \times 1000} = 0.00066\ \Omega \quad X_{300} = \frac{0.22 \times 25}{\sqrt{3} \times 1000} = 0.0032\ \Omega$$

$$Z_{EFL} = \sqrt{0.0055^2 + 0.01328^2}$$
$$= 0.01437\ \Omega$$

The line-to-earth fault current is:

$$I_{EF} = \frac{230}{0.01437} = 16{,}006\ \text{A}$$

To verify the size of CPC as stated in Step 8, the minimum cross-sectional area of the CPC from LP1 to busbar 2 is:

$$S_{min} \geq \frac{I_{EF}\sqrt{t_{bk,Ief}}}{k}$$
$$= \frac{16{,}006 \times \sqrt{0.1}}{143} = 35.4\ \text{mm}^2$$

The selected CPC size of 120 mm$^2$ is thus more than the minimum required size of 35.4 mm$^2$ (step 8).

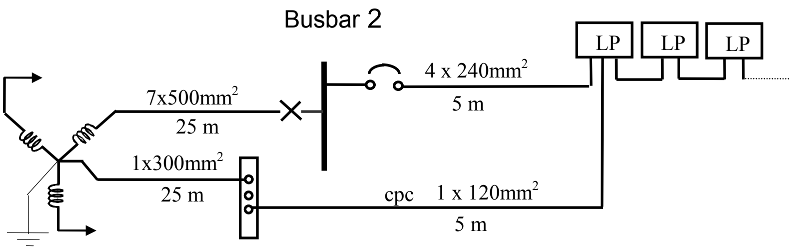



Fig 6.16 Illustration of earth fault loop impedance at level 1

In the distribution board LP at level 1, there is a socket-outlet circuit of 2 x 4 mm$^2$ copper conductor cable with a 1 x 4 mm$^2$ CPC of 15 m length protected by a type C 32 A MCB. The resistance values of the phase conductor and CPC are:

$$R_4 = \frac{11 \times 15}{2 \times 1000} = 0.0825\ \Omega$$
$$R_{CPC,4} = 0.0825\ \Omega$$

The earth fault current at the socket outlet is:

$$I_{F,LE} = \frac{230}{\sqrt{(0.0055 + 0.0825 + 0.0825)^2 + 0.01328^2}}$$
$$= \frac{230}{0.171} = 1345\ \text{A}$$

For a current of 1345 A, the 32-A MCB will operate within the specified time of 0.4 s (Step 7). The touch voltage for an earth fault at the appliance connected to the socket outlet if it is within the earthed equipotential zone is:

$$V_t = Z_{CPC} \times I_A$$
$$V_t = Z_{CPC} \times 320$$
$$= \sqrt{(R_{CPC,4} + R_{CPC,120})^2 + X_{CPC,120}^{\ 2}} \times 320$$
$$= \sqrt{(0.0825 + 0.00092)^2 + 0.00066^2} \times 320$$
$$= 26.7\ \text{V}$$

The value of 26.7 V is within the maximum limit of 50 V.

## 6.5 REFERENCES


[1] "Regulations for Electrical Installations", 16th Edition, IEE, 1991.
[2] CP5 : 1988, "Code of Practice for Wiring of Electrical Equipment of Buildings", SISIR, 1988/1995.
[3] P J S Chram, "The National Electrical Code 1987 Handbook", National Fire Protection Association, 4th Edition, 1987.
[4] IEEE Standard 241-1983, "IEEE Recommended Practice for Electric Power Systems in Commercial Buildings", IEEE, 1983.
[5] "Guidance Note on Selection and Erection", Guidance Note No. 1, IEE, 1992.
[6] "Guidance Note on Protection against Overcurrent", Guidance Note No. 6, IEE, 1992.

## CHAPTER 7

## CALCULATIONS OF SHORT-CIRCUIT CURRENTS

Calculation of short-circuit currents in low-voltage systems is usually simpler than in high-voltage systems. Certain simplifying assumptions are made when calculating fault current. An important assumption is that the fault is shorted through a zero fault impedance. This assumption simplifies the calculation process and also applies a safety factor since the calculated values represent the worst case condition. Furthermore, a three-phase fault is usually assumed as this type of fault generally results in the maximum short-circuit current in a circuit. The actual fault current is normally less than the calculated three-phase value since the fault impedance may always be higher than zero. Line-to-line short-circuit currents are about 87% of the three-phase fault currents while line-to-neutral short-circuit currents are also lower than the three-phase fault currents. For a system with neutral solidly grounded, the line-to-earth short-circuit currents can range from 60% to 125% of the three-phase value depending on the construction of the ground-return circuit. However, the line-to-ground fault currents of more than the three-phase value rarely occurs in industrial and commercial systems.

Calculation of short-circuit currents at various sections in a low-voltage system is essential for the proper selection of MCCBs, MCBs, fuses, busbars and cables. All of these electrical components should withstand the thermal and magnetic stresses imposed by the maximum possible short-circuit currents. In addition, circuit breakers and fuses should interrupt safely these maximum short-circuit currents.

### 7.1 SOURCES OF FAULT CURRENTS

The basic sources of fault currents are the utility supply system, local generators, synchronous motors and induction motors. All the running generators in the utility system contribute to the fault current in a low-voltage system. However, transmission and distribution lines and transformers introduce impedances between the utility generators and the low voltage system. As a result, the contribution of these generators to the fault current in the low-voltage system is substantially reduced. Nevertheless, the utility system is still the main source of the fault currents. The amount of the short-circuit current from the utility system is normally expressed as the fault level at the service entrance. The value of the fault level should normally be obtained from the utility. Typical values of fault level at 22 kV are in the range of 300 MVA to 1000 MVA, and for 6.6 kV, in the range of 150 MVA to 200 MVA. For intake at 400 V, the fault level is in the range from 15 MVA to 25 MVA.

Fault current contributed from a local generator decreases exponentially from a high initial value to a lower steady-state value which is equivalent to the current generated by a constant voltage behind a variable reactance. As the generator continues to be driven by its prime mover and to have its field energised from its exciter, the steady-state value of fault current will persist. For purposes of fault-current calculations, industry standards have established three specific names for values of this variable reactance, namely sub-transient reactance ($X_d''$), transient reactance ($X_d'$) and synchronous reactance ($X_d$). $X_d''$ determines the fault current during the first cycle (up to 0.02 second) after a fault occurs. The reactance increases to $X_d'$ which is used to determine the fault current from 0.5 to 2 seconds. The reactance will then increase to $X_d$ which determines the current flow after steady-state condition is reached. In low-voltage systems, as the protective devices such as MCCBs, MCBs or fuses are activated mostly within the first cycle by the primary current, $X_d''$ is recommended for the calculation of fault current contributed by the local generator. Typical values for $X_d''$ are in the range from 10% to 15% on generator kVA rating.

The fault current contributed from induction motor is generated by inertia driving the motor in the presence of a field flux produced by induction from the stator. Since this flux decays on a loss of the source voltage or on a substantial reduction of the source voltage during fault, the current contribution of an induction motor reduces and disappears completely after a few cycles. In the calculation of the fault current, induction motors are assigned only a sub-transient reactance $X_d''$. A typical value for $X_d''$ is 25% based on the individual motor kVA rating or on the total kVA of a group of motors.

## 7.2 STEP-BY-STEP CALCULATIONS

The example of the fault calculation presented here is based on a 400-V three-phase system shown in Figure 7.1. The system data shown are typical of those required to perform the calculations. Bolted three-phase short circuits at locations F1 and F2 are assumed separately. Resistances are usually significant and their effect may be evaluated either by a complex impedance reduction or by separate X and R reductions. The complex reduction leads to the most accurate solution but the separate X and R reductions are simpler and more conservative. Thus, the latter is adopted in all the step-by-step calculations.

### 7.2.1 Common Base Values

The base MVA is selected as 1 MVA and the base kV as 0.4 kV. The base impedance and base current can than be obtained as follows :

$$\text{Base Impedance} = \frac{(\text{ base kV })^2}{\text{base MVA}} = \frac{(0.4)^2}{1} = 0.16\Omega$$

$$\text{Base current} = \frac{\text{base MVA} \times (1000)}{(\text{base kV}) \times \sqrt{3}}$$

$$= \frac{1 \times 1000}{0.4 \times \sqrt{3}} = 1443 \text{ A}$$

**Utility Fault Level**

The utility fault level is given as 800 MVA with a X/R ratio of 15. The values for the common base of the equivalent utility resistance ($R_u$) and reactance ($X_u$) can be obtained as follows:

$$Z_U = \frac{\text{Base MVA}}{\text{Fault MVA}} = \frac{1}{800} = 0.00125 \text{ per unit}$$

$$\text{since } Z_U = \sqrt{R_U^2 + X_U^2} \text{ and } X_U / R_U = 15$$

$$R_U = \frac{Z_s}{\sqrt{1 + (15)^2}} = \frac{0.00125}{15.033} = 0.000083 \text{ per unit}$$

$$X_U = 15 \times R_U = 0.00125 \text{ per unit}$$

**Transformer Impedance**

The 1000 kVA transformer has an impedance of 5.75% on 1000 kVA and the value of resistance is 1.21%. The reactance can be obtained by $\sqrt{Z^2 - R^2} = 5.62\%$.

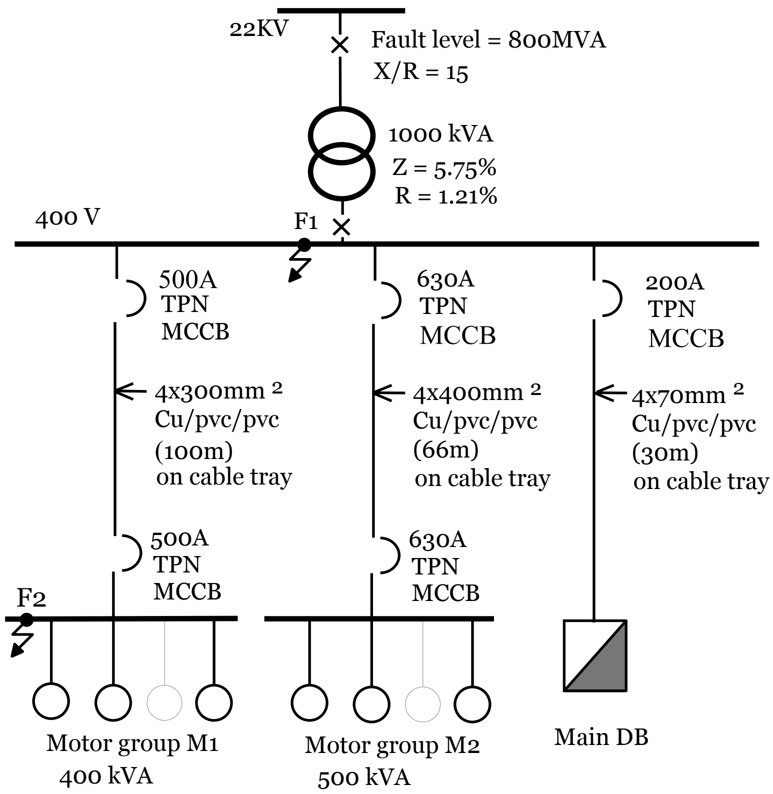



Figure 7.1 Sample network

As the transformer rating of 1000 kVA is the same as the base MVA, the percentage values of the transformer resistance ($R_T$) and reactance ($X_T$) remain the same.

$$R_T = 1.21\% = 0.0121 \text{ per unit}$$
$$X_T = 5.62\% = 0.0562 \text{ per unit}$$

## 300mm$^2$ Cable

The resistance and reactance values of the 300 mm$^2$ cable can be obtained from table 4D1B of the IEE Wiring Regulations. The resistance is (0.00013 $\Omega$) $/\sqrt{3}$ per m, and the reactance is (0.00014 $\Omega$)/$\sqrt{3}$ per m. The per unit values of resistance ($R_{300c}$) and reactance ($X_{300c}$) for 100 m of the 300 mm$^2$ cable can be obtained as follows :

$$R_{300c} = \frac{0.00013 \times 100}{\sqrt{3} \times 0.16} = 0.0469 \text{ per unit}$$

$$X_{300c} = \frac{0.00014 \times 100}{\sqrt{3} \times 0.16} = 0.0505 \text{ per unit}$$

**400 mm$^2$ Cable**

The per unit values of the resistance and reactance of the 400 mm$^2$ cable for a length of 66 m can be obtained as follows :

$$R_{400c} = \frac{0.000105 \times 66}{\sqrt{3} \times 0.16} = 0.025 \text{ per unit}$$

$$X_{400c} = \frac{0.00014 \times 66}{\sqrt{3} \times 0.16} = 0.033 \text{ per unit}$$

**70 mm$^2$ Cable**

The values of the resistance and reactance of the 70 mm$^2$ cable for a length of 30 m are:

$$R_{70c} = \frac{0.00055 \times 30}{\sqrt{3} \times 0.16} = 0.0595 \text{ per unit}$$

$$X_{70c} = \frac{0.0016 \times 30}{\sqrt{3} \times 0.16} = 0.01732 \text{ per unit}$$

**Motor Groups**

The average sub-transient reactance is 25% based on the total rating of a group of motors. Based on a typical X/R ratio of 6, the resistance is 25%/6 = 4.167%. The values of the equivalent resistance and reactance converted to the common base for the motor groups M1 and M2 are:

$$R_{M1} = \frac{0.04167 \times 1000}{400} = 0.1042 \text{ per unit}$$

$$X_{M1} = \frac{0.25 \times 1000}{400} = 0.625 \text{ per unit}$$

$$R_{M2} = \frac{0.04167 \times 1000}{500} = 0.0833 \text{ per unit}$$

$$X_{M2} = \frac{0.25 \times 1000}{500} = 0.5 \text{ per unit}$$

### 7.2.2 Fault at Location F1

The equivalent resistance and reactance networks for the fault at F1 are shown in Figure 7.2 and Figure 7.3 respectively.

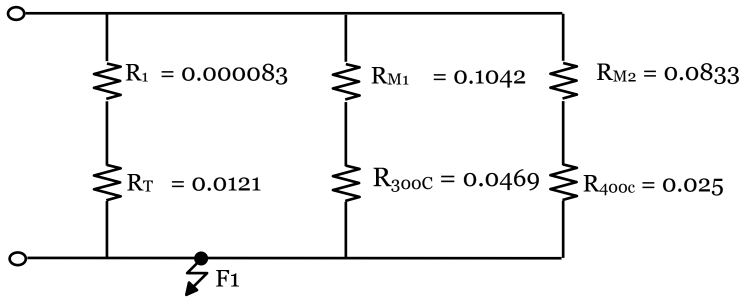



Figure 7.2 Equivalent resistance network for Fault at F1

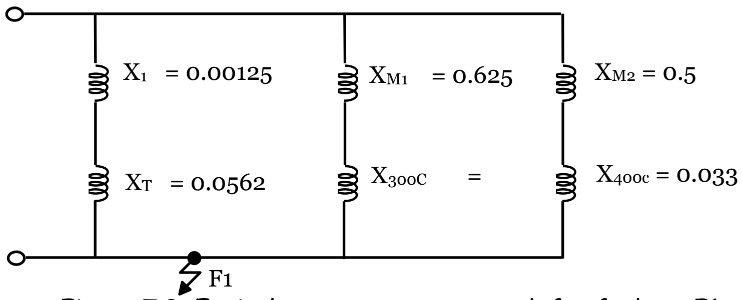



Figure 7.3 Equivalent reactance network for fault at F1

The equivalent resistance $R_{eq}$ and reactance $X_{eq}$ are :

$$R_{eq} = \left(R_u + R_T\right) // \left(R_{M1} + R_{300c}\right) // \left(R_{M2} + R_{400c}\right)$$

$$= \frac{1}{\frac{1}{0.00083 + 0.0121} + \frac{1}{0.1042 + 0.0469} + \frac{1}{0.0833 + 0.025}}$$

$$= \frac{1}{82.08 + 6.618 + 9.234}$$

$$= \frac{1}{97.932}$$

$$= 0.01021 \text{ per unit}$$

$$
\begin{aligned}
X_{eq} &= \left(X_U + X_T\right) // \left(X_{M1} + X_{300c}\right) // \left(X_{M2} + X_{400c}\right) \\
&= \frac{1}{\dfrac{1}{0.00125 + 0.0562} + \dfrac{1}{0.625 + 0.0505} + \dfrac{1}{0.5 + 0.033}} \\
&= \frac{1}{17.41 + 1.48 + 1.88} \\
&= 0.04814 \text{ per unit}
\end{aligned}
$$

The equivalent per unit impedance and the fault current at F1 are :

$$Z_{eq,F1} = \sqrt{\left(R_{eq}\right)^2 + \left(X_{eq}\right)^2} = \sqrt{0.01021^2 + 0.04814^2} = 0.0492 \text{ per unit}$$

$$I_f = \frac{1}{0.0492} = 20.325 \text{ per unit}$$

$$
\begin{aligned}
I_{f1} &= 1443 \text{ A} \times 20.325 \\
&= 29.329 \text{ kA}
\end{aligned}
$$

The X/R ratio of the system impedance for the fault at F1 is :

$$\frac{X}{R} = \frac{0.04814}{0.01021} = 4.715$$

### 7.2.3 Fault at Location F2

The equivalent resistance and reactance network for the fault at F2 are shown in Figure 7.4 and Figure 7.5 respectively.

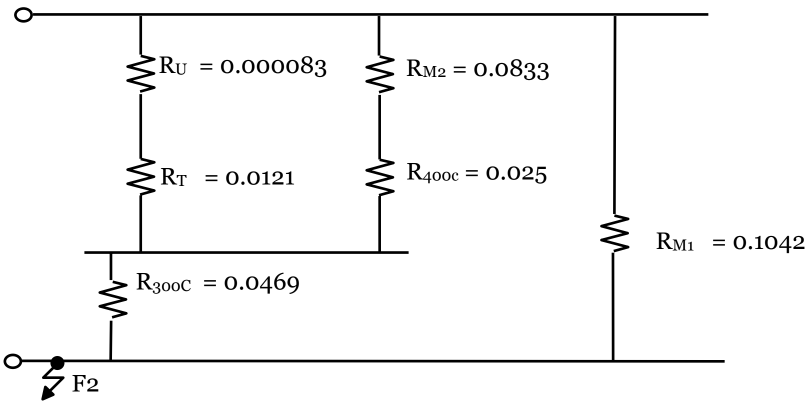



Figure 7.4 Equivalent resistance network for fault at F2

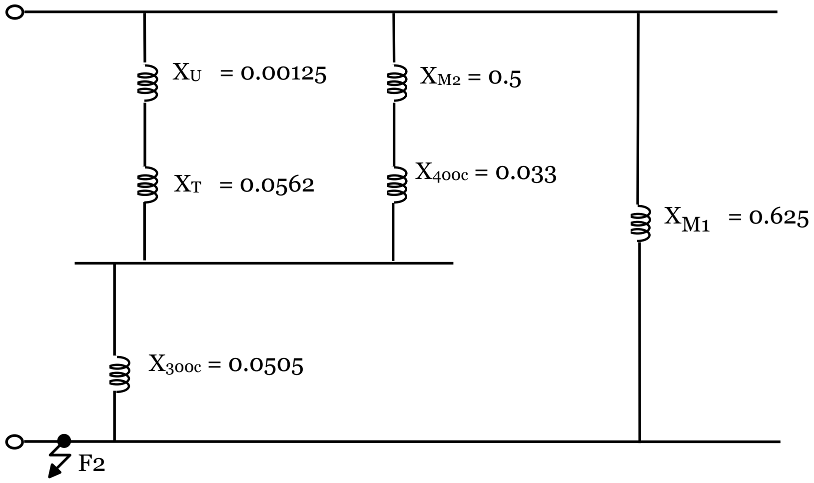



Figure 7.5 Equivalent reactance network for fault at F2

The equivalent resistance $R_{eq}$ and reactance $X_{eq}$ for the fault at F2 are:

$$R_{eq} = (R_{M1}) // (R_{300c} + (R_u + R_T) // (R_{M2} + R_{400c}))$$

$$R_{eq} = \frac{1}{\frac{1}{0.1042} + \frac{1}{0.0469 + 0.01095}}$$

$$= \frac{1}{\frac{1}{0.1042} + \frac{1}{0.05785}}$$

$$= 0.0372 \text{ per unit}$$

$$X_{eq} = (X_{M1}) // (X_{300c} + (X_u + X_T) // (X_{M2} + X_{400c}))$$

$$= \frac{1}{\frac{1}{0.625} + \frac{1}{0.0505 + 0.0519}}$$

$$= 0.0879 \text{ per unit}$$

The equivalent impedance $Z_{eq}$ and fault current at F2 are :

$$Z_{eq,\,F2} = \sqrt{(R_{eq})^2 + (X_{eq})^2} = \sqrt{0.0372^2 + 0.0879^2} = 0.0954 \text{ per unit}$$

$$I_{F2,p.u.} = \frac{1}{0.0954} = 10.48 \text{ per unit current}$$

$$\begin{aligned} I_{F2} &= 1443 \times 10.48 \\ &= 15.123\text{kA} \end{aligned}$$

The X/R ratio of the system impedance for the fault at F2 is :

$$\frac{X}{R} = \frac{0.0879}{0.0372} = 2.36$$

## 7.3 SYSTEMATIC CALCULATION BY COMPUTER

By referring to the same common base, the sample network can be re-arranged to a network consisting of 4 nodes and 3 lines as shown in Figure 7.6(a). The complex impedance network in Figure 7.6(a) can also be re-arranged to a simplified impedance network by using $Z = \sqrt{R^2 + X^2}$ for each circuit element as shown in Figure 7.6(b). The admittance matrix (called Y-matrix) can then be formulated for the 4-node system as follows :

$$y_{11} = \frac{1}{0.05875} + \frac{1}{0.06892} + \frac{1}{0.0414} + \frac{1}{0.06197} = 71.82$$

$$y_{12} = \frac{-1}{0.0689} = -14.51 \quad y_{13} = \frac{-1}{0.0414} = -24.15$$

$$y_{14} = \frac{-1}{0.0620} = -16.14$$

$$y_{22} = \frac{1}{0.0689} + \frac{1}{0.6336} = 16.09$$

$$y_{33} = \frac{1}{0.0414} + \frac{1}{0.5069} = 26.12$$

$$y_{44} = \frac{1}{0.0620} = 16.14$$

The Y-matrix and the inverted Y-matrix are as follows:

$$Y = \begin{bmatrix} 71.820 & -14.510 & -24.150 & -16.140 \\ -14.510 & 16.090 & 0.000 & 0.000 \\ -24.150 & 0.000 & 26.120 & 0.000 \\ -16.140 & 0.000 & 0.000 & 16.140 \end{bmatrix}$$

$$Y^{-1} = \begin{bmatrix} 0.0493 & 0.0444 & 0.0456 & 0.0493 \\ 0.0444 & 0.1022 & 0.0411 & 0.0444 \\ 0.0456 & 0.0411 & 0.0804 & 0.0456 \\ 0.0493 & 0.0444 & 0.0456 & 0.1113 \end{bmatrix}$$

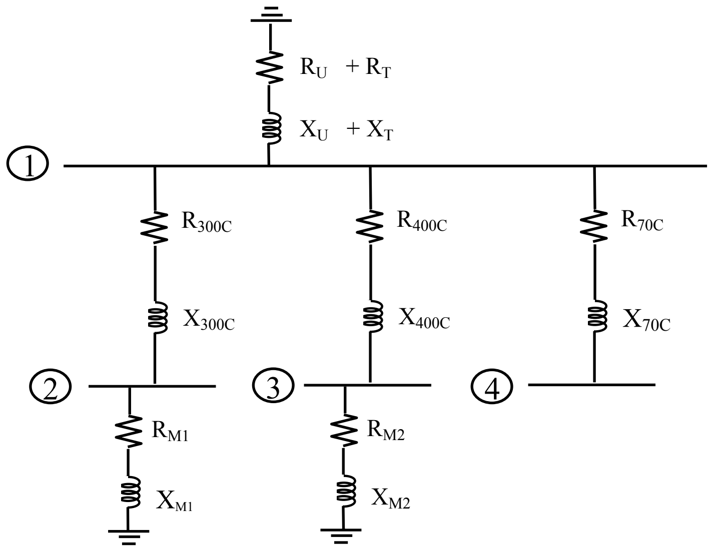



Figure 7.6(a) Complex Representation

Let $z_{11}$ denotes the first diagonal element, $z_{22}$ the second diagonal element and $z_{nn}$ the last diagonal element of the inverse of the Y-matrix. The total fault current at any particular node (say node q) can be obtained by $1/z_{qq}$. Thus, the fault current for the fault at location F1 can be obtained by :

$$I_{F1} = \frac{1}{z_{11}} = \frac{1}{0.0493} = 20.28 \text{ per unit } = 29.264 \text{ kA}$$

The fault current at location F2 is:

$$I_{F2} = \frac{1}{z_{22}} = \frac{1}{0.1022} = 9.78 \text{ per unit} = 14.113 \text{ kA}$$

Similarly, the fault current at node 3 is $1/z_{33}$ and at node 4 is $1/z_{44}$. In addition, the distribution of the fault currents can also be calculated. The computational flow chart is shown in Figure 7.7. A display of the total fault current and its distribution in amperes for a fault at node 1 through node 4 are shown in Figure 7.8 through Figure 7.11 respectively.

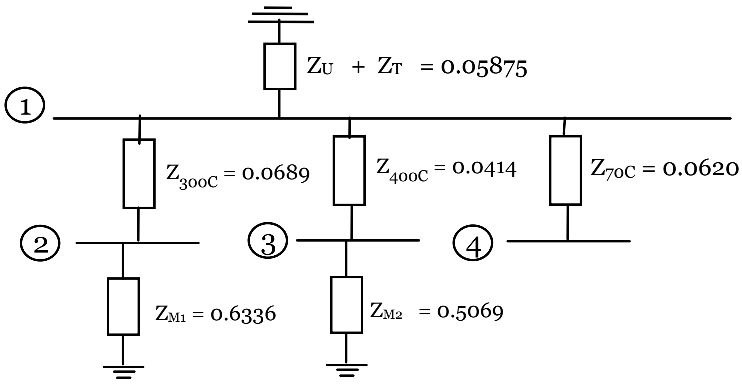



Figure 7.6(b) Simplified Representation

These calculated fault currents are slightly lower than the values obtained by the step-by-step calculation using the separate X and R reduction. If more accurate values are required, the Y-matrix should be formulated as a complex matrix and inverted using the complex representation.

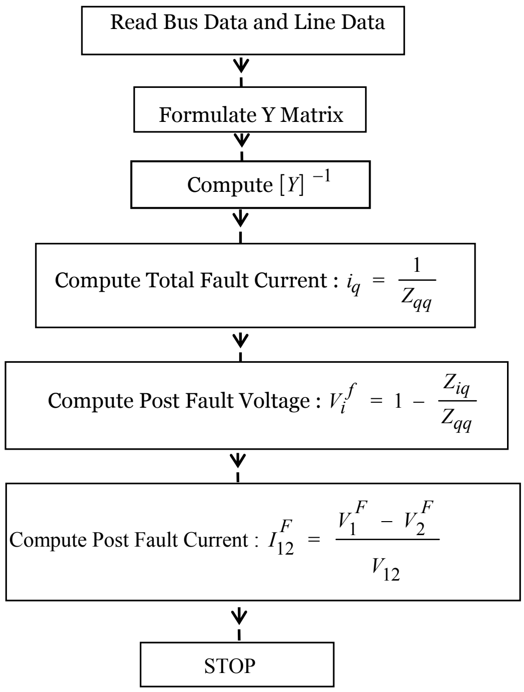



Figure 7.7 Computational flow chart

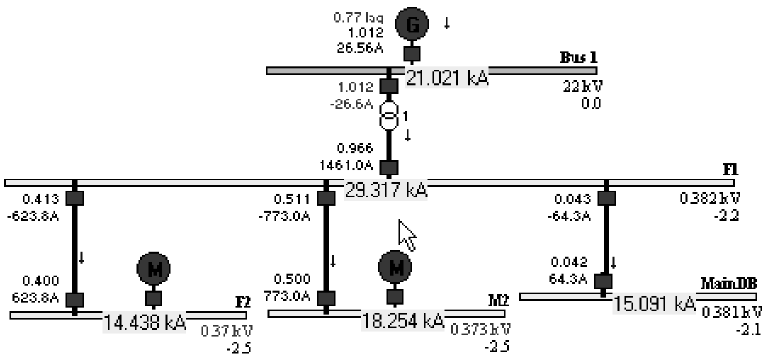



Figure 7.8 Total Fault current for a 3-phase fault at each node

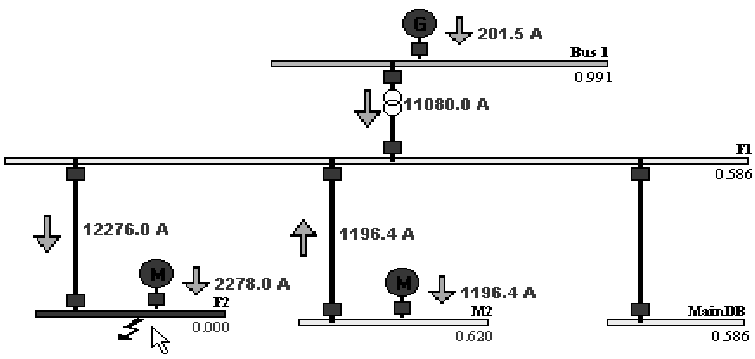



Figure 7.9 Fault current distribution for fault at node F2 (14.438 kA)

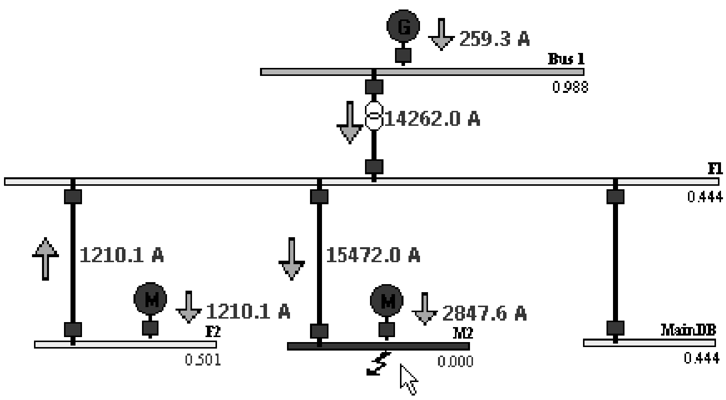



Figure 7.10 Fault current distribution for fault at node M2 (18.254 kA)

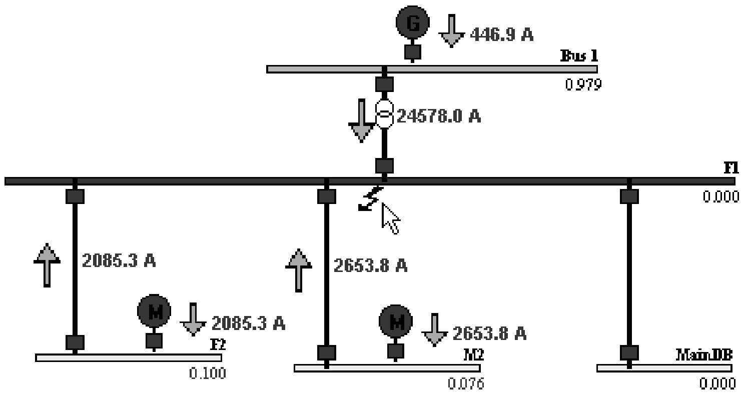



Figure 7.11 Fault current distribution for fault at node F1 (29.317 kA)

## 7.4 A CASE STUDY

The electricity supply to a high-rise luxurious apartment is fed by a 1 MVA 22/0.4-kV transformer located on the ground floor of the building. The schematic diagram of part of the electrical installation is shown in Figure 7.12. As some of the distribution boards on the lower floors are closer to the transformer, the fault level at these apartment DBs will be high. However, by mistake, the contractor has installed the M6 MCBs in all the apartment DBs. Since the M6 MCBs have a breaking capacity of 6 kA, the utility company insisted all the MCBs be replaced with M9 MCBs which have a breaking capacity of 9 kA. This case study was conducted to examine whether the replacement of MCB was essential or not.

In the fault current calculation, all the utility's generators are represented by a single equivalent impedance. The impedance value is determined by an assumed fault level of 1000 MVA at 22 kV. This is a very conservative assumption as the switchgear at 22 kV is rated at 1000 MVA. The impedance of the 22-kV/LV transformer is assumed as 5%. For the entire three-phase network, per-unit values are used to determine the three-phase fault current. For the single-phase network, the representation of system elements is in ohm which provides an easier and more straight-forward calculation. Two different methods are illustrated and compared.

### 7.4.1 Method A

The single-phase representation of a three-phase balanced system uses per-phase impedances and the line-to-neutral system driving voltage. All calculations up to the floor DB use per-unit values for impedances and voltages. However, from the floor DB to each apartment DB, impedances in ohms and voltages in volts are used to determine the fault current for the line-to-neutral short-circuit. All the cable impedances are based on Table 4D1B of the IEE Wiring Regulations using half of the single-phase tabulated voltage-drop constant as the per-phase per-metre cable impedance.

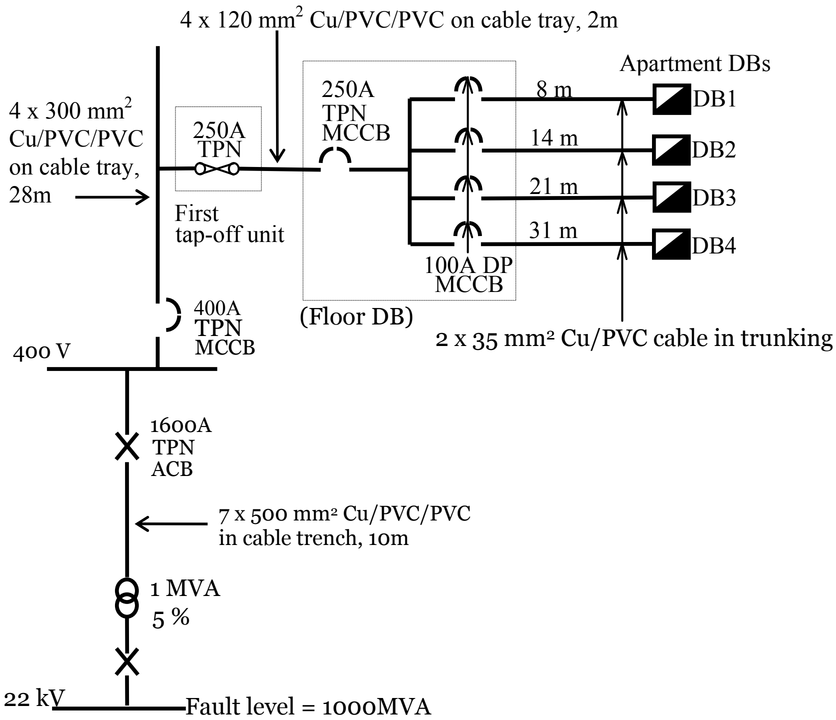



Figure 7.12 Schematic diagram of the electrical installation

For the per-unit calculation, values of the base MVA and base kV are as follows:

At 22 kV : Base MVA = 1 MVA  Base kV = 22 kV

At 400 V : Base MVA = 1 MVA  Base kV = 400 V

$$\text{Base Impedance} = \frac{(\text{base kV})^2}{\text{base MVA}} = \frac{(0.4)^2}{1} = 0.16\ \Omega$$

$$\text{Base current} = \frac{\text{base MVA } 1000}{\sqrt{3}(\text{base kV})} = \frac{1000}{\sqrt{3} \times 0.4} = 1443\ \text{A}$$

$$V_{LN} = 400 / \sqrt{3} = 230.9\ \text{V} = 231\ \text{V}$$

For a fault level of 1000 MVA at 22 kV, the per-unit impedance (Z) is:

$$Z = \frac{1}{1000} = 0.001 \text{ p.u.}$$

**Fault Current at Transformer LV Terminal**

The equivalent circuit for the fault at the transformer LV terminal is shown in Figure 7.13.

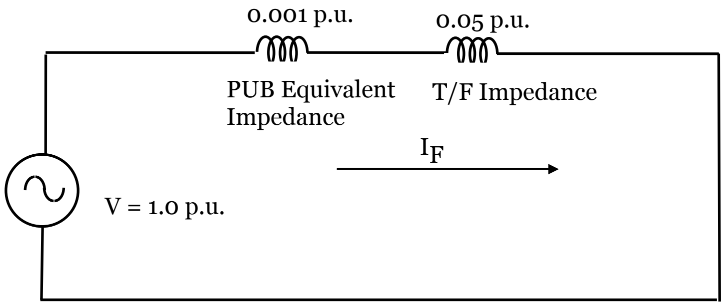



Figure 7.13 Equivalent circuit at LV terminal

The three-phase fault current at LV terminal is :

$$I_{F,\,LV,\,p.u.} = \frac{1}{0.001 + 0.05} = \frac{1}{0.051} = 19.61 \text{ p.u. current}$$

$$I_{F,LV} = 1443 \text{ x } 19.61 = 28{,}297 \text{ A}$$

**Fault Current at the Main Switchboard**

The per-phase impedance of the 7 x 500 mm$^2$ pvc-insulated copper conductor cable in a cable trench (installation method 1, 10 m and two cables per phase) is:

$$Z_{500} = 0.185 \times 0.5 \times 10 \times 10^{-3} \times 0.5\ \Omega$$
$$= 0.0004625\ \Omega$$

$$Z_{500,\,p.u.} = \frac{0.0004625}{0.16} = 0.002891 \text{ p.u.}$$

The equivalent circuit for the fault at the main switchboard is shown in Figure 7.14 and the three-phase fault current at the main switchboard is :

$$I_{F,\,MS,\,p.u.} = \frac{1}{0.001 + 0.05 + 0.002891} = 18.556 \text{ p.u.}$$

$$I_{F,MS} = 1443 \text{ A} \times 18.556 = 26{,}776 \text{ A}$$

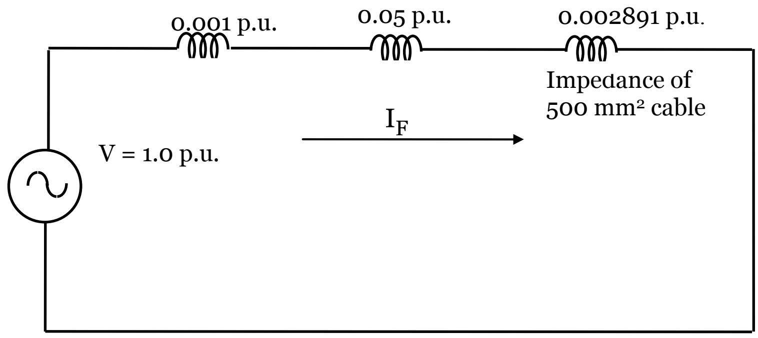



Figure 7.14 Equivalent circuit at the main switchboard

**Fault Current at First Tap-off Unit**

The per-phase impedance of the 4 x 300 $mm^2$ pvc-insulated copper conductor cable on a cable tray (installation method 11, 28 metres) is :

$$Z_{300} = 0.22 \times 0.5 \times 28 \times 10^{-3}\ \Omega = 0.00308\ \Omega$$

$$Z_{300,\,p.u.} = \frac{0.00308}{0.16} = 0.01925 \text{ p.u.}$$

The equivalent circuit for the fault at the first tap-off unit is shown in Figure 7.15 and the three-phase fault current at the first tap-off is :

$$I_{F,TAP1,p.u.} = \frac{1}{0.001 + 0.05 + 0.002891 + 0.01925}$$

$$= \frac{1}{0.07314} = 13.6724 \text{ p.u.}$$

$$I_{F,TAP1} = 1443 \text{ x } 13.6724 = 19{,}729 \text{ A}$$

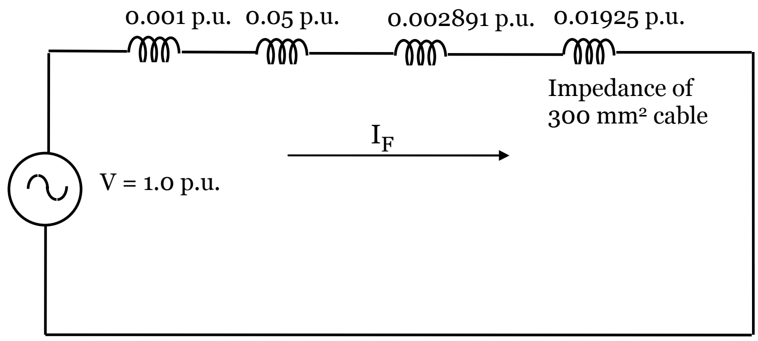



Figure 7.15 Equivalent circuit at the first tap-off unit

**Fault Current at Floor DB**

The per-phase impedance of the 4 x 120 mm$^2$ pvc-insulated copper conductor cable on cable tray (installation method 11, 2 metre) is :

$$Z_{120} = 0.41 \times 0.5 \times 2 \times 10^{-3}\ \Omega = 0.00041\ \Omega$$

$$Z_{120,\text{p.u.}} = \frac{0.00041}{0.16} = 0.0025625\ \text{p.u.}$$

The equivalent circuit for fault at the floor DB is shown in Figure 7.16 and the three-phase fault current at the floor DB is:

$$I_{\text{F, DBF, p. u.}} = \frac{1}{0.001 + 0.05 + 0.002891 + 0.01925 + 0.0025625}$$
$$= \frac{1}{0.757} = 13.21\ \text{p.u.}$$
$$I_{\text{F,DBF}} = 1443\ \text{A} \times 13.21 = 19{,}062\ \text{A}$$

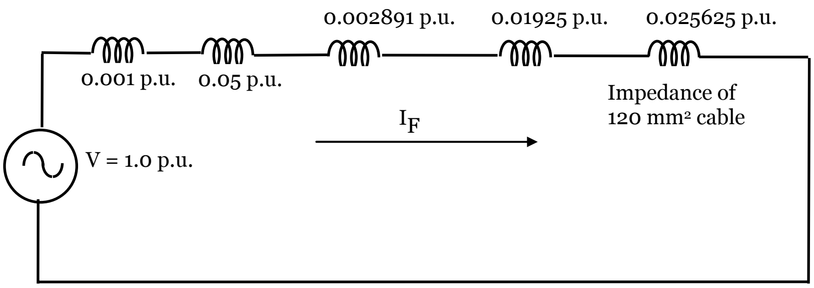



Figure 7.16 Equivalent circuit floor DB

**Fault Current at Apartment DB**

To calculate the line-to-neutral short-circuit current at each apartment DB, the line-to-neutral voltage behind an internal impedance from each apartment DB to the utility infeed is applied. The equivalent circuit is shown in Figure 7.17.

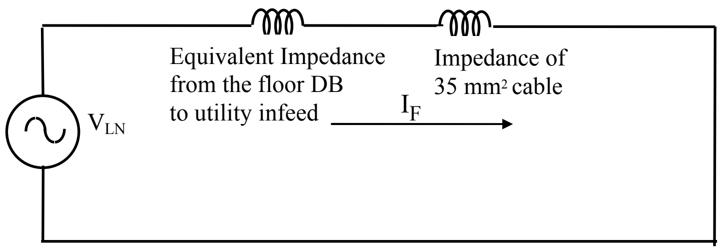



Figure 7.17 Equivalent circuit at apartment DB by method A

The equivalent impedance from the floor DB to the supply intake at 22 kV is :

$$Z_{eq,DBF} = \frac{V_{LN}}{I_{F,DBF}} = \frac{231}{19{,}062} = 0.01212\Omega$$

The impedances of the 2 × 35 mm$^2$ pvc-insulated copper conductor cables in trunking (installation method 3, 8 m for DB1, 14 m for DB2, 21 m for DB3, and 31 m for DB4) are:

$$Z_{DB1} = 1.3 \times 0.5 \times 8 \times 10^{-3} = 0.0052\ \Omega$$
$$Z_{DB2} = 1.3 \times 0.5 \times 14 \times 10^{-3} = 0.0091\ \Omega$$
$$Z_{DB3} = 1.3 \times 0.5 \times 21 \times 10^{-3} = 0.01365\ \Omega$$
$$Z_{DB4} = 1.3 \times 0.5 \times 31 \times 10^{-3} = 0.02015\ \Omega$$

The fault current at the four apartment DBs are :

$$I_{F,DB1} = \frac{231}{0.01212 + 0.0052 + 0.0052} = 10{,}258\ \text{A}$$

$$I_{F,DB2} = \frac{231}{0.01212 + 0.0091 + 0.0091} = 7{,}619\ \text{A}$$

$$I_{F,DB3} = \frac{231}{0.01212 + 0.01365 + 0.01365} = 5{,}860\ \text{A}$$

$$I_{F,DB4} = \frac{231}{0.01212 + 0.02015 + 0.02015} = 4{,}407\ \text{A}$$

### 7.4.2 Method B

In method A, the three-phase fault level at the floor DB is calculated first, and then a single-phase equivalent is used to calculate the fault level at each apartment DB. As the main focus of the analysis is to estimate the fault level for line-to-neutral at each apartment DB and not to estimate the fault level at other locations, the more accurate method should be based on a single-phase equivalent at the LV terminal of the 22 kV/LV transformer.

As the three-phase fault level at the transformer's LV terminal has been calculated as 28,297 A in section 7.4.1, the single-phase equivalent impedance at the LV terminal can be expressed as :

$$Z_{eq,LV} = \frac{V_{LN}}{I_{F,LV}} = \frac{231}{28{,}297} = 0.00817\ \Omega$$

The equivalent circuit for the line-to-neutral short-circuit at the apartment DB is shown in Figure 7.18.

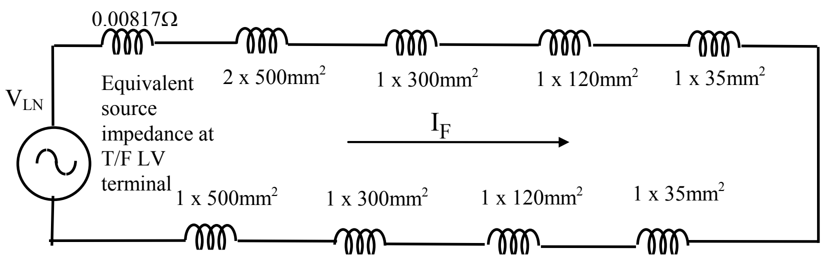



Figure 7.18 Equivalent circuit at apartment DB by method B

The per-phase impedance of the 500 mm$^2$ cable has to be divided by two as there are two cables per-phase, however, division is not necessary for the neutral cable as there is only one 500 mm$^2$ cable for the neutral. The per-phase impedance in ohms for each cable which has been calculated from section 7.4.1 is summarized in Table 7.1.

The total cable impedance from the transformer's LV terminal to the floor DB during a line-to-neutral short-circuit at the apartment DB is :

$$Z_{DBF} = 0.0004625 + 0.000925 + 2 \times (0.00308 + 0.00041) = 0.008368\ \Omega$$

The fault current at each apartment DB can thus be calculated by :

$$\begin{aligned} I_{F,DB} &= \frac{231}{Z_{eq,LV} + Z_{DBF} + 2 \times Z_{35}} \\ &= \frac{231}{0.00817 + 0.008368 + 2 \times Z_{35}} \end{aligned}$$

The line-to-neutral source impedance at each apartment DB and the fault currents are summarized in Table 7.2.

### 7.4.3 Accuracy and Comparison

For the exact calculation, cable impedance should not be added directly as the impedance Z is a complex quantity containing the resistance R and reactance X expressed in the form of R + jX. The resistance and reactance must be added separately and then Z can be computed by $Z = \sqrt{{R_T}^2 + {X_T}^2}$. The approximate approach by adding all the impedances will result in slightly higher total impedance and thus the calculated fault current can be slightly lower.

**Table 7.1 Summary of Cable Impedance**

| Cable size ($mm^2$) | Cable length (m) | Impedance (ohm) |
|---|---|---|
| 2 × 500 | 10 | 0.0004625 |
| 1 × 500 | 10 | 0.000925 |
| 1 × 300 | 28 | 0.00308 |
| 1 × 120 | 2 | 0.00041 |
| 1 × 35 | 8 | 0.0052 |
| 1 × 35 | 14 | 0.0091 |
| 1 × 35 | 21 | 0.01365 |
| 1 × 35 | 31 | 0.02015 |

**Table 7.2 Line-to-Neutral Fault Current at each DB**

| Location | Cable length (m) | Source Impedance (Ω) * | Fault Current (A) |
|---|---|---|---|
| DB1 | 8 | 0.02694 | 8,575 |
| DB2 | 14 | 0.03474 | 6,649 |
| DB3 | 21 | 0.04384 | 5,269 |
| DB4 | 31 | 0.05684 | 4,064 |

* The equivalent source impedance is ($Z_{eq,LV} + Z_{DBF} + 2 \times Z_{35}$) Ω

**Table 7.3 Fault Current Calculated by Two Methods**

| Type of Fault | Location | Method A | Method B |
|---|---|---|---|
| 3-phase | T/F LV Terminal | 28, 297 | 28, 297 |
| 3-phase | Main Busbar | 26, 776 | - |
| 3-phase | First tap-off Unit | 19, 729 | - |
| 3-phase | Floor DB | 19, 062 | - |
| L - N | Apartment DB1 | 10, 258 | 8, 575 |
| L - N | Apartment DB2 | 7, 619 | 6, 649 |
| L - N | Apartment DB3 | 5, 860 | 5, 269 |
| L - N | Apartment DB4 | 4, 407 | 4, 064 |

To determine only the line-to-neutral short-circuit current at the apartment DB, results obtained by method A are not recommended. For a line-to-neutral short-circuit, the fault current returns from the faulted point through each section of the neutral conductors up to the LV terminal of the 22 kV/LV transformer. By calculating a 3-phase fault level at the floor DB and then transferring to a single-phase equivalent source impedance at the floor DB may not represent accurately the line-to-neutral short-circuit at the apartment DB. Thus, the results obtained by method B that utilises a single-phase equivalent source impedance at the LV terminal of the 22 kV/LV transformer are recommended. The calculated fault currents by the two methods are summarised in Table 7.3.

## CHAPTER 8

## COMPUTER-AIDED DESIGN AND SIMULATION

For many years, the design of electrical installations in buildings has been done manually. The work involved is rather tedious, time consuming and repetitive in nature. The designers may not have the time and resources to make a complete check on every item of the installation designed by them. With the availability of computer facilities, the design, calculation, modelling and checking processes can be done in a more efficient and effective manner. Building structure and the large volume of design elements such as various types of cables and their installation methods, various types of circuit breakers and their time-current characteristics, can now be streamlined into a record structure. Technical analysis, assessment and costing can all be done by computers. The presentation of the completed design in a single-line diagram can also be automated.

### 8.1 DESIGN ELEMENT REPRESENTATION

During the design process, instead of referring to various cable tables, catalogues for various types of breakers, etc., a computer-aided design (CAD) package, which normally provides one master file or many structured files to store all the design elements, may be used. These files contain all the required technical specifications and unit cost for all the electrical parts including various types of cables, busways, busbars, meters and a whole range of breakers. Facilities are normally provided for the designer to update and/or add on new elements to the relevant design element files whenever required. During runtime and at each design stage, through the interactive dialogue with the designer, the CAD package will select the relevant files and display a number of records, with the relevant technical specifications, for the required design element.

**Cable Data**

In a typical CAD package, VipTein [Ref. 1], most of the cable tables in Appendix 4 of the IEE Wiring Regulations [Ref. 2] are grouped according to the installation methods, conductor material, insulation material, and the cable construction methods. They are classified into twelve element files for copper conductor cables, two element files for mineral insulated copper conductor cables (MICC) and another twelve element files for aluminium conductor cables. These files are named and referred according to the definition as shown in Table 8.1.

**Table 8.1 Cables File Identification**

| Installation Methods | | Conductor and Insulation Material | | Construction | |
|---|---|---|---|---|---|
| M1 | Clipped direct | D | Copper/pvc | 1 | Single-core non-armoured |
| M3 | Conduit/Trunking | E | Copper/XLPE | 2 | Multi-core non-armoured |
| M11 | Cable Tray | J | Copper/MICC | 3 | Single-core armoured |
| M12 | Free air | | | 4 | Multi-core armoured |

For example, file M1D1 refers to the cable element file for copper conductors, pvc-insulated, clipped direct, single-core non-armoured cables. File M11D4 refers to the cable element file for copper conductors, pvc-insulated, installed on tray, multi-core-armoured cables. For each cable element file, each record contains the size of the conductor's cross-sectional area, current rating, voltage drop constant, R value, X value and the cable cost per metre for both the single-phase cable and three-phase cable. Figure 8.1 shows 3 pop-up windows for selection of cable types and installation methods. Figure 8.2 shows a pop-up window containing the technical parameters of four relevant sizes of cables, together with another pop-up window indicating the voltage drop of the cable under consideration. The declaration of the cable data structure in Turbo Pascal is shown in Figure 8.3.

**Breaker Data**

Breakers are grouped under six element files, namely air circuit-breaker (ACB), single-phase MCB (MCB1), three-phase MCB (MCB3), moulded case circuit-breaker (MCCB), single-phase RCCB (RCCB1), and three-phase RCCB (RCCB3). In the breaker element files, each record contains the current rating, voltage rating, breaking capacity, type of instantaneous tripping, unit cost, thermal tripping time constants A and B, and the value of instantaneous tripping current. A typical display of short-circuit protection test with breaker tripping curves are shown in Figure 8.4. The declaration of the breaker data structure in Pascal is shown in Figure 8.5.

**Other Data**

There are two element files for busbars, one element file for busway systems and one element file for standby generators. Typical number of records in each element file may vary from 20 records in the generator file to 150 records in the breaker element file.

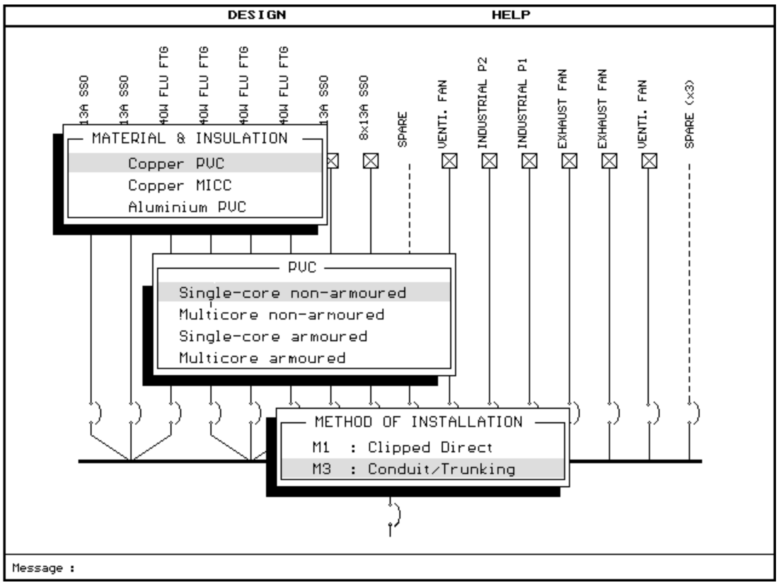



Figure 8.1 Selection of cable types and installation methods

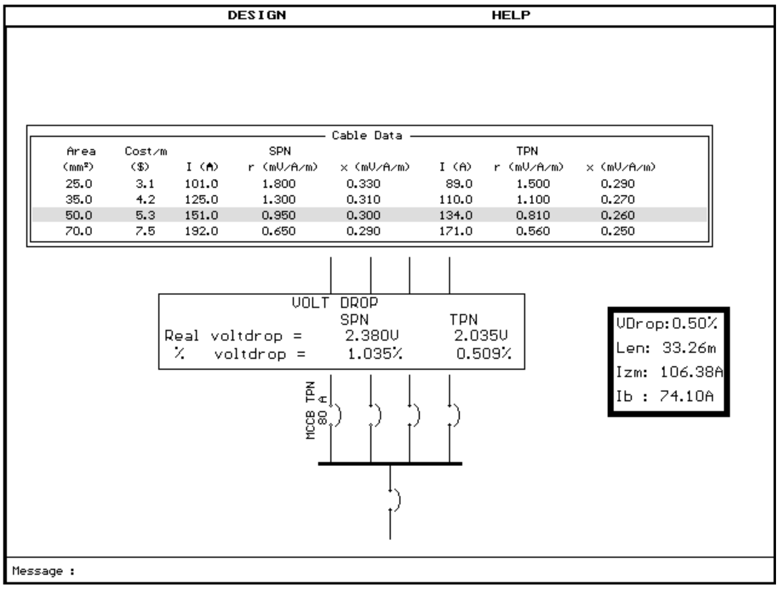



Figure 8.2 Selection of cable sizes

```
SpecRec = record
    i, r, x  : real;
End;

Cable_rec = record
  Xsectarea : real;   (* e.g. 25 mm2   *)
  Costpm    : real;   (* e.g. $8 per m  *)
  S_pu  : SpecRec; (* e.g. i = 126 A, r = 1.75mΩ/m, x = 0.2mΩ/m for Single-phase *)
  T_pu  : SpecRec; (* e.g. i = 112 A, r = 1.50mΩ/m, x = 0.175mΩ/m for 3-phase *)
End;
```

Figure 8.3 Declaration of cable data structure in Pascal

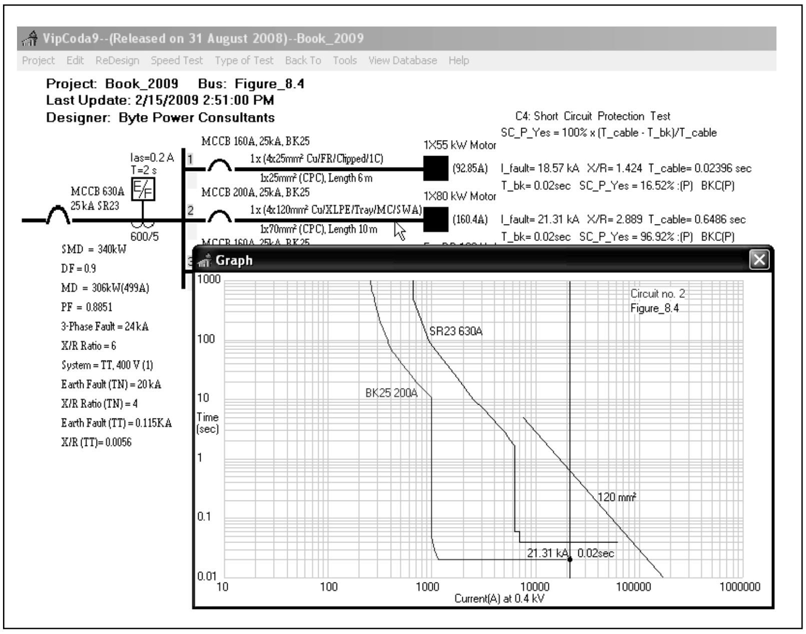



Figure 8.4 Short-circuit protection test with breaker tripping curves

```
Brk_rec = record
 IRating   : integer; (* e.g. 63 A   *)
 VRating   : integer; (* e.g. 415 V  *)
 Bkcap     : byte;    (* e.g. 9 kA   *)
 CBType    : str3;    (* e.g. Type3  *)
 Cost      : real;    (* e.g. $61.00 *)
 Curve_A   : real;    (* e.g. 119.2  *)
 Curve_B   : real;    (* e.g. 190.0  *)
 IMax      : real;    (* e.g. 630 A Instantaneous tripping current *)
            End;
```

Figure 8.5 Declaration of breaker data structure in Pascal

## 8.2 DESIGN METHODS AND DESIGN FILES

Prior to the design of an electrical installation, the designer has to know the types of load, the wattage, the power factor, and the physical location of each connected load, the floor plan, the number of floors and the height of each floor. A normal CAD package should provide dedicated file structure for the designer to specify the building structure and the specifications of various types of load in the building. A CAD package should be able to display the layout of the building and enable the designer to zoom in and out to complete the design of the whole electrical installation.

### Design Methods

Basically, there are two design methods [Ref. 3] commonly used in a CAD implementation. Design method 1 is based on the standard design files which are summarised from a large pool of proven designs and grouped under different categories, such as commercial complex, condominium, multi-storey flatted factory and high-rise domestic flat. The designer may display, alter, delete or insert new circuits/DBs, and copy the completed design to a new design file.

Design method 2 is normally based on a computer dialogue. It is used when the designer's idea is very much different from the standard design files. This method involves the design of all the final DBs, main DBs and the main switchboard. The design work is initiated circuit by circuit starting from a final DB. Based on the specified connected load, the CAD package calculates the design current and determines the type of breaker, breaker ratings, cable type, installation method, cable size, circuit length, voltage drop, etc. At each stage, the design current is shown and the designer has an option to overwrite the value selected by the package. In such case, a list of appropriate values will be displayed and the designer may select the appropriate value at his own discretion.

### Design File

The completed design for a particular building should be stored in a master design file or several related design files. Normally, it is divided into two sections, namely, the main switchboard and the distribution boards. The specifications of the main switchboard can be stored in one file which contains the building information and the specifications of the incoming circuit and every outgoing circuits. The distribution board sections may consist of many small files. Each file stores the specification of one distribution board.

Each outgoing circuit of the main switchboard may be connected to a distribution board or a directly connected load such as water pump, fire pump, etc. If it is connected to a DB, the connection identification refers to the file name of the connected DB, such as M1, T1, etc. If it is connected to a load, the connection identification refers to the name of the directly connected load such as water pump, sprinkler pump, etc. The specification of each incoming and outgoing circuit in the main switchboard or in the DB files contains the busbar identification, feeder position identification, cable specification (cable filename and record number), breaker specification (breaker filename and record number), the maximum demand in watts and VArs, etc.

For example, if the completed design for a shophouse is identified as SH1, the filename of the main design file will be SH1.DES. If there are two types of DBs, namely M1 and T1 connected at the outgoing circuit from the main switchboard, the design files of the two DBs are M1.SH1 and S1.SH1. A sample main design file SH1.DES of a two-storey shophouse is shown in Figure 8.6, distribution board design file, M1.SH1 in Figure 8.7 and another distribution board design file, T1.SH1 in Figure 8.8.

## 8.3 ASSESSMENT AND COSTING

The assessment and costing of the completed design can also be integrated to the CAD implementation. Based on the completed design files, the assessment module usually includes load simulation to estimate the loading of each individual circuit to detect overcurrent; voltage drop simulation to identify those circuits which have their voltage drop exceeding the specified tolerance; and fault level calculations to verify that all the breakers have adequate breaking capacity and that all the circuits can withstand the short-circuit currents. It may also include verification of discrimination among various protective devices and the checking with the recommended code of practice and regulations [Ref.4].

Based on the design files, the costing module gives the overall cost with breakdown for each category, such as circuit breakers, busbars, cables, DBs, etc. The costing module normally adds up the project cost by going through the material cost and installation cost of each category. The program commences with the first category and checks through the design files circuit by circuit for all the items to obtain the total cost for the first category. It then proceeds to the next category until the end of the last category. A sample printout [Ref. 4] of the costing module for a particular design, XYZ.DES is shown in Figure 8.9.

```
SH10 0.0  2 4.5
1 1
0 Gen
1 CuBbar    5 P2 1   2 0 0    203940   151760 MCCB104
1  1 BUSWAY   0 MCCB  64     76600    56120 2
MCCB 52  1      47874     35077 D M1
MCCB 52  2      47874     35077 D M1
1  2   M1D1   7 MCCB 64      61111    45833 0
     0  1     61111      45833 S WATER PUMP
1  3   M1D1   9 MCCB 74      88889    66667 0
     0  1     888889     66667 S SPRINKLER PUMP

***  File List ***
S1.SH1
M1.SH1
```

Figure 8.6 Main design file SH1.DES for a shophouse

```
M1     4
  M3D1  0 MCCB 52 RCCB     2 2
4 MCCB 30   M1D1  6  1    29921     21923 T D T1
4 MCCB 30   M1D1  6  1    29921     21923 T D T1
```

Figure 8.7 DB design file M1.SH1

```
T1     5
  M3D1  0 MCCB  30 RCCB3   6 5 2
1 MCB1 40   M3D1   2  6      300     145 R S 6x13A SSO
1 MCB1      M1D1     0        0      0 Y S SPARE
1 MCB1      M1D1     0        0      0 B S SPARE
1 MCB1 40   M3D1   1  8      300     145 R S 8x13A SSO
1 MCB1 40   M3D1   2  8      300     145 Y S 8x13A SSO
1 MCB1 40   M3D1   2  6      300     145 B S 6x13A SSO
1 MCB1  8   M3D1   0 10       61      38 R S 10x40W FLU FTG
1 MCB1  8   M3D1   0 10       61      38 Y S 10x40W FLU FTG
1 MCB1      M1D1     0        0      0 B S SPARE
4 MCB3 72   M3D1   3  1    11111    8333 T S COMPRESSOR
4 MCB3106   M3D1   4  1    16667   12500 T S DOL MOTOR
```

Figure 8.8 DB design file T1.SH1

## 8.4 AUTOMATIC DRAFTING

Most of the electrical consultants use AutoCAD for the drafting of the single-line diagrams, and there is currently no convenient means to link the AutoCAD diagrams to various design calculations, technical assessment and costing. Another approach is to complete the design, assessment and costing as described in Section 8.2 first, and then by making use of the design files, the package generates automatically the single-line diagram of the completed design on a large plotter [Ref. 4].

c:\VIP_PROJ\Bench_Mark_Dollar\cost.dbf

| BUS_ID | CABLECOST | INSTALCOST | BREAKRCOST | DB | PERUNCOST | CONNECT | TOTALCOST |
|---|---|---|---|---|---|---|---|
| M2_FDB | 543.6 | 800 | 329.2 | 3300 | 4972.8 | 1 | 4972.8 |
| Main Riser | 4612.74 | 2480 | 568 | 0 | 7660.74 | 1 | 7660.74 |
| Main Switch Board | 11350.805 | 2285 | 3265 | 8500 | 25400.805 | 1 | 25400.805 |
| T11_UB | 1002.146 | 6024 | 63 | 1100 | 8189.146 | 1 | 8189.146 |
| T12_B | 1002.146 | 6024 | 61.1 | 1100 | 8187.246 | 1 | 8187.246 |
| M1_MDB | 1324.44 | 1260 | 331.1 | 3300 | 6215.54 | 1 | 6215.54 |
| GRAND_TOTAL | 19835.877 | 18873 | 4617.4 | 17300 | | | 60626.277 |

c:\VIP_PROJ\Bench_Mark_Dollar\material_bill.dbf

| BREAK_TYPE | IRATING | BK_CAP | BREAKER_NO | COST |
|---|---|---|---|---|
| MCB | 6 | 10 | 4 | 22 |
| MCB | 16 | 10 | 4 | 22 |
| MCB | 20 | 10 | 2 | 11 |
| MCB | 25 | 10 | 2 | 11 |
| MCB | 32 | 10 | 2 | 11 |
| MCB | 63 | 15 | 3 | 67.8 |
| MCB | 100 | 15 | 1 | 24.5 |
| MCCB | 125 | 20 | 3 | 852 |
| MCCB | 125 | 25 | 1 | 284 |
| MCCB | 200 | 25 | 2 | 910 |
| MCCB | 150 | 25 | 1 | 455 |
| MCCB | 225 | 25 | 1 | 500 |
| MCCB | 630 | 25 | 1 | 1400 |
| MCB | 100 | 10 | 1 | 24.5 |
| MCB | 63 | 10 | 1 | 22.6 |
| TOTAL_COST | | | | 4617.4 |

Figure 8.9 Sample print out from the costing module

In the second approach, a file transfer module is required to extract data from the design files and rearrange them in the order in which they can be plotted efficiently. The file transfer module reads the design files, e.g. SH1.DES, M1.SH1, T1.SH1, and creates a drawing file with a file extension DRW, e.g. SH1.DRW. The drafting module reads the drawing file and produces the required single-line diagram on an A1 or A0-sized plotter. Based on the number of main busbars, the number of floors of the building, number of outgoing circuits in each main busbar, etc., the drafting module calculates the space required and positions the X and Y co-ordinates of each outgoing feeder at the respective floor level. It plots the first incoming main busbar on the left-hand side of the paper and the subsequent incoming main busbar towards the right. It then plots each outgoing circuit according to the automatically calculated positions. If a feeder is connected to a DB, the program will test whether there is enough space for plotting the details of all outgoing feeders connected to this DB. If the space is adequate, the details will be plotted, otherwise it will append all the data of the outgoing circuits of the DB to a second- page drawing file with a file extension DR2, such as SH1.DR2. The DR2 file will be plotted on the second page. This algorithm will be repeated on another feeder until the first page of the single-line diagram is completed.

The program then searches through the second-page drawing file, e.g. SH1.DR2, and displays all the names of the DBs which have not been plotted on the first page. The designer may select all or any combination of the DBs to be plotted on the second page. Based on the number and the sizes of the selected DBs, the program calculates the size and determines dynamically, the space for each DB and plots all the selected DBs on the second page [Ref. 4].

The required symbols and standard drawing elements are grouped into two categories, namely the discrete drawing elements and the integrated drawing elements. The discrete drawing elements are the simple electrical symbols such as MCCB, ACB, busbar, cable, CT, fuse, transformer, starter, etc. The integrated drawing elements are more elaborate symbols consisting of a combination of several discrete drawing elements. The typical integrated drawing elements are the type 1 incoming busbar, type 2 incoming busbar, emergency busbar with generator, main distribution board, etc. A sample plot of the integrated element of the type 1 incoming busbar is shown in Figure 8.10.

## 8.5 SIMULATION TESTS

Although there are standard rules used to guide the design of an installation, it is always difficult for the designer to visualise how well the design has been done. One may have to wait until the installation has been completed and observed for a number of years before a fair decision can be made. A more comprehensive CAD package, such as MIPTEIN [Ref. 1], however, provides a series of simulation tests which model the normal loading, overloading and short-circuit conditions so that the designer can visualise the performance of the installation under various simulated conditions, and experience the consequences due to the design errors. There are altogether six simulation tests to be carried out for each circuit in the whole installation.

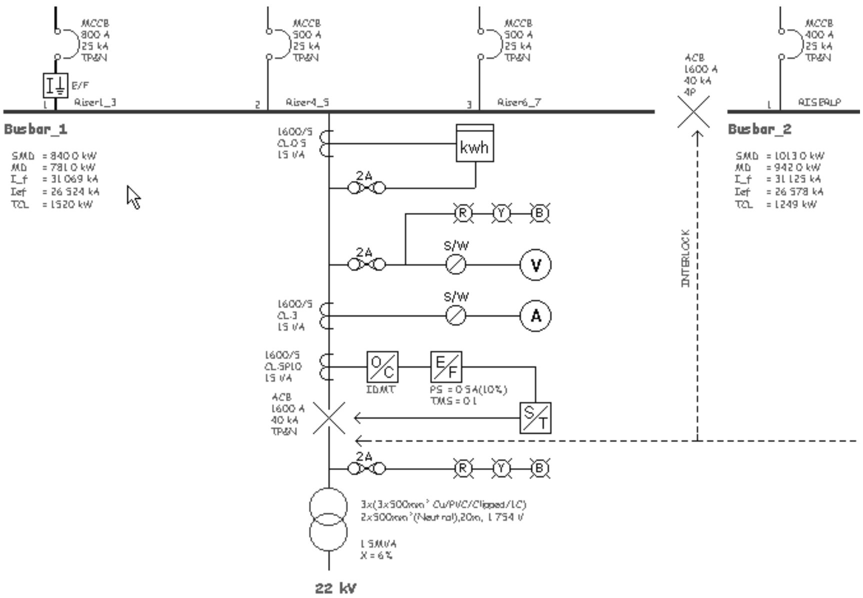



Figure 8.10 A sample plot of an integrated element

**Breaker and Cable Load Test**

The Breaker load test checks whether the design current, $I_B$, exceeds the protective device's current rating, $I_N$. The breaker loading is defined as ($I_B/I_n$) x 100%. If this value is less than 100%, the breaker load test will indicate a pass, "BK (P)". On the other hand, "BK (F)" will be displayed if the design current is greater than the protective device's nominal current.

The cable load test checks whether the current carrying capacity of the conductor, under a particular installation condition, is greater than the design current. This test gives an indication whether the conductor will be overloaded under normal loading condition.

The Cable loading is defined as ($I_B/I_z$) x 100%. If the cable loading is less than 100%, "L (P)" is displayed. While "L (F)" indicates that the design current is greater than the conductor current rating under the particular installation methods. The display of breaker and cable loading test is shown in Figure 8.11. Based on the current rating of the protective device ($I_N$), it detects whether $I_N > I_B$ and $I_Z > I_B$. Circuit loading ($I_B/I_Z$) in percentage of the rated capacity under the specified conditions is also calculated and circuit loading exceeding 100% is considered as fail and highlighted. Figure 8.11 shows a cable loading failure (108% in red) for circuit 4 and a breaker failure ( $I_N$ = 16 A < $I_B$ = 17.32 A) in circuit 5.

At the incoming circuit, the summation of the maximum demand of all the outgoing circuits is calculated as 21.85 kW and 13.99 kVAr. Based on a demand factor of 0.8, the maximum demand at the incoming circuit is 18.42 kW. Based on the calculated power factor of 0.8421, the design current is calculated as 31.57 A. As the incoming MCB is rated at 63 A, it is thus shown as " Incoming Breaker Test (P)" for the incoming circuit at the bottom on Figure 8.11.

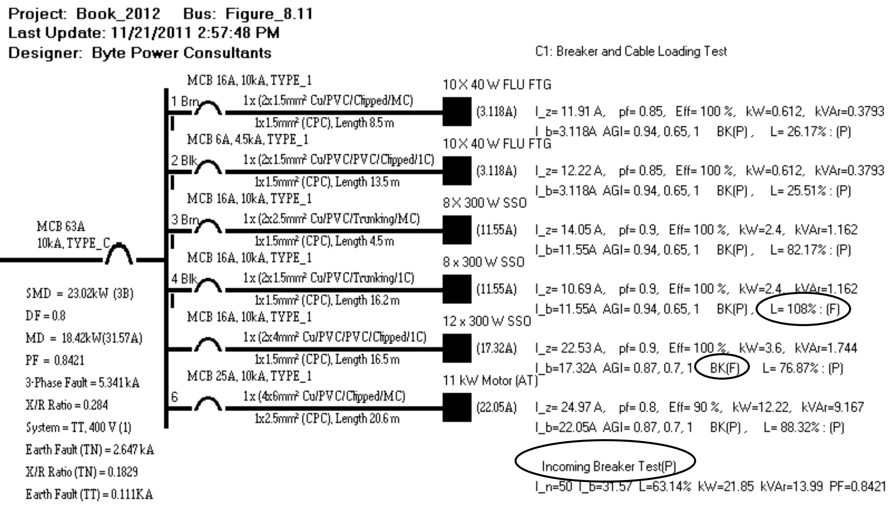



Figure 8.11 Cable utilisation test

**Overload Protection Test**

For overload protection test, the load current in each circuit is increased to 145% of the cable rated capacity and the operating time of the breaker protecting the circuit is modelled. If the operating time is less than two hours, it is considered to have passed the test. If it does not trip (i.e. it has a tripping time exceeding 2 hours), it is considered to have failed the overload protection test, and the circuit will be highlighted. For the overload protection test as shown in Figure 8.12, the second circuit fails since the breaker protecting this circuit will not trip within 2 hours when the cable is overloaded to 145%. Circuits 1, 5 and 6 have adequate protection against overloading within 56.65%, 38.96% and 11.51% respectively shown in Figure 8.12. For a special case, a circuit connected directly to a motor may fail the overload protection test such as circuits 3 and 4. However, it is still considered acceptable and shown as '(OK!)' in Figure 8.12 as long as each motor is equipped with a built-in overload protection in the starter.

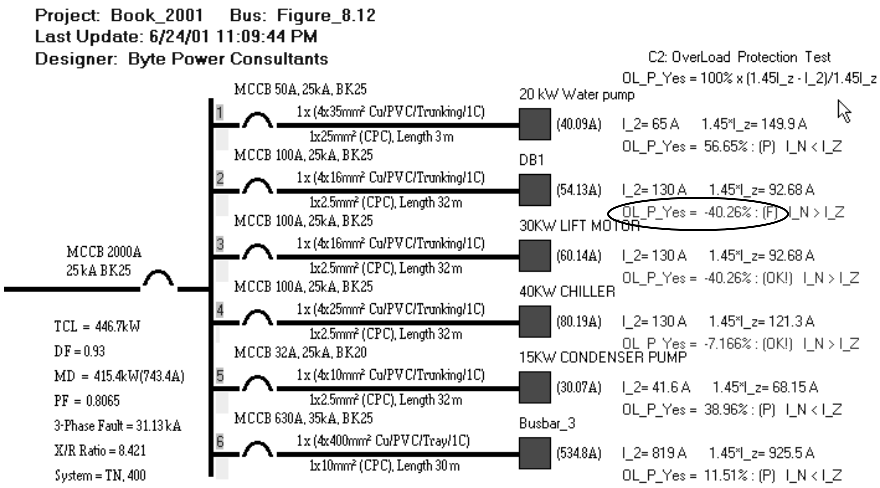



Figure 8.12 Overload protection test

**Voltage Drop Test**

Based on the load current, method of installation, type and size of the cable in each circuit, the voltage drop in every circuit is modelled. The calculated voltage drop is displayed in volts and in percentage of the rated voltage. These values are then compared with the specified voltage drop tolerance at each section of the installation. Those circuits, which exceed the specified tolerance, are considered to have failed the test and will be highlighted.

**Short-Circuit Protection Test**

In the short-circuit protection test, the package compares the breaking capacity of each breaker in each circuit to the prospective short-circuit current at the point of installation. A breaker is considered to have failed if its breaking capacity is less than the short-circuit current. The package then models the operating time of each breaker based on the short-circuit current at the point of installation. A breaker is considered to have failed if the breaker's operating time exceeds the critical operating time. The critical operating time is the maximum allowable time in seconds required to disconnect the circuit to ensure that the temperature in the conductor will not exceed its thermal limit during the fault condition. This critical value is calculated for each circuit based on the fault current, insulation material and the type and cross-sectional area of the conductors. A typical display of the short-circuit protection test is shown in Figure 8.13. Circuit 2 fails since the maximum withstand time of this cable is 3.186 seconds but the breaker operating time is 6.5 seconds resulting a failure of -104% as shown in Figure 8.13. Similarly for circuit 5, it fails with -526%. All other circuits pass from 74.88% for circuit 1 to 99.73% for circuit 6.

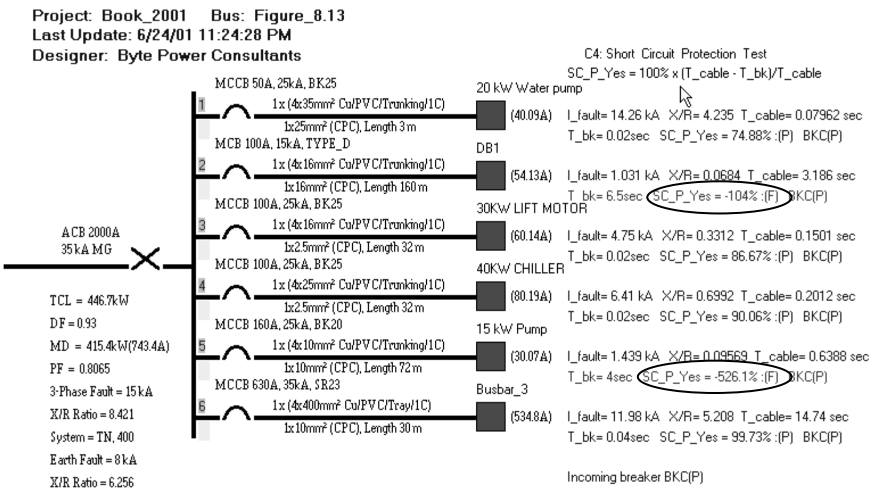



Figure 8.13 Short-circuit protection test

## Motor Starting Test

For each motor circuit, the package calculates the starting current based on the connected load and the type of starter. The starting current is assumed as four times the full load current for 15 seconds for a star-delta starter, and seven times the full load current for 10 seconds for a direct-on-line (DOL) starter. Based on the assumed starting currents, the operating time of each breaker is modelled. If this operating time exceeds the starting duration, it is considered to have passed the test. Figure 8.14

shows circuits 3 and 4 fail and circuits 1 and 5 pass. For circuit 3, the starting current is 421 A and the 80-A MCCB operating time is 1 second which is shorter the stating duration of 10 second for DOL starter. Similarly, for circuit 4, the 100-A MCCB operating time is 11 seconds which is shorter than the duration of 15 seconds for AT80% starter.

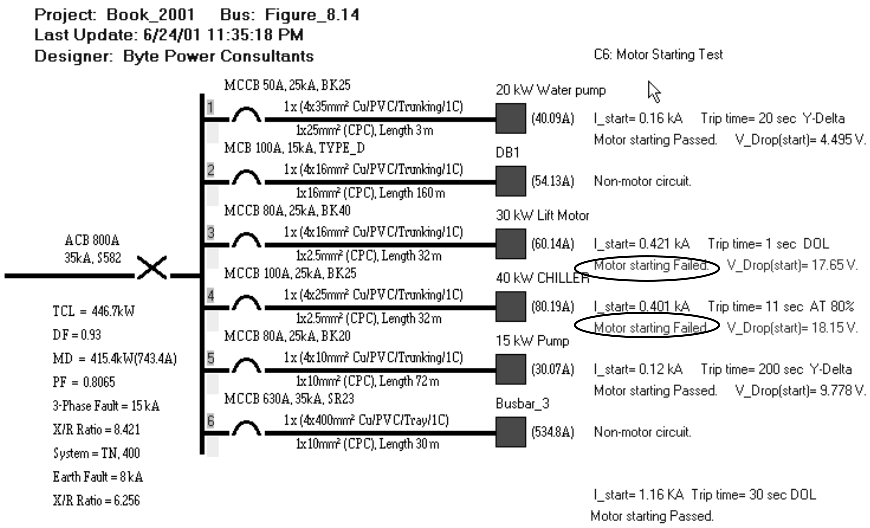



Figure 8.14 Motor starting test

## 8.6 INTEGRATED TOOLS FOR TEACHING

An innovative approach of using computer-aided design tools to support the teaching of electrical installations through hands-on design exercises has been used at Nanyang Technological University and Singapore Polytechnic [Ref. 1, Ref. 6]. It is implemented by an integrated package with all the built-in facilities, which guide the students step-by-step to complete the design of two electrical installations, namely, a 300-kVA two-storey building and a 2-MVA seven-storey flatted factory. The dedicated file structure enables the students to get a direct access to the building information, details of each type of load and the technical parameters of all the electrical parts required for the design exercise. Errors made by the student are prompted on the spot and the student's performance is evaluated automatically through error logs and a demerit point system. The series of simulation tests described in section 8.5 enable the students to visualise the performance of the installations designed by them under a series of loading conditions, and to foresee consequences which may be resulted due to the design errors.

### 8.6.1 Automated Marking and Grading

The errors made by the student in the design exercise are stored under 36 separate items classified under 9 types of errors. For example, errors such as wrong types of cables, wrong installation methods, undersized cables, oversized cables are classified as type 3 errors (cable specification), and each error carries 2 demerit points. A second attempt with hint given is classified as a type 9 error (2nd attempt) and each error carries 1 demerit point. Errors such as motor tripping during starting or wrong types of motor starters are classified as type 5 error (motor circuit specification) which carries 3 demerit points for each error made. There is, however, a special type 10 variable, which is used to store the bonus points. For example, if the three phases of a final DB can be balanced at 95% or above, one bonus point is given. An error checking data file, Points.dat, which has 36 error records is shown in Figure 8.15. Each record contains the record number, demerit points, error type and the specific error message.

The evaluation of the student's performance is based on 9 types of errors which can be quantified as demerit points. The conversion from the total demerit points to an appropriate grade is specified in the same error checking data file, Points.dat, from record 38 to record 42. The instructor can adjust and fine-tune the parameters in these few records to match the level of learning of the students. The overall score summary and the 9 types of errors are also shown in Figure 8.16.

### 8.6.2 Full Test and Partial Test

To accelerate the design and learning process, three categories of designs, namely full design, partial design and automatic design can be accommodated in VipTein [Ref 1, Ref 6]. The instructor can specify in the building data file, in advance, the type of design for each circuit. For a full design, the student has to complete all the design procedures including the calculation of the design current, selection of breaker type, breaker rating, cable rating, calculation of voltage drop and sizing of protective conductor. If it is a partial design, the design current and the voltage drop will be calculated by the package and displayed in the side windows to help the student in selecting the size of the conductor. For circuit under automatic design, all the design works will be done by the package and displayed. The last category of the design is aimed at eliminating the routine or repetitive design works which cannot be avoided in the process of completing the design of the whole installation.

```
0  -2  1   wrong circuit breaker type
1  -2  1   underestimated category of duty for circuit breaker
2  -2  1   overestimated category of duty for circuit breaker
3  -2  1   circuit breaker rating under rated
4  -2  1   circuit breaker rating over rated
5  -2  2   wrong design current,Ib, calculation
6  -3  5   wrong starter type
7  -2  3   wrong cable type
8  -2  3   wrong installation method
9  -2  3   undersized cable
10  -2  3   oversized cable
11  -2  2   wrong voltdrop calculation
12  -2  3   voltdrop exceeded specified %
13  -2  2   wrong Izmin calculation
14  -2  6   wrong correction factors
15  -2  6   underestimation of ways for DB
16  -2  6   overestimation of ways for DB
17  -2  6   DF/CF not acceptable
18  -2  6   wrong number of load connected to riser
19  -2  1   under rated RCCB
20  -2  1   over rated RCCB
21  -2  8   unconnected load
22  -2  8   unbalanced load - 15%
23  -3  5   motor trip during starting
24  -1  9   second attempt/hints given
25  -2  4   undersized busbar riser
26  -2  4   oversized busbar riser
27  -2  4   undersized busbar
28  -2  4   oversized busbar
29  -2  7   wrong postion of meters,devices and class of CT,etc
30  -2  7   under rating of generator
31  -2  7   over rating of generator
32  -2  7   wrong cpc selection
33  -2  7   incorrect type of incoming
34   1 10   practical connection of loads to riser
35   1 10   percentage balanced < 5%
36   1 10   reserve
37   0  0   END
38  -1  0   A
39  -4  0   B
40 -12  0   C
41 -19  0   D
42 -28  0   E
43  14  0   FINAL
```

Figure 8.15 Error checking data file Point.dat

### 8.6.3 Implementation of VipTein

The specially developed package known as VipTein, is abbreviated from 'Visually Interactive Package for Teaching of Electrical Installation Network'. It is implemented in a project course to teach EEE second-year students in the design of electrical installation [Ref. 5, Ref 6]. The students are divided into 24 groups of 30 students each using 15 microcomputers at a time. Although numerous modifications and three versions of updates have been made, the simulator has been run quite successfully for three years. Almost all students find it interesting and challenging.

F1 - HARDCOPY F10 - NEXT STAGE

Overall Score

| Type of Error | Number of Error | Demerit Point |
|---|---|---|
| Breaker Spec. | 1 | -2 |
| Calculation | 2 | -4 |
| Cable Spec. | 2 | -4 |
| Busway/Cable Spec. | 0 | 0 |
| Motor Circuit Spec. | 0 | 0 |
| Assumptions | 0 | 0 |
| Incoming Spec. | 1 | -3 |
| Unconnected load | 0 | 0 |
| 2nd Attempt | 2 | -2 |

Number of Bonus : 1
Bonus points : 1
Total demerit points : -14
Overall grade : C

STUDENT NAME : Chang San CLASS/GROUP : S12/B
: Lee Si Date : 19 Oct 1996
SUPERVISOR : A/Prof Teo Cheng Yu Time : 10:23:12

Figure 8.16 Summary of an assessment report

## 8.7 REFERENCES


[1] Teo C Y, "A New Integrated Tool for Design Exercise of Electrical Installations Using a Microcomputer", Journal of Electric Power Systems Research, vol.36, no. 2, PP 81-91, 1996.

[2] "Regulations of Electrical Installation", 16th Edition, IEE, 1991.

[3] Teo C Y, "Computer-aided Design and Simulation of Low Voltage Electrical Distribution Systems", Journal of Computers in Industry, vol. 34, no. 1, PP 87-94,1997.

[4] Teo C Y, "Computer-aided Design, Assessment and Costing System for Electrical Installation in Building", NTI Applied Research Report RP18/83, 1987.

[5] Gooi H B, Teo C Y, "A Project-oriented Power Engineering Curriculum", IEEE Transactions on Power Systems, vol. 10, no.1, 1995.

[6] Teo Cheng Yu, "Teaching of Power Engineering Through E-Learning with Laboratory Automated Assessment", ICEE 2009, International Conference on Engineering and Education, 2009

## APPENDIX A

## COMMON TECHNICAL TERMS

**Arcing Contact**

A contact on which the arc is intended to be established.

**Break Time**

The interval of time between the beginning of the operating time of a mechanical switching device and the end of the arcing time. This is also known as total operating time.

**Breaking Capacity**

A value of prospective breaking current that a switching device is capable of breaking at a stated voltage under prescribed conditions of use and behaviour.

**Breaking Current**

The current in a pole of a switching device at the instant of initiation of the arc during a breaking process.

**Circuit Breaker**

A mechanical switching device, capable of making, carrying and breaking currents under normal circuit conditions. It is also capable of making and carrying currents for a specified time, and breaking currents under specified abnormal circuit conditions such as those of short-circuit.

**Conventional Non-tripping Current**

A specified value of current which the relay or release can carry for a specified time (conventional time) without operating.

**Conventional Tripping Current**

A specified value of current which causes the relay or release to operate within a specified time (conventional time). This time is normally specified as 1 hour, 2 hours or 4 hours.

**Definite Time-delay Over-current Relay or Release**

An over-current relay or release which operates with a definite time-delay which may be adjustable but is independent of the value of the over-current.

**Exposed-Conductive-Part**

A conductive part which an be readily touched and which normally is not live, but which may become live under fault conditions.

**Impulse withstand Voltage**

The highest peak value of an impulse voltage of prescribed form and polarity which does not cause breakdown under specified conditions of test.

**Instantaneous Relay or Release**

A relay or release which operates without any intentional time-delay.

**Inverse Time-delay Over-current Relay or Release**

An over-current relay or release which operates after a time-delay inversely dependent upon the value of the over-current.

**Making Capacity**

A value of prospective making current that a switching device is capable of making at a stated voltage under prescribed conditions of use and behaviour. For a.c., the rated making capacity is expressed by the r.m.s. value of the symmetrical component of the current, assumed to be constant.

**Main Contact**

A contact included in the main circuit of a mechanical switching device, intended to carry, in the closed position, the current of the main circuit.

**Opening Time**

The interval of time between the specified instant of initiation of the opening operation and the instant when the arcing contacts have separated in all poles. This is equivalent to pre-arcing time of a fuse.

**Over-current Relay or Release**

A relay or release which causes a mechanical switching device to open with or without time-delay when the current in the relay or release exceeds a pre-determined value.

**Power-frequency withstand Voltage**

The r.m.s. value of the sinusoidal voltage at power frequency which the insulation of the circuit-breaker withstands and does not cause breakdown under specified conditions.

**Prospective Current**

The current that would flow in the circuit, if each pole of the switching device or the fuse were replaced by a conductor of negligible impedance.

**Relay**

A device designed to produce sudden, pre-determined changes in one or more electrical output circuits when certain conditions are fulfilled in the electrical input circuits controlling the device.

**Release**

A device, mechanically connected to a mechanical switching device, which releases the holding means and permits the opening or the closing of the switching device.

**Residual Current**

Vector sum of the instantaneous values of the current flowing in the main circuit of the RCCB (expressed as r.m.s. value).

**Short-circuit (making and breaking) Capacity**

The alternating component of the prospective current, expressed by its r.m.s. value which the circuit-breaker is designed to make, carry for its opening time and to break under specified conditions.

**Short-time withstand Current**

The current that a circuit breaker can carry in the closed position during a specified short time under prescribed conditions of use and behaviour.

**Shunt Release**

A release energised by a source of voltage.

**Trip-free Mechanical Switching Device**

A mechanical switching device, the moving contacts of which return to and remain in the open position when the opening (i.e. tripping) operation is initiated after the initiation of the closing operation, even if the closing command is maintained.

**APPENDIX B**

**FORMULAE FOR DESIGN CALCULATIONS**

## B.1 Design current (A) for a 3-phase load

$$I_b = \frac{kW}{\sqrt{3} \text{ x } 400 \text{ x p.f.}} \text{ x } 1000 \quad \text{or} \quad I_b = \frac{\sqrt{kW^2 + kVAr^2}}{\sqrt{3} \text{ x } 400} \text{ x } 1000$$

$$\text{p.f.} = \cos\left(\tan^{-1}\frac{kVAr}{kW}\right)$$

## B.2 Design current (A) for a 1-phase load

$$I_b = \frac{W}{230 \times \text{p.f.}}$$

## B.3 Design current (A) for a motor

$$I_b = \frac{kW}{\sqrt{3} \text{ x } 400 \text{ x p.f. x } E_{ff}} \text{ x } 10^3$$

## B.4 Design current (A) for discharge lighting

$$I_b = \frac{\text{Wattage of Lamp} \times 1.8}{230}$$

## B.5 Minimum CPC size (mm$^2$)

$$S_{min} = \frac{\sqrt{I_{EF}^2 \times t}}{k}$$ subject to $S_{min} \geq 2.5 \text{ mm}^2$

## B.6 Minimum $I_t$ value (A)

Overload protection required : $I_{t,\ min} = \dfrac{I_N}{C_g \text{ x } C_a \text{ x } C_i}$

Overload protection not required : $I_{t,\ min} = \dfrac{I_B}{C_g \text{ x } C_a \text{ x } C_i}$

## B.7 Stand-by generator capacity (kVA)

Recommended generator capacity = 1.2 x design load

### B.8 Motor starting

If manufacturer's data is not available, the following starting conditions are recommended:

DOL starter : $I_{starting} = 7 \times I_{FL}$ for 10 s
Other starter: $I_{starting} = 4 \times I_{FL}$ for 15 s

## B.9 Demand and the coincidence factors

Emergency load : DF = 1 CF = 1

Other Load : DF = 0.8 to 0.95 CF = 0.75 to 0.95

## B.10 Voltage drop (V)

$$V_{drop} = \frac{(r \cos\theta + x \sin\theta)}{1000} \times I_B \text{ x length}$$

## B.11 Three-phase short-circuit current (A per phase)

$$I_{F,3\phi} = \frac{V_{L-L}/\sqrt{3}}{\sqrt{\left(R_S + R_1\right)^2 + \left(X_S + X_1\right)^2}}$$

## B.12 Line-to-neutral short-circuit current (A)

$$I_{F,LN} = \frac{V_{L-L}/\sqrt{3}}{\sqrt{\left(R_S + R_1 + R_n\right)^2 + \left(X_S + X_1 + X_n\right)^2}}$$

## B.13 Socket outlet circuit

MCB current rating : use a minimum of 16 A to a maximum of 32 A
Cable size : use a minimum of 2.5 $mm^2$ to a maximum of 4 $mm^2$

## B.14 Line-to-Earth Short-circuit Current (A)

$$I_{F,LE} = \frac{V_{L-L}/\sqrt{3}}{Z_{EFL}}$$

## TOUCH VOLTAGE AND FAULT CURRENT DISTRIBUTION

### C.1 Three-Phase Representation of a TN-S System

In the sample TN-S system as shown in Figure C.1, the utility 22 kV network connected to DU is represented by an equivalent generator with $Z_1$=$Z_2$=$Z_0$. Based on a fault level of 800 MVA with a X/R ratio of 10, the value of $Z_1$ is 0.01244+j0.1244 p.u. on a 100 MVA, 22 kV base. The 6.5 Ω earthing resistor at the 22 kV incoming source is modeled as a resistor connected from the neutral of the equivalent generator to earth.

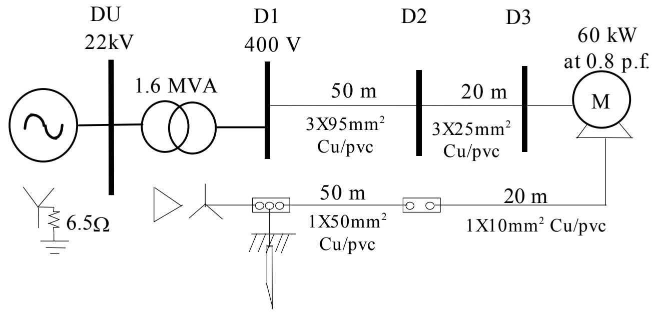
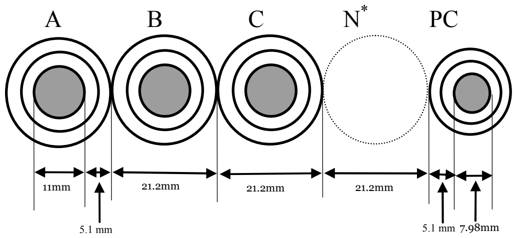



Figure C.1 A sample TN-S system

The 1.6 MVA delta-earthed-wye transformer has a leakage reactance of 6% on a 1.6 MVA base i.e. 3.75 p.u. on a 100 MVA base. The 50-m circuit from D1 to D2 consists of three single-core, pvc-insulated copper conductor cables of 95 $mm^2$ with a PC of 50 $mm^2$ . The 20-m circuit from D2 to D3 is fed by similar cables of 25 $mm^2$ with a PC of 10 $mm^2$ . Based on the layout of circuit conductors as shown in Figure C.2, the self reactance of each single-core cable and their mutual reactances are calculated. The 60-kW motor is modeled as an un-earthed generator with a sub-transient reactance of 25% on 75 KVA base with $X_1$=$X_2$=$X_0$. The value of $X_1$ is 333.33 p.u. on a 100 MVA, 400 V base.

The post-fault voltages including touch voltages and the current distribution for an earth fault from phase A to the frame of the motor is shown in Figure C.3.




* In a 3-phase 3-wire system, the neutral conductor is removed, but the space is kept

Figure C.2 The layout of circuit conductors from D1 to D2

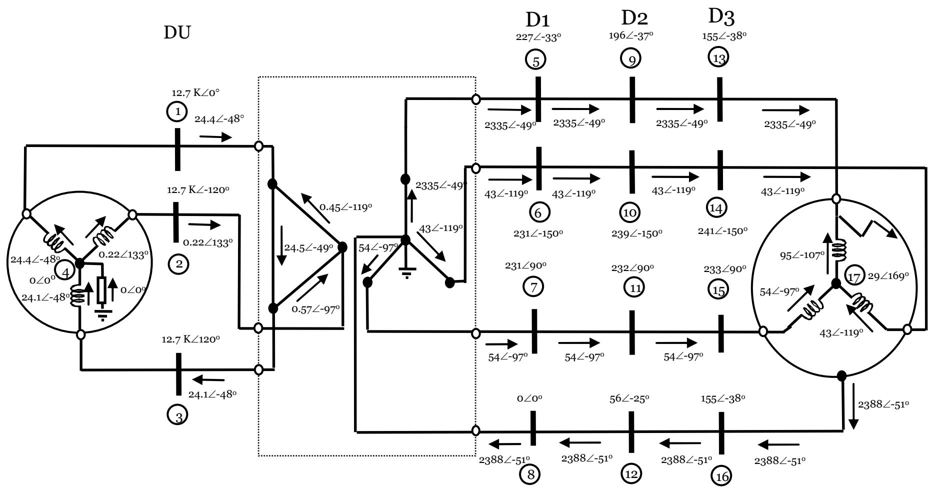



Figure C.3 The post fault voltages and current distribution for the TN-S

To illustrate the existence of non-zero touch voltages, it is assumed that the earth fault current has blown the fuse at phase A of the circuit from D2 to D3. This phenomena can be modeled by inserting a node 18 as shown in Figure C.4 in which the calculated post-fault voltages and current distribution are also shown.

## C.2 Three-Phase Representation of a TT System

In the TT system as shown in Figure C.5, the utility 22 kV network connected to EU and the 22 kV/400 V transformer are represented by one equivalent generator connected to E1 with $Z_1 = Z_2 = Z_0$ as shown in Figure C.6. Based on a fault level of 25 MVA with a X/R ratio of 5 at E1

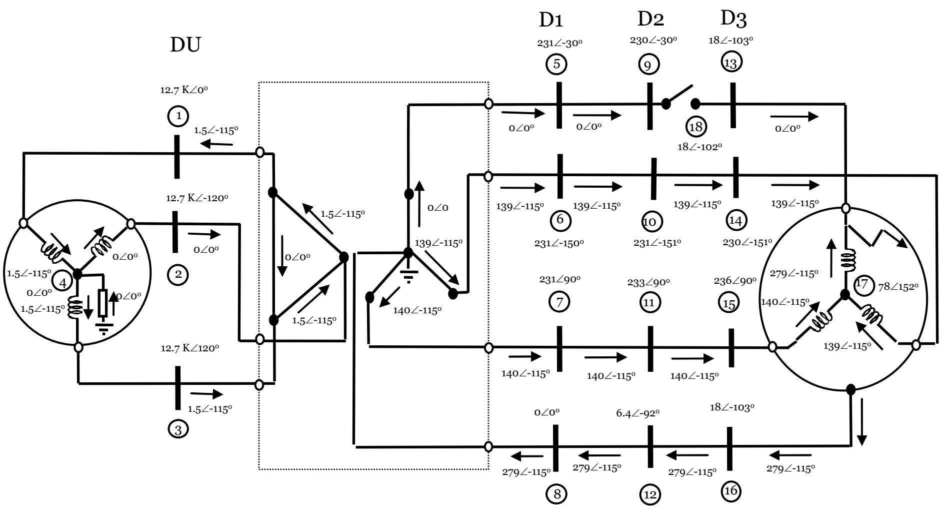



Figure C.4 Fault current distribution after the operation of one fuse at node 18

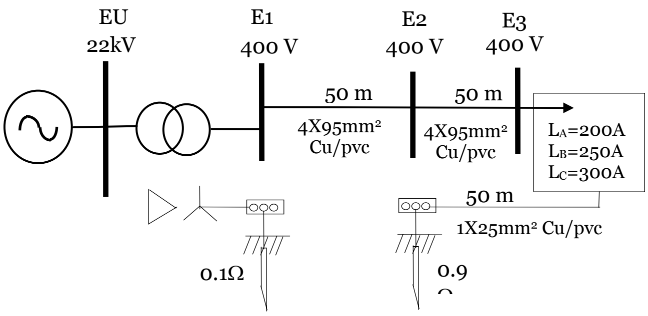



Figure C.5 A sample TT System

the value of $Z_1$ is 0.7845+j3.9225 p.u. on a 100 MVA, 400V base. The 50-m circuit from E1 to E2 consisting of four identical single-core, pvc-insulated copper conductor cables of 95 mm$^2$ without PC, and the other 50-m circuit from E2 to E3 has an additional PC of 25 mm$^2$. The layout of the circuit conductors is the same as those shown in Figure C.2. It is assumed that the unbalanced load can be lumped at E3 as $L_A$=200 A, $L_B$=250 A and $L_C$= 300 A with a power factor of 0.8. It is also assumed that the earth electrode resistance at the installation is 0.9 Ω and that at the equivalent generator at E1 is 0.1 Ω. The prefault voltages and current distribution is shown in Figure C.6.

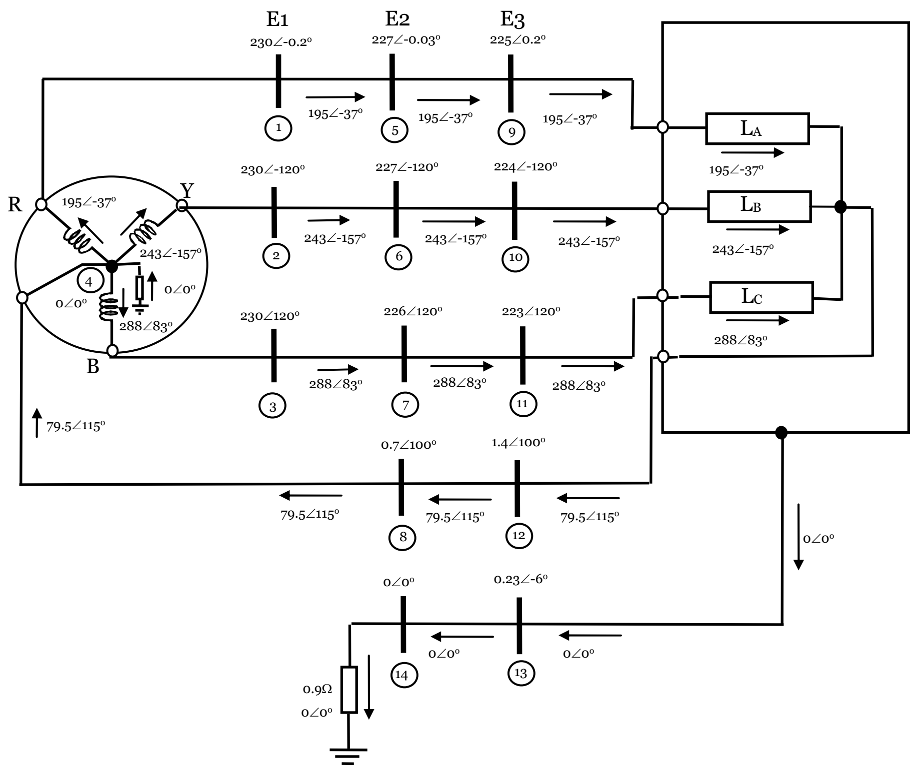



Figure C.6 . The pre-fault voltages and current disribution for the TT

For an earth fault from phase A to the exposed conductive part at E3 as shown in Figure C.7, the earth fault current is actually less than the load currents in the other two healthy phases. The shock voltages are also higher than those in the TN-S system. The fault current distribution and the post-fault voltages including shock voltages and neutral voltages are also shown in Figure C.7.

## C.3 Single Phase Representation

Without using computer programs, the calculation of earth-fault currents can be approximated by using a single phase equivalent. The values of cable impedance can also be approximated by using the voltage drop constant given in the IEE cable tables.

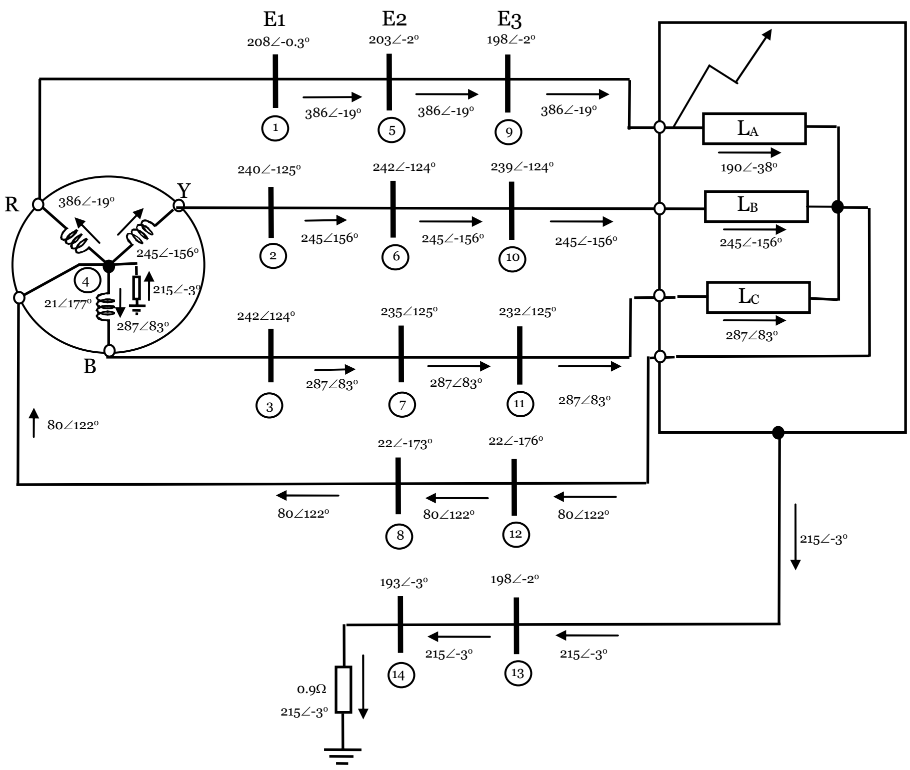


Figure C.7 The post fault voltages and current distribution for the TT system

For the same sample TN-S system as shown in Figure 1, the combined impedance of the utility and the transformer can be transferred from 22 kV to 400 V. This impedance is :

$$
\begin{aligned}
Z_S &= Z_G + Z_{TF} \\
&= 0.0016\Omega \times (0.01244 + j0.1244) + 0.0016\Omega \times (j3.75) \\
&= 0.00002 + j0.0002 + j0.006\ (\Omega) \\
&= 0.00002 + j0.0062\ (\Omega)
\end{aligned}
$$

From IEE cable Table 4D1B, column 8

$$Z_{95} = (0.00041 + j0.00023) \times 50/\sqrt{3} = 0.01184 + j0.00664\ (\Omega)$$

$$Z_{25} = (0.0015 + j0.00025) \times 20/\sqrt{3} = 0.01732 + j0.00289\ (\Omega)$$

$$Z_{10} = (0.0038 + j0.0) \times 20/\sqrt{3} = 0.04388\ (\Omega)$$

$Z_{50}$ = (0.00080 + j0.00024) x 50/$\sqrt{3}$ = 0.02309+j0.00693 ($\Omega$)

By using IEE cable table, the earth fault current is

$$I_{F,LE,T} = \frac{400/\sqrt{3}}{Z_S + Z_{95} + Z_{25} + Z_{10} + Z_{50}}$$

$$= \frac{230.9}{0.09615 + j0.02266}$$

$$= 2337\angle{-13^\circ}\ (A)$$

Alternatively the cable impedance can be obtained by calculating the self and mutual reactances based on the layout of circuit conductors as shown in Figure C.2.

Based on the self reactance only, the impedance of each conductor is:

$$Z_C = R_C + jX_C$$

$$= \rho\frac{L}{A} + j2\pi fk(\ln\frac{2L}{Ds} - 1) \text{ x } L$$

where $\rho$=2.25x10$^{-8}$ $\Omega$.m at 70°C , K=2x10$^{-7}$ H/m, $D_S$= 0.7788 multiplied by the radius of the cylindrical conductor, and f=50 Hz.

$$Z_{C95} = 2.25\text{x}10^{-8}\text{x}\frac{50}{95\text{x}10^{-6}} + j0.6283\text{x}10^{-4}\text{x}(\ln\frac{2\text{x}50}{0.7788\text{x}5.5\text{x}10^{-3}} - 1)\text{x}50$$

= 0.01184+j0.02845 ($\Omega$)

$Z_{C25}$=0.01732+j0.01106 ($\Omega$)
$Z_{C10}$=0.04388+j0.01164 ($\Omega$)
$Z_{C50}$=0.02309+j0.02944 ($\Omega$)

The mutual reactance between phase A conductor and the PC is :

$$Z_M = j2\pi fk(\ln\frac{2L}{D_m} - 1)\text{x}L$$

where the value of $D_m$ is the distance between the centres of the phase A conductor and the PC.

$$Z_{M50,95} = Z_{M95,50} = j0.6283x10^{-4}\, x(\ln\frac{2x50}{83.3x10^{-3}} - 1)x50$$

$$= j0.01912\ (\Omega)$$

$$Z_{M25,10} = Z_{M10,25} = j0.00693\ (\Omega)$$

By using the self and mutual reactances, the fault current is

$$I_{F,LE,M} = \frac{400 / \sqrt{3}}{Z_S + Z_{S95} + Z_{S25} + Z_{S10} + Z_{S50} - 2Z_{M95,50} - 2Z_{M25,10}}$$

$$= \frac{230.9}{0.09615 + j0.03470}$$

$$= 2259\angle{-20^\circ}\ (A)$$

The earth fault current calculated by using the 3-phase representation as shown in Figure C.3 is 2388 $\angle$-51°.

**APPENDIX D**

# PER UNIT CALCULATION

## D.1 Calculation of Per Unit Impedance

Case 1:
For base MVA = 100 MVA and base voltage = 400 V,

$$\text{Per Unit Impedance} = \frac{(\text{base voltage})^2}{\text{base MVA}}$$

$$= \frac{400 \text{ x } 400}{100 \text{ x } 10^6} = 0.0016\ \Omega$$

Case 2:
For base MVA = 1 MVA and base Voltage = 400 V,

$$\text{Per Unit Impedance} = \frac{400 \text{ x } 400}{1 \text{ x } 10^6} = 0.16\ \Omega$$

Case 3:
For base MVA = 100 MVA and base Voltage = 22 kV,

$$\text{Per Unit Impedance} = \frac{(22 \text{ x } 22)\text{x } 10^6}{100 \text{ x } 10^6} = 4.84\ \Omega$$

## D.2 Conversion from Fault Level to Per Unit Impedance

**Example D.2.1**

Calculate the equivalent impedance for a fault level of 25 MVA at 400 V with a X/R ratio of 5.

Solution

Select base MVA = 1 MVA and base voltage = 400 V.

The equivalent per unit impedance ($Z_{S,\,p.u.}$) of the 25 MVA fault level is :

$$Z_{S,\,p.u.} = \frac{1}{25} = 0.04\text{p.u.}$$

since $Z = \sqrt{R^2 + X^2}$ and X/R = 5 ,

$$0.04 = \sqrt{R_s^2 + 25R_s^2} = R_s\sqrt{26}$$

$$R_{S,pu} = \frac{0.04}{\sqrt{26}} = 0.0078 \text{ p.u.}$$

$R_S$ = 0.16Ω x 0.0078 = 0.001248 Ω at 400 V

$X_{S,pu}$ = 0.0078 x 5 = 0.039 p.u.

$X_S$ = 0.16 Ω x 0.039 = 0.00624 Ω at 400 V

**Example D.2.2**

Calculate the equivalent impedance of a fault level of 800 MVA at 22 kV with a X/R of 10.

Solution

Select base MVA = 100 MVA and base voltage = 22 kV. As the per unit voltage is 1.0 and the fault current resulted from the fault level of 800 MVA is 800 MVA / 100 MVA = 8 per unit current, the equivalent per unit impedance of the 800 MVA fault level is

$$Z_{S,\,p.u.} = \frac{1}{8} = 0.125 \text{ p.u.}$$

since $Z = \sqrt{R^2 + X^2}$ and X/R = 10 ,

$$0.125 = \sqrt{R_s^2 + 100R_s^2} = R_s\sqrt{101}$$

$$R_{S,pu} = \frac{0.125}{\sqrt{101}} = 0.0124 \text{ p.u.}$$

$R_S$ = 4.84 Ω x 0.0124 = 0.06 Ω at 22 kV

$$X_{S,pu} = 10 \times 0.0124 = 0.124 \text{ p.u.}$$

$X_S$ = 4.84 Ω x 0.124 = 0.6 Ω at 22 kV

**Example D.2.3**

Calculate the equivalent impedance of the fault level of 35 kA at 400 V with a X/R ratio of 5.

Solution

Since the three-phase short-circuit current $I_F$ is

$$I_F = (400 / \sqrt{3}) / Z_S$$

The equivalent per phase impedance $Z_S$ resulted by the 35 kA fault current is:

$$Z_S = (400 / \sqrt{3}) / (35{,}000) = 0.006598\ \Omega$$

$$R_S = 0.006598 / \sqrt{26} = 0.001294\ \Omega$$

$$X_S = 5\ R_S = 0.00647\ \Omega$$

If the base MVA is 1 MVA and the base voltage is 400 V, the per unit values are :

$$R_{S,pu} = 0.001294\ \Omega / 0.16\ \Omega = 0.00808 \text{ per unit}$$

$$X_{S,\,pu} = 0.00647\ \Omega / 0.16\ \Omega = 0.04044 \text{ per unit}$$

**APPENDIX E**

**TUTORIAL FOR**
**IEE SHORT COURSE**

**E1**

Determine the type of protective device, current rating and the required breaking capacity for a circuit to a 3-phase motor that is rated at 25 kW, 95% efficiency and 0.85 power factor. This motor has a DOL starter. The main switchboard is fed by a 1-MVA, 22-kV/LV transformer that has a leakage impedance of 6% as shown in Figure E.1. The fault level at 22 kV is 800 MVA and the ambient temperature is 40°C. If the motor circuit is a 4 x 25 mm$^2$, single-core copper conductor pvc-insulated cable installed in trunking at a length of 15 m, determine whether this circuit is adequately protected against both overload and short-circuit currents when a fault occurs at the motor terminal.

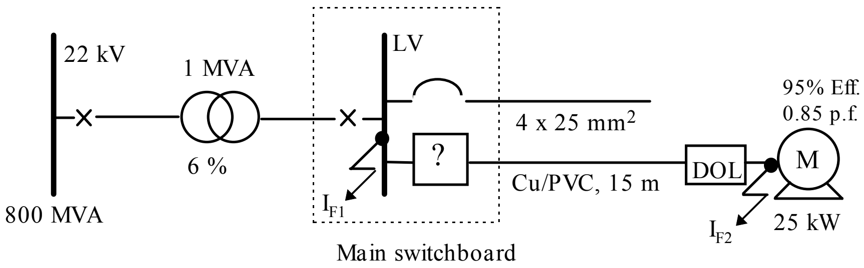



Figure E.1

**E2**

The design current of DB1 is 39 A and it is fed by a 4 x 10 mm$^2$ single-core, copper conductor, pvc-insulated cables and protected by a 40 A MCCB as shown in Figure 4.2.

(a) Does this circuit satisfy the requirements for overload protection?

(b) State the range of small overload that this circuit is not protected.

(c) If this circuit is upgraded to a 4 x 25 mm$^2$ cable, can this circuit be loaded up to 100% of its rated capacity?

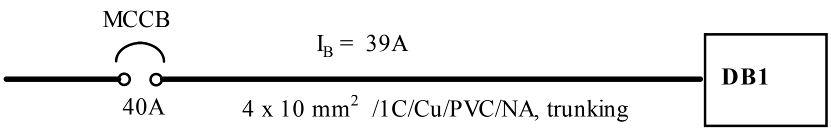



Figure E.2

**E3**

The low-voltage supply to a high-rise block is shown in Figure E.3. A short circuit occurs inside a final distribution board at the top floor. The fault current is 500 A.

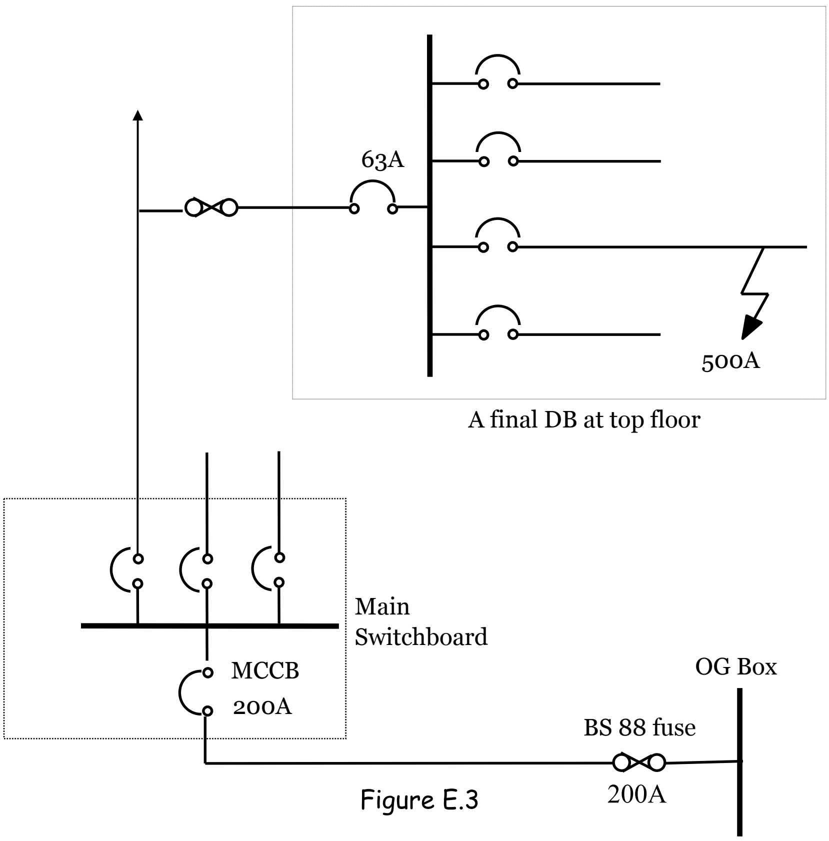



Figure E.3

(a) What is the operating time of the incoming protective device at the final DB if it is a BS EN 60898, 63-A type C MCB, or an IEC 1008, 63-A RCCB with a rated residual operating current of 0.1 A?

(b) Determine the operating time of the MCCB rated at 200 A at the main switchboard.

(c) Determine the operating time of the BS 88 fuse rated at 200 A at the OG Box.

**E4**

As shown in Figure E.4, the 4 x 10 mm$^2$ copper conductor, pvc-insulated cable which has a 'k' value of 115 is protected by a BS EN 60898 100-A type C MCB.

(a) Determine the ranges of short-circuit current in which this circuit is not protected. Suggest an appropriate correction so that the unprotected range can be reduced or totally eliminated.

(b) The breaking capacity of the 100-A MCB is 10 kA but the expected fault current is 14 kA. Determine the current rating of a BS 88 fuse that can be used to back-up the MCB. Will the operating time of the fuse be greater than the operating time of the MCB?

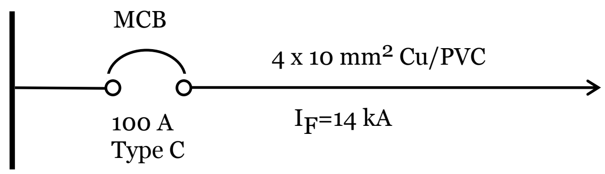



Figure E.4

**E5**

A 4 x 10 mm$^2$ circuit, clipped directly on a non-metallic surface as shown in Figure E.5 is protected by a 60-A MCCB which has a maximum operating time of 0.1 s. The short-circuit current is 5000 A.

(a) Explain why this circuit is not adequately protected against short circuit and recommend the necessary remedial solution.

(b) Determine the maximum short-circuit current that this circuit can withstand.

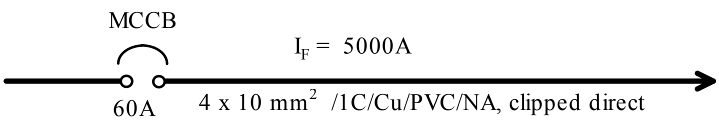



Figure E.5

**E6**

For protection against indirect contact for electric shock in an installation which is part of a TN system, determine the maximum earth fault loop impedance for a final circuit supply only stationary equipment if it is solely protected by:

(a) A BS EN 60898, 63-A type C MCB,

(b) A BS EN 60898, 63-A type B MCB, or

(c) An IEC 1008, 63-A RCCB with a rated residual operating current of 0.03 A.

**E7**

An installation that is part of a TT system has a final circuit with a length of 20 m for socket outlets. The circuit is a single-core, pvc-insulated copper conductor cable of 4 $mm^2$ with a separate CPC of the same size as shown in Figure E.6. The CPC from the final DB to the main earthing terminal is 16 $mm^2$ at 30 m and the earthing conductor is 25 $mm^2$ at 10 m. All the CPC are single-core pvc-insulated copper conductors and the earth electrode resistance is 0.3 Ω. Assume that the ambient temperature is $30^0$ C and the average CPC temperature during fault condition is $95^0$ C. Does this final circuit satisfy the protection requirement for electric shock if the protective device is?

(a) BS 3871, 20-A type 1 MCB,

(b) A BS EN 60898, 20-A type C MCB, or

(c) An IEC 1008, 20-A RCCB with a rated residual operating current of 0.03 A.

**E8**

A 230-V supply to an electric heater utilizes a circuit of pvc-insulated, copper conductor cable of 6 $mm^2$, with a separate bare copper conductor CPC size of 4 $mm^2$ at a length of 18 m as shown in Figure E.7. The external earth fault loop impedance has a resistance value of 0.12 Ω and a reactance value of 0.8 Ω. Determine whether the size of the 4 $mm^2$ CPC can satisfy the electric shock protection as well as the thermal constraint if the circuit is protected by a BS EN 60898, 40-A type B MCB.

If this circuit is protected by an IEC 1008, 40-A RCCB with a rated residual current of 0.03 A, determine the maximum allowable disconnection time based on the thermal limit of the 4 mm$^2$ CPC.

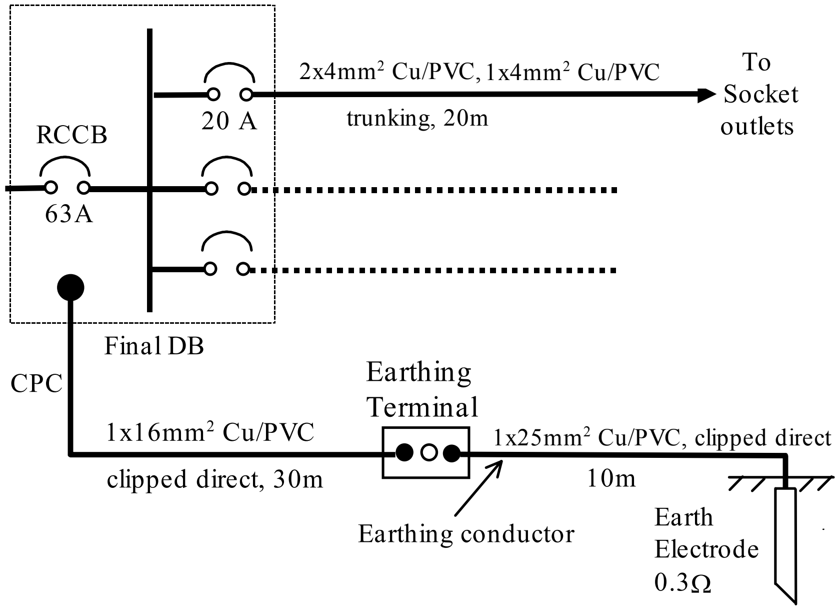



Figure E.6

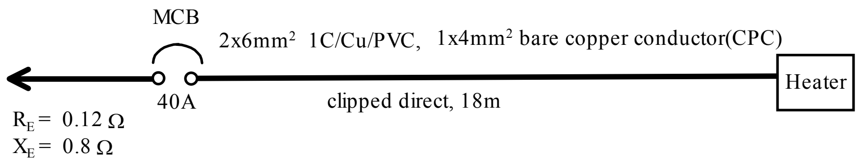



Figure E.7

## E9

The electrical supply to a factory is fed by a 1.6-MVA, 22/0.4-kV transformer that has a reactance of 6 % as shown in Figure E.8. The resistance of the transformer is negligible. All the MCCBs have the same time-current characteristic as given in Table E.1. The current ratings and the values of resistance and reactance of each circuit are given in Table E.2. Determine the magnitude of the earth-fault current for an earth fault at the motor terminal and confirm whether the motor circuit has adequate protection against electric shock? Give reasons with calculation.

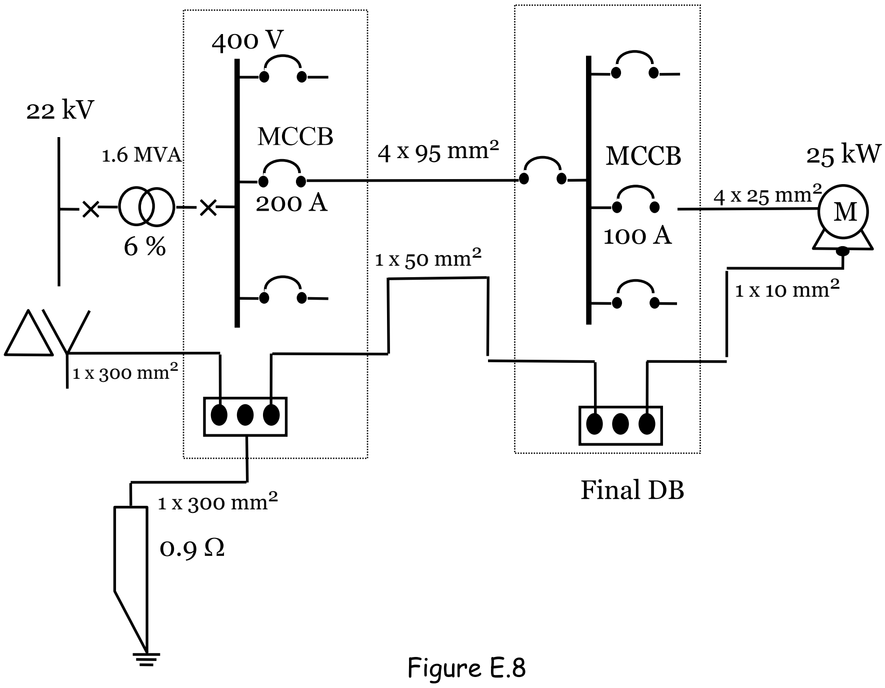



Figure E.8

**Table E.1 Time-current Characteristic of MCCBs**

| Multiple of rated current | Operating time (seconds) |
|---|---|
| > 10 | 0.03 |
| 5 | 0.1 |
| 4 | 5 |
| 3.3 | 12 |
| 2 | 100 |
| 1.3 | 7200 |

**Table E.2 Cable Characteristic**

| Cable Size | Current rating | Resistance* | Reactance* |
|---|---|---|---|
| 4 x 95 $mm^2$ | 207 A | 0.007 Ω | 0.004 Ω |
| 4 x 25 $mm^2$ | 89 A | 0.008 Ω | 0.002 Ω |
| 1 x 50 $mm^2$ | - | 0.014 6Ω | 0.003 Ω |
| 1 x 10 $mm^2$ | - | 0.022 Ω | 0.0 Ω |
| 1 x 300 $mm^2$ | - | 0.0 Ω | 0.0 Ω |

* Per-phase value for the whole circuit length and no temperature correction is required.

# SOLUTION TO TUTORIAL E

## F.1 Solution to E1

$$I_B = (25 \times 10^3) / (0.95 \times 0.85 \times \sqrt{3} \times 400) = 44.69 \text{ A}$$

$$I_S = 7 \times 44.69 = 313 \text{ A}$$

Select a base of 1.0 MVA and 0.4 kV. The equivalent source impedance of a fault level of 800MVA is 0.00125 p. u. The three-phase short-circuit current at the main switchboard is:

$$I_{F,3\phi} = \frac{1}{0.06 + 0.00125} = \frac{1}{0.06125} = 16.33 \text{ p.u.}$$

$$I_{F,3\phi} = 16.33 \times 1.443 \text{ kA} = 23.56 \text{ kA}$$

The type of protective device should be a MCCB with a breaking capacity of more than 23.56 kA. The current rating of the MCCB should be higher than the design current of 44.69 A and it must not operate within 10 s at a starting current of 313 A. From the time-current characteristic of MCCB at $40^0$ C and for the operating time of 10 s, the corresponding current multiplier is 2.2. Thus, the current rating of the MCCB should be higher than 313/2.2 =142 A. A current rating of 200 A is selected.

From Table 4D1A, the tabulated current rating ($I_t$) of the 25 mm$^2$ circuit is 89 A.

$$I_Z = 89 \times 0.87 = 77 \text{ A}, \qquad I_2 = 1.30 \times 200 = 260 \text{ A},$$

$$1.45\, I_Z = 1.45 \times 89 \times 0.87 = 112 \text{ A}$$

Since $I_N$ is not $\leq I_Z$, and $I_2$ is not $\leq 1.45\, I_Z$, this circuit does not satisfy the requirement for overload protection.

The per unit resistance and reactance of the 25 mm$^2$ cable from Table 4D1B are:

$$r = \frac{1.5 \times 15}{\sqrt{3} \times 0.16 \times 1000} = 0.0812 \text{ per unit}$$

$$x = \frac{0.29 \times 15}{\sqrt{3} \times 0.16 \times 1000} = 0.0157 \text{ per unit}$$

The three-phase short circuit current at the motor terminal is

$$I_{F,3\phi} = \frac{1}{\sqrt{(0.00125 + 0.06 + 0.0157)^2 + 0.0812^2}} = 8.94 \text{ per unit} = 12.9 \text{ kA}$$

The maximum duration for the 25mm$^2$ cable to withstand a fault current of 12.9 kA is

$$t_{cable,max} = \frac{k^2 S^2}{I_F^2} = \frac{115^2 \times 25^2}{(12900)^2} = 0.0496 \text{ s}$$

Since the operating time of the MCCB at a current of 12.9 kA is 0.1 s which is greater than the critical time of 0.0496 s, this circuit is not adequately protected against short-circuit current.

## F.2 Solution to E2

(a) This circuit satisfies the requirements for overload protection based on IEE Regulation 433:

(i) since $I_Z$ = 50 A and $I_N$ = 40 A, it satisfies $I_N \leq I_Z$

(ii) since $I_2$ =1.3 x 40 =52 A and $1.45I_Z$ = 72.5 A, it satisfies $I_2 \leq 1.45\ I_Z$

(b) The unprotected range is from 50.1 A to 51.9 A.

(c) The maximum circuit loading is: $I_2 / I_Z$ = 52 / 89 = 58%

## F.3 Solution to E3

(a) The operating time for a BS EN 60898 63-A type C MCB is 6.5 s. (from Figure 2.9). If it is a line-to-neutral fault, the RCCB will not operate. If it is a line-to-earth fault, the operating time is 0.04 s since the residual current is 500/0.1 = $5000I_{\nabla N}$.

(b) The operating time of the 200 A MCCB varies from 9 s to 150 s depending on the ambient temperature and the setting of the MCCB. (from Figure 2.13).

(c) The operating time of the BS 88 fuse rated at 200 A is 300 s (from Figure 5.7).

## F.4 Solution to E.4

(a) If the maximum operating time of the MCB is 0.01 s and from the adiabatic equation, $t_{cable,\ max} = k^2S^2/I^2$, the corresponding maximum current that the cable can withstand is:

$$0.01 = \frac{115^2 \times 10^2}{I^2}, \quad \text{or} \quad I = \frac{115 \times 10}{\sqrt{0.01}} = 11.5\ \text{kA}$$

Thus, the cable will not be protected if the fault current is higher than 11.5 kA. If the fault current is in the range from 514 A to 1000 A, the operating time of the MCB is greater than $t_{cable,\ max}$ and thus, this circuit is also not protected. The unprotected range from 514 A to 1000 A can be eliminated by (i) replacing the 100 A type C MCB by type B or (ii) replacing the 100 A type C MCB by a 50 A type C MCB. The unprotected range from 11.5 kA onwards can be eliminated by using a backup BS 88 fuse (Illustrated in Figure 5.13)

(b) The current rating of a backup fuse is normally double the rating of the MCB (i.e. 200 A if the MCB is 100 A). However, it must be verified with the time current characteristic curves of the MCB and the fuse. For the fault current below the breaking capacity of the MCB, the MCB should operate first, and for fault current at approximately equal or higher than the breaking capacity of the MCB, the fuse should be operated first.

### F.5 Solution to E5

$$\text{(a) } t_{cable,\ max} = \frac{k^2S^2}{I^2} = \frac{115^2 \times 10^2}{5000^2} = 0.0529\ \text{s}$$

Since the operating time of the MCCB at a current of 5,000 A is 0.1 s, which is greater than $t_{cable,\ max}$, this circuit is not adequately protected against short-circuit current. The remedial action is to increase the conductor's size to:

$$S_{min} = \frac{I\sqrt{t_{max}}}{k} = \frac{5000 \times \sqrt{0.1}}{115} = 13.75\ \text{mm}^2$$

(b) The maximum short circuit that this circuit can withstand is:

$$I_{F,\max} = \frac{kS}{\sqrt{t}} = \frac{115 \times 10}{\sqrt{0.1}} = 3637\ \text{A}$$

### F.6 Solution to E6

For final circuit connecting to stationary equipment, the disconnection time is 5 s.

(a) The current causing the 63-A type C MCB to operate within 5 s is 630 A. Thus,

$$Z_{EFL,max,63\,A,MCB,C} = \frac{230}{630} = 0.365\ \Omega$$

(b) The current causing the 63-A type B MCB to operate within 5 s is 315 A. Thus,

$$Z_{EFL,max,63\,A,MCB,B} = \frac{230}{315} = 0.73\ \Omega$$

(c) If protection is provided by a RCCB, the maximum earth fault loop impedance is:

$$Z_{EFL,max,\,RCCB,0.03} = \frac{50}{I\Delta n} = \frac{50}{0.03} = 1666\ \Omega$$

**F.7 Solution to E7**

For a TT system, the condition that limits the touch voltage to not more than 50 V is: $R_L I_A \leq 50$ V, where $I_A$ is the current causing the automatic operation of the protection device within 5 s. From Table 4D1B of the IEE Wiring Regulation:

$$R_{4,CPC} = \frac{11 \times 20\,(230 + 95)}{2 \times 1000\,(230 + 70)} = 0.1192\ \Omega$$

$$R_{16,CPC} = \frac{2.8 \times 30\,(230 + 95)}{2 \times 1000\,(230 + 70)} = 0.0455\ \Omega$$

$$R_{25,CPC} = \frac{1.75 \times 10\,(230 + 95)}{2 \times 1000\,(230 + 70)} = 0.0095\ \Omega$$

$$\begin{aligned} R_L &= R_{4,CPC} + R_{16,CPC} + R_{25,CPC} + R_e \\ &= 0.1192 + 0.0455 + 0.0095 + 0.3 = 0.4742\ \Omega \end{aligned}$$

$$I_A = \frac{50}{0.4742} = 105.4\ \text{A}$$

(a) For a BS 3871 20-A type 1 MCB, the operating time for a current of 105.4 A is within 5 s and thus, it satisfies the requirement for earth fault protection.

(b) For a BS EN 60898 20-A type C MCB, the operating time is 11 s, which exceeds 5 s, and thus, it does not satisfy the requirement.

(c) For an IEC 1008 20-A RCCB, the operating time for a residual current of 105.4 A is 0.04 s and obviously, it satisfies the requirement.

**Solution to E.8**

Assume that the average phase conductor temperature during the fault is (70+160)/2 = 115$^{O}$C and the CPC is (30$^{o}$C + 200) / 2 = 115$^{o}$C. From Table 4D1B of the IEE Wiring Regulations, the resistance values are:

$$R_6 = \frac{7.3}{2} \times \left( \frac{230 + 115}{230 + 70} \right) \times \frac{18}{1000} = 0.0756\ \Omega$$
$$R_4 = \frac{11}{2} \times \left( \frac{230 + 115}{230 + 70} \right) \times \frac{18}{1000} = 0.1139\ \Omega$$

The earth fault loop impedance is:

$$Z_{EFL} = \sqrt{(R_6 + R_4 + R_E)^2 + X_E{}^2}$$
$$= \sqrt{(0.0756 + 0.1139 + 0.12)^2 + 0.8^2} = 0.858\ \Omega$$

The line-to-earth fault current is:

$$I_{F,LE} = \frac{230}{0.858} = 268\ A$$

For a current of 268 A, the operating time of the 40-A type B MCB is 0.1 s which is less than the required time of 5 s and thus, it satisfies the requirement for protection against electric shock.

To satisfy the thermal constraint, the minimum cross-sectional area of the cpc for type B MCB is:

$$S_{min,\ type\ B} = \frac{\sqrt{I^2 t}}{k} = \frac{\sqrt{268^2 \times 0.1}}{159} = 0.533\ mm^2$$

Thus, the CPC size of 4 mm$^2$, which is greater than 0.533 mm$^2$, satisfies the thermal constraints. The maximum disconnection time based on the thermal limit of the 4 mm$^2$ CPC is:

$$t_{max} = \frac{k^2 s^2}{I_{F,LE}^2} = \frac{159^2 \times 4^2}{268^2} = 5.63\ s$$

**F.9 Solution to E9**

Select a base of 1.6 MVA and 0.4 kV. The line-to-earth short-circuit current at the motor terminal is:

$$I_{EF,motor} = \frac{230}{Z_{TF} + Z_{95} + Z_{25} + Z_{10} + Z_{50} + Z_{300}}$$

The transformer impedance $Z_{TF}$ expressed in ohms is,

$$Z_{TF,\Omega} = Z_{TF,p.u.} \text{ X } 0.1\ \Omega = 0.06 \text{ X } 0.1\ \Omega = 0.006\ \Omega$$

$$I_{EF,motor} = \frac{230}{\sqrt{(0.006 + 0.004 + 0.002 + 0.003)^2 + (0.007 + 0.008 + 0.022 + 0.014)^2}}$$

$$= \frac{230}{\sqrt{0.015^2 + 0.051^2}} = \frac{230}{0.0532} = 4323 \text{ A}$$

As the motor is stationary equipment, the disconnection time for earth fault is 5 s. The operating time of the 100 A MCCB at the earth fault current of 4323 A is 0.03 s and thus, it satisfies the requirement for protection against electric shock.

## APPENDIX G

## MODEL EXAMINATION QUESTIONS WITH SOLUTION

**G1**

The electrical supply to a factory is fed by a utility through an ACB rated at 1600 A as shown in Figure G.1. The fault level at the 400-V intake substation is 25 MVA (36 kA) with a X/R ratio of 5. The maximum demand at the MCC is 260 kW and the power factor is 0.8. All the installed circuits are pvc-insulated, copper conductor cables clipped direct in trefoil on the wall. The rated current and voltage drop data for each cable are given in Table G.1.

Correction factors for temperature, grouping and thermal insulation are not required. The calculated earth fault current at the MCC is 400 A and that at the 40-kW motor terminal is 250 A. All the MCCBs have the same time-current characteristic as given in Table G.2.

(a) State the conditions necessary for protection against overload current. Does the circuit from the intake substation to the MCC satisfy the requirements for overload protection? Support your answer by numerical calculation. Determine the range of small overload for which this circuit is not protected.

(12 marks)

(b) Verify by calculation whether the 500-A MCCB provides adequate protection for the circuit from the intake substation to the MCC when a 3-phase short-circuit occurs at the MCC.

(8 marks)

(c) Calculate the touch voltage at the 40 kW motor frame if the red-phase cable is shorted to the motor frame. The combined resistance of the earthing conductor and the earth electrode is 0.3 Ω and the earthing system is a TT system.

(5 marks)

**Table G.1 Current Rating and Voltage Drop for 3-phase 4 cables**

| Cable Size ($mm^2$) | Rated Current (A) | Voltage Drop (mV per ampere per metre) | |
|---|---|---|---|
| | | R | X |
| 25 | 110 | 1.50 | 0.175 |
| 50 | 167 | 0.80 | 0.165 |
| 120 | 308 | 0.32 | 0.150 |
| 300 | 561 | 0.13 | 0.140 |

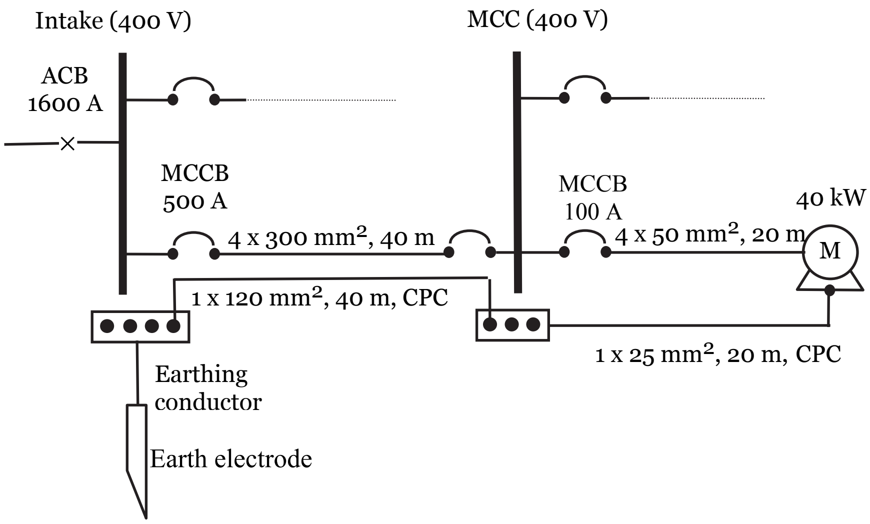



Figure G.1

**Table G.2 Time-current Characteristic of MCCBs**

| Multiple of Rated Current | Operating Time (Seconds) |
|---|---|
| > 10 | 0.03 |
| 5 | 0.10 |
| 3.3 | 12.0 |
| 2 | 100 |
| 1.3 | 3600 |
| 1.0 | ∞ |

**Solution to G1**

(a) Required conditions for protection against overload:

$$\text{(i) } I_N \leq I_Z \quad \text{(ii) } I_2 \leq 1.45\, I_Z$$

For the circuit from intake substation to MCC,

$I_N$ =500 A, $I_Z$ = 561 A, $I_2$ = 1.3 x 500 A =650 A,

1.45 $I_Z$ = 1.45 x 561 A =814 A

Thus, conditions (i) and (ii) are satisfied and this circuit is adequately protected against overload current accordingly to IEE Regulation 433. The range of small overload that this circuit is not protected is from 561.1 A to 649.9 A.

(b) Select base MVA = 1 MVA and base voltage = 400 V. The equivalent per unit impedance of the 25 MVA fault level is:

$Z_{S,pu} = 1 / 25 = 0.04$ p.u

$R_{S,pu} = 0.04 / \sqrt{26} = 0.0078$ p.u. (from X/R = 5)

$R_S = 0.16\ \Omega \times 0.0078 = 0.001248\ \Omega$ at 400 V

$X_{S,pu} = 0.0078 \times 5 = 0.039$ p.u.

$X_S = 0.16\ \Omega \times 0.039 = 0.00624\ \Omega$ at 400 V

$Z_{300mm} = 40\times (0.13 + j0.14) / (\sqrt{3} \times 1000) = 0.003 + j\ 0.00323\ \Omega$

The 3-phase fault current at the MCC is

$I_{F,3\text{-phase}} = V_{LN} / (Z_S + Z_{300mm})$

$=(400 / \sqrt{3})/ (0.004248 + j0.00947) = 22.250\ kA \angle -65.8$

$t_{cable,max} = k^2\ S^2 / I_F^{\,2} = (115^2 \times 300^2) / 22250^2 = 2.4$ s

Since $t_{MCCB}$ is less than $t_{cable\ max}$, this circuit provides adequate protection against short- circuit currents.

(c) The tough voltage at the motor frame is:

$250\ A \times ( Z_{25mm} + Z_{120mm} + 0.3)$

$= 250 \times ( 0.3247 + j\ 0.005484)$

$= 81.19$ V

***G2***

The electrical supply to a high-rise apartment is fed by a 1 MVA, 22/0.4 kV transformer. The schematic diagram of part of the electrical installation is shown in Figure G.2. All the installed circuits are pvc-insulated copper conductor cables clipped direct in trefoil on the wall. Voltage-drop data for each cable is given in Table G.3. Temperature correction for cable resistive value is not required.

(a) Calculate the short-circuit current for a line-earth fault developed at the socket outlet. (10 marks)

(b) Calculate the touch voltage for an earth fault at the appliance connected to the socket outlet within the earthed equipotential zone. (5 marks)

(c) State the two necessary conditions which will provide adequate protection against electric shock and determine whether the 60 A RCCB can be replaced by an MCCB. (10 marks)

**Table G.3 Three-phase voltage-drop data (mV per ampere per metre)**

| Cable Size ($mm^2$) | R | X | Z |
|---|---|---|---|
| 4 | 9.5 | - | - |
| 16 | 2.4 | - | - |
| 35 | 1.10 | 0.170 | 1.10 |
| 50 | 0.80 | 0.165 | 0.82 |
| 120 | 0.32 | 0.150 | 0.36 |
| 300 | 0.13 | 0.140 | 0.190 |

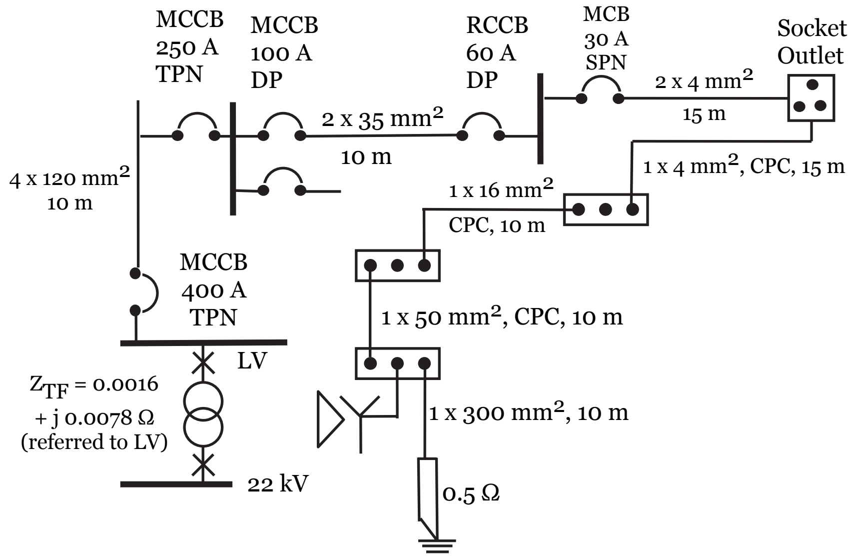



Figure G.2

**Solution to G2**

The transformer impedance $Z_{TF}$ is (0.0016 + j0.0078) Ω. The per phase resistance and reactance of all the cables in the earth fault loop are:

$R_{cable} = R_{120} + R_{35} + R_4 + R_4 + R_{16} + R_{50} = 0.1912\Omega$

$X_{cable} = X_{120} + X_{35} + X_4 + X_4 + X_{16} + X_{50} = 0.0028\Omega$

The earth fault current at the socket outlet $I_{EF,SSO}$ is

$$I_{EF,SSO} = \frac{230}{Z_{TF} + Z_{120} + Z_{35} + Z_4 + Z_4 + Z_{16} + Z_{50}}$$

$$= \frac{230}{0.1928 + j0.0106} = 1191 \quad A \angle -3.15$$

(b) For an earth fault current of 1196 A, the operating time of the 30 A MCB is 0.1 s for any current exceeding 300 A. Thus, the touch voltage is

$$V_T = Z_{CPC} \times I_A = (Z_4 + Z_{16} + Z_{50}) \times I_A$$

$$= (0.1007 + j0.001) \times 300 = 30.2 \text{ V}$$

(c) Conditions for a TN system to have adequate protection against electric shock are: (i) the maximum disconnection time for hand-held equipment and for fixed equipment is 0.4 s and 5 s respectively. (ii) For hand-held equipment, the disconnection time can be increased to 5 s if the touch voltage is within 50 V. For protection by MCCB alone, the operating time of the breaker for an earth fault current of 1196 A is 0.1 s which meets condition (i). Similarly, the touch voltage is 30 V which is less than 50 V and such touch voltage can be disconnected within 0.1 s. Thus the 60 A RCCB can be replaced by an MCCB.

**G3**

In the TN-S system as shown in Figure G.3, the three-phase fault level at D1 is 25 MVA with a X/R ratio of 5. The 50-m circuit from D1 to D2 consists of three single-core, pvc-insulated copper conductor cables of 95 mm$^2$ with a CPC of 50 mm$^2$. The 20-m circuit from D2 to the motor consists of similar cables of 25 mm$^2$ with a CPC of 10 mm$^2$. The motor is rated at 60 kW with 90 % efficiency and 0.8 power factor. The motor has a direct-on-line starter. The starting current is seven times the full-load current and lasts for 10 s. Voltage-drop constants for cables at 70 degree C are given in Table G.4. Temperature correction on the resistive value is not required.

(a) Determine the current rating and the breaking capacity of the MCCB at D2 for the motor circuit at an ambient temperature of 40 degree C.

(10 marks)

(b) Determine the maximum allowable operating time for the MCCB at D2 if this MCCB is designed to provide adequate short-circuit protection for a three-phase fault at the motor terminal. The k constant of the 25-mm$^2$ copper conductor cable is 143 at 30 degree C and 115 at 70 degree C.

(5 marks)

(c) For a short-circuit from the blue phase to the frame of the motor, calculate the earth fault current and the touch voltages at the motor and at the earthing terminal at D2.

(10 marks)

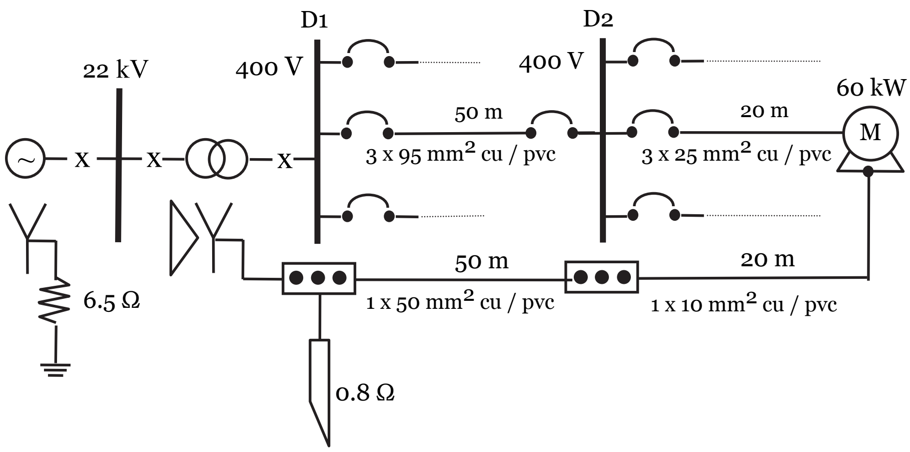



Figure G.3

**Table G.4 Voltage Drop Constants**

| Conductor cross-sectional area ($mm^2$) | Voltage drop in mV per ampere per metre | | | | | |
|---|---|---|---|---|---|---|
| | 2 cables Single-phase ac | | | 3 or 4 cables Three-phase ac | | |
| | r | x | Z | r | x | z |
| 10 | 4.4 | 0 | 4.4 | 3.8 | 0 | 3.8 |
| 25 | 1.75 | 0.20 | 1.75 | 1.5 | 0.25 | 1.55 |
| 50 | 0.93 | 0.19 | 0.95 | 0.80 | 0.24 | 0.84 |
| 95 | 0.47 | 0.18 | 0.50 | 0.41 | 0.23 | 0.47 |

**Solution to G3**

(a) $I_B = (60 \times 10^3) / (0.9 \times 0.8 \times \sqrt{3} \times 400) = 120$ A,

$$I_S = 7 \times 120 = 840 \text{ A}$$

The current rating of the MCCB should be higher than 840/2.2 = 382 A.

Select base MVA = 1 MVA and base voltage = 400 V. The equivalent per unit impedance of the 25 MVA fault level is :

$$Z_{S,pu} = 1 / 25 = 0.04 \text{ p.u}$$

$$R_{S,pu} = 0.04 / \sqrt{26} = 0.0078 \text{ p.u. (from X/R = 5)}$$

$$R_S = 0.16\ \Omega \times 0.0078 = 0.001248\ \Omega \text{ at 400 V}$$

$X_{S,pu}$ = 0.0078 x 5 = 0.039 p.u.

$X_S$ = 0.16 Ω x 0.039 = 0.00624 Ω at 400 V

$Z_{95mm}$ = 50x (0.41 + j0.23) / ( $\sqrt{3}$ x 1000) = 0.0118 + j 0.006639 Ω

The 3-phase fault current at D2 is

$I_{F,3\text{-phase},D2} = V_{LN} / (Z_S + Z_{95mm})$

$= (400 / \sqrt{3}) / (0.0131 + j0.01263) = 12{,}691 \text{ A} \angle -44$

The breaking capacity of the MCCB should be higher than 12,691 A.

(b) The current for a 3-phase fault at the motor terminal is:

$I_{F,3\text{-phase},motor} = V_{LN} / (Z_S + Z_{95mm} + Z_{25})$

$= (400 / \sqrt{3}) / (0.03042 + j0.01552) = 6{,}762 \text{ A} \angle -27$

$t_{cable,\,max} = k^2 S^2 / I_F^2 = (115^2 \times 25^2) / 6{,}762^2 = 0.18 \text{ s}$

Since $t_{MCCB}$ is less than $t_{cable\ max}$, this circuit provides adequate protection against short- circuit current.

(c) The earth fault current at the motor frame is:

$$I_{EF,motor} = \frac{230}{Z_{TF} + Z_{95} + Z_{25} + Z_{10} + Z_{50}}$$

$$= \frac{230}{0.0974 + j0.02245} = 2301 \text{ A}$$

The touch voltage at the motor is:

$V_T = I_{EF,motor} \times (Z_{10} + Z_{50}) = 2301 \times (0.06698 + j0.00693) = 154.9 \text{ V}$

The touch voltage at the earthing terminal at D2 is:

$V_{T,D2} = I_{EF,motor} \times Z_{50} = 2301 \times (0.0231 + j0.00693) = 55.5 \text{ V}$

**G4**

The electrical supply to a factory using a TN-S system is shown in Figure G.4. The 750-kVA, 6.6/0.4-kV transformer has a leakage reactance of 5 %. The source impedance at the 6.6-kV network can be neglected. The cable parameters of circuits A and B are given in Table G.5.

(a) Determine the current rating and the breaking capacity of the MCCB for circuit A connecting to the motor rated at 100 kW with 90 % efficiency and 0.85 power factor. The motor has a Y-Δ starter and the starting current is four times the full-load current for 15 s. (8 marks)

(b) Determine whether circuit A is adequately protected against overload current and three phase short-circuit current at the motor terminals.

(8 marks)

(c) Calculate the fault current in circuit B for an earth fault at the motor terminals and confirm whether circuit B is adequately protected against electric shock. Verify whether the size of CPC for circuit B is appropriate.

(9 marks)

**Table G.5 Cable Parameters**

| | | Circuit A | Circuit B |
|---|---|---|---|
| | Size | 3 x 95 $mm^2$ cu / pvc | 3 x 120 $mm^2$ cu / pvc |
| Phase Conductor | R* | 0.007 Ω per phase | 0.006 Ω per phase |
| | X* | 0.004 Ω per phase | 0.004 Ω per phase |
| | $I_Z$ | 207 A | 239 A |
| | Size | 1 x 50 $mm^2$ cu / pvc | 1 x 50 $mm^2$ cu / pvc |
| CPC | R* | 0.014 Ω | 0.014 Ω |
| | X* | 0.003 Ω | 0.003 Ω |

*The values of R and X are for the whole circuit and no temperature correction is required.

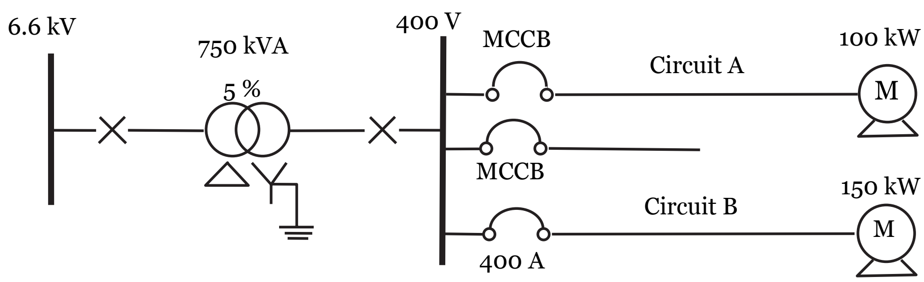



Figure G.4

**Solution to G4**

(a) $I_B = (100 \times 10^3) / (0.9 \times 0.85 \times \sqrt{3} \times 400) = 189$ A

$$I_S = 4 \times 189 = 756 \text{ A}$$

The current rating of the MCCB should be higher than 756/2 = 378 A. A current rating of 400 A is recommended. For a base of 0.75 MVA and 400 V, the per unit impedance is 0.213 Ω and the per unit current is 1083 A. The three-phase short-circuit current at the MCCB terminal is

$$I_{F,3\text{-phase}} = 1 / 0.05 = 20 \text{ per-unit current} = 21.66 \text{ kA}$$

Thus, the breaking capacity of the 400 A MCCB should be higher than 21.66 kA and a breaking capacity of 25 kA is recommended.

(b) Required conditions for protection against overload are:

(i) $I_N \leq I_Z$ (ii) $I_2 \leq 1.45\ I_Z$

For circuit A

$I_N$ =400 A, $I_Z$ = 207 A, $I_2$ = 1.3 x 400 A =520 A,

1.45 $I_Z$ = 1.45 x 207 A =300 A

Since conditions (i) and (ii) are not satisfied, circuit A is not protected against overload current accordingly to IEE Regulation 433. The 3-phase fault current at the motor terminal is 14.15 kA and the $t_{cable\ max}$ is 0.59 s. Since the breaker operating time for a current of 14.15 kA is 0.017 s, (from Fig. 2.13), circuit A is adequately protected against short-circuit currents.

(c) The earth fault current at the motor frame is:

$$I_{EF,\text{motor, circuit B}} = \frac{230}{Z_{TF} + Z_{120} + Z_{50}}$$

$$= \frac{230}{0.02 + j0.01765} = 8{,}623 \text{ A}$$

The operating time of the 400 A MCCB at a current of 8623 A is 0.017 s which is less than the required 5 s. Thus circuit B satisfies the protection against electric shock. The maximum time for the CPC to withstand the earth fault current of 8623 A is 0.69 s which is greater than the breaker operating time of 0.017 s. Thus, the size of the CPC is appropriate.

**G5**

The electrical supply to a factory is fed by a 1.6-MVA, 22/0.4-kV transformer that has a reactance of 6 % as shown in Figure 3. The resistance of the transformer is negligible. All the MCCBs have the same time-current characteristic as given in Table G.1. The current ratings and the values of resistance and reactance of each circuit are given in Table 2.

a) Recommend the current rating and the minimum breaking capacity of the MCCB for the circuit connecting to the motor, which is rated at 25 kW, 90 % efficiency and 0.9 power factor. The motor utilises a DOL starter. The starting current is seven times the full-load current and such a current would exist for 10 s. (8 marks)

b) Determine whether the 200-A MCCB for the 4 x 95 mm$^2$ circuit can adequately protect against overload current. State the range of small overload for which this circuit is not protected. If the maximum operating time of the 200-A MCCB is 0.03 s, determine whether the MCCB can adequately protect against short-circuit current for a three-phase fault at the final DB. (9 marks)

c) Determine the magnitude of the earth-fault current for an earth fault at the motor terminals and confirm whether the motor circuit has adequate protection against electric shock? Give reasons with calculation. (8 marks)

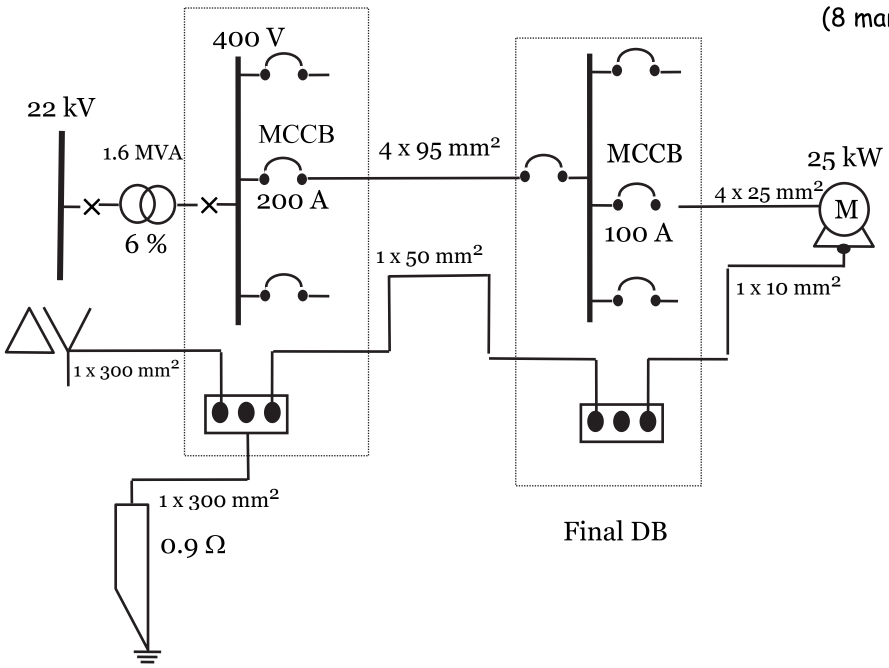



Figure G.5

**Table G.6 Cable Characteristic**

| Cable Size | Current rating | Resistance* | Reactance* |
|---|---|---|---|
| 4 x 95 mm$^2$ | 207 A | 0.007 Ω | 0.004 Ω |
| 4 x 25 mm$^2$ | 89 A | 0.008 Ω | 0.002 Ω |
| 1 x 50 mm$^2$ | - | 0.014 Ω | 0.003 Ω |
| 1 x 10 mm$^2$ | - | 0.022 Ω | 0.0 Ω |
| 1 x 300 mm$^2$ | - | 0.0 Ω | 0.0 Ω |

* for the whole circuit length and no temperature correction is required

**Solution to G5**

(a) $I_B = (25 \times 10^3) / (0.9 \times 0.9 \times \sqrt{3} \times 400) = 44.55$ A,

$$I_S = 7 \times 44.55 = 312 \text{ A}$$

The current rating of the MCCB should be higher than 312/3.3 = 94.5 A.
For a base of 1.6 MVA and 0.4 kV, the reactance of the transformer is:

$$X_S = 0.1\ \Omega \times 0.06 = 0.006\ \Omega \text{ at } 400 \text{ V}$$

The 3-phase fault current at the final DB is:

$$I_{F,3\text{-phase,final DB}} = V_{LN} / (Z_S + Z_{95mm})$$

$$=(400 / \sqrt{3}) / (0.007 + j0.01) = 18.9 \text{ kA} \angle -55$$

$$t_{cable,max} = k^2 S^2 / I_F^2 = (115^2 \times 95^2) / 18{,}900^2 = 0.334 \text{ s}$$

The minimum breaking capacity of the MCCB should be higher than the 3-phase fault current at the final DB(i.e. 18.9 kA).

(b) Required conditions for protection against overload:

$$\text{(i) } I_N \le I_Z \quad \text{(ii) } I_2 \le 1.45\, I_Z$$

For the 4 x 95 mm$^2$ circuit,

$I_N$ =200 A, $I_Z$ = 207 A, $I_2$ = 1.3 x 200 A = 260 A,

$1.45\, I_Z$ = 1.45 x 207 A =300 A

Conditions (i) and (ii) are satisfied and this circuit is adequately protected against overload current. The range of small overload that this circuit is not protected is from 207.1 A to 259.9 A. Since $t_{cable,max}$ is greater than 0.03 s, this circuit is adequately protected against short-circuit current.

(c) The earth fault current at the motor frame is:

$$I_{EF,motor} = \frac{230}{Z_{TF} + Z_{95} + Z_{25} + Z_{10} + Z_{50} + Z_{300}}$$

$$= \frac{230}{0.051 + j0.015} = 4326 \text{ A}$$

The operating time of the 100 A MCCB at a current of 4326 A is 0.03 s which is less than the required 5 s and thus it provides adequate protection against electric shock.

**APPENDIX H**

# VipCoda

VipCoda: Visually Interactive Program for Consultant and Owner to Design and Assess electrical systems in building.

By utilizing the visually interactive window programming technique and facilities on database access, VipCoda provides an user friendly, visually interactive tool to automate the design process producing a sound and reliable design which meets the code of practice of CP5 (1998) and BS 7671:1992 (IEE wiring regulations, 16$^{th}$ Edition). VipCoda can also be used to automatically assess and evaluate any submitted electrical network systematically within a short time. By utilizing the built-in database structure, all the design assumptions are automatically documented and stored together with the completed design network. Thus, it is also a comprehensive tool for training and upgrading engineers on how to design and assess an electrical network.

The completed design including all the technical parameters can be displayed and viewed in exactly the same presentation as reading a single-line diagram generated by AutoCAD. In addition, the calculated fault level and the cumulative voltage drops from the main incoming circuit up to each final circuit are graphically displayed. Facilities are provided to simulate the normal loading, overloading, short circuit and earth fault conditions. A result of pass or fail will be given by assessing through seven critical tests and three non-critical tests. A full explanation as to why, how and by how much the design fails will also be included.

## H1. Design Element Database

All the cable tables given in the IEE wiring regulation and CP5 (1998) are structurally stored in the cable database grouped according to the conductor material, insulation material, and cable construction and installation methods. In addition, fire resistant cables and busways are also represented. Currently, eight types of cables, namely copper PVC, copper MICC, aluminum PVC, aluminum XLPE, copper XLPE, copper fire resistant, copper busway and aluminum busway are available in 969 records. The installation methods include clipped direct, conduit/trunking, thermal insulation and tray for single-core non-armored, multi-core non-armored, single-core armored and multi-core-armored cables. All the cables can be interactively selected from a number of simple dialogue boxes and built-in facilities are provided for the user to have a speed search for all CP5 cable tables.

Five types of overcurrent protective device, namely ACB, MCCB, MCB, RCCB and fuse are represented. The complete range of the preferred rated current and breaking capacity from the relevant BS and IEC standard are included in a total of 106 records for breakers and fuses. Four types of typical time-current characteristic curves for breaker and fuses are modeled. Current transformers and earth fault relays by IDMT, DTL and ELR are available.

**H2. Simulation and Testing**

Seven types of critical tests and two types of non-critical tests are conducted for each circuit in each DB to assess whether a given design is acceptable under normal loading, overloading and short-circuit conditions.

**Breaker and Cable Load Test.** Compute design current ($I_B$) and the rated circuit capacity ($I_Z$) by considering the ambient temperature and grouping factor. Based on the current rating of the protective device ($I_N$), detect whether $I_N > I_B$ and $I_Z > I_B$. Compute the circuit loading in percentage of the rated capacity under the specified conditions.

**Overload Protection Test.** Increase the load current in each circuit to 145% of the rated circuit capacity ($I_Z$) and model the operating time of the protective device. Detect whether the operating time of the protective device is less than the effective operating time of 2 hours. ( i.e. $I_2 < 1.45\ I_Z$ and $I_N < I_Z$)

**Voltage Drop Test.** Calculate the voltage drops in volts and in percentage of the rated operating voltage. Check whether the voltage drop is within the required voltage drop tolerance.

**Short circuit Protection Test.** Calculate the 3-phase short-circuit current at the end of each circuit. Check whether the braking capacity of the protective device is higher than the calculated short-circuit current. Model the operating time of protective device under the fault condition. Detect whether the circuit will be disconnected within the critical time, which is the maximum allowable time in seconds to ensure that the temperature in the conductor will not exceed its thermal limit resulting in a failure in insulation material.

**Earth Fault and CPC Test.** Calculate the earth fault current at the end of each circuit. Detect whether the cable size of each circuit protective conductor (CPC) is adequate to withstand the earth fault current.

**Motor Starting Test.** Based on the type of starter and the motor rating, calculate the motor starting current. Model the operating time of the protective device and detect whether the protective device will trip during the starting period. Based on the circuit impedance and the source impedance, calculate the voltage dips at the instant when the motor starts. Detect whether the voltage dips will release the contactor in the starter.

**Electric Shock Protection Test.** Calculate the earth fault current and the touch voltage at the end of each circuit. Based on the IEE regulations and solely based on the direct acting overcurrent protective device, check whether the touch voltage is less than 50 V and whether the disconnection time is less than 5 s for a TT system. For a TN system, the earth fault loop impedance is calculated and a check is made to detect whether the disconnection time is less than 0.4 s for hand-held equipment and 5 s for fixed equipment. If the direct acting overcurrent protective device fails to provide the requirements for electric shock protection, the relevant residual protective devices such as RCCB, ELR, E/F and IDMT will be suggested. The operating time is modeled based on the specified CT ratio, time and current settings of the device. The user will be prompted to specify new settings until the requirement on electric shock protection is met.

### H3. Computer-aided Interactive Design

The user may carry out the design work for a main switchboard (MSW), a main distribution board (MDB) or a final distribution board (FDB). Facilities are provided for the user to link the complete network by backward chaining from FDB, MDB to MSW, or a forward chaining from MSW, MDB to FDB. For each circuit, based on the user's specification on the required type of load and power rating, type of cable, circuit length, fault level of the incoming source etc, the program automates the design process and shows the appropriate breaker and cable including CPC in a single line diagram. Through several built-in rules, the automated design done by VipCoda will ensure that it meets all the seven critical tests.

The user may simply click on the single line diagram to change a breaker or a cable in any circuit, or to enter a design done by a contractor. The user may click the 'speed test' button to obtain summaries of those tests that have detected failure. The user may then click for a particular test to find out the cause of failure or click the 'redesign' button to carry out a redesign by the program for one particular circuit, the whole DB or the entire project to automatically rectify all the design errors. Options are provided for load balancing either manually or automatically.

Facilities are provided for the user to list or print a technical summary or a cost summary of the whole project. In the technical summary, all the DBs in the specified project are tabulated together with the maximum demand, fault current, earth fault current and the cumulative voltage drop at each DB. For cost summary, the cost for each DB and the total cost of the whole project are listed with breakdown in cable and breaker costs. Tools are also provided for the user to delete or insert a circuit, copy a DB to a project or create a project by modifying from a list of standard projects or previously completed projects. Utilities are also provided for the user to print the single line diagram of a particular DB together with the result of each simulation test.

### H4. Project Database

The successfully designed network of a project can be saved by the built-in project database. This database contains the description of all the switchboards and DBs of the whole project in an automatically arranged structure. Built-in editing facilities are provided for the user to view or edit the project database, design element database or lookup tables that contain the design rules and design assumptions. For verification and confirmation that the design process by VipCoda is accurate, three benchmark projects have been created with all the connected loads and design assumptions specified. In these three benchmark networks, the completed design done by VipCoda represents the unique solution that meets all the given design requirements and specifications, and at the same time there is no over-design in any circuit. Thus the completed network given by VipCoda can be used as a reference to compare a design done manually or by using any other computer aided design program.

### H5. Visual User Interface

VipCoda utilizes all standard Window facilities such as pull down menus, pop-up windows, symbolic icons and various visually interactive dialogue boxes, etc. It is arranged such that all the menus, icons and dialogue boxes are self-documented. The user may simply click a load icon to view the detailed load information, click a circuit icon to view or change the type of cable, temperature correction and grouping factor or click a breaker icon to re-specify the type of breaker or its tripping curve. Tools are provided for the user to have an enlarged view on a DB or an overview of the whole project including riser with tap-off and the incoming transformer connection.

## H6. Related Publications

[1] Teo C Y, "A new integrated tool for exercises on the design of electrical installations using a microcomputer", Electric Power Systems Research, Vol. 36, No. 1 PP 81-91, 1996.

[2] Teo C Y, "Computer aided design and simulation of low voltage electrical distribution systems", Computers in Industry, Vol. 34, No. 1, PP 87-94, 1997.

[3] Teo C Y, Shen Feng, "Application of artificial intelligence in the design of low voltage electrical system", Proceeding of the 2000 IEEE Winter Meeting, pp 1784-1789, Vol. 3, 2000.

[4] Teo C Y, "An innovative program for the design and assessment of electrical system in buildings", IEM Bulletin, pp 46-49, 2001.

[5] Teo C Y, "Integrated Assessment of Electrical Systems in Buildings Through Simulation Tests", The Singapore Engineers, pp 27-32, 2003

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**APPENDIX I**

# VipTein

VipTein: Visually Interactive Package for the Teaching of Electrical Installation Network in buildings

An innovative approach using computer aided design tools to support the teaching of electrical installation through hands-on design exercises is described. It is implemented by an integrated package with all the built-in facilities, which guide students step by step to complete the design of two sizeable electrical installations. The dedicated database structure enables students to get direct access to the building information, details of each type of load and the technical parameters of all the electrical parts required for the design exercise. The built-in dynamic test specification eliminates routine and repetitive design studies and also accelerates the design and learning process. Each error made by each student is prompted on the spot and after each second attempt; the right answer and the student's wrong answer are shown for comparison. The performance of each student is evaluated automatically through error logs and is summarized by showing the total number of demerit points, which is then converted to a grade of A B C D or E.

## I1. Training Scope

The integrated package is designed to familiarize students with the criteria and procedure for the design of electrical installations in buildings. It guides the student to complete the whole design process. By displaying the floor plan and the connected loads, the student can practise on the estimation of maximum demand based on an assumed demand factor or coincidence factor, and the determination of the design current for various circuits including the incoming circuit. The student can also practise on the selection of appropriate types of breakers, current ratings and the category of duty against overcurrent, fault current and electric shock. It is then followed by the choice of conductor material, type of insulation, installation method and the determination of conductor size. Correction factors to cater for circuit grouping, ambient temperature and thermal insulation as well as voltage drop and motor-starting conditions will be included. Various methods to determine the size of protective conductor, and the requirements for individual main incoming circuit including current transformers (CT) for protection and for measurement will be assessed. Knowledge of wiring regulations and the standard code of practice for electrical installation will be inherently acquired through the design process.

## I2. Size of Design

The main menu provides access to the two modules i.e. assess 1 and assess 2. In assess 1, the student is given a hands-on exercise to complete the design of a TT system of a two-level building, which has two shops on each floor. Each shop has a final DB serving a floor area of 15 m x 10 m. The two final DBs on each floor are fed by a main DB, which is then connected to a cable riser. The main switchboard feeds one cable riser, a 55 kW DOL motor, an 80 kW star-delta motor and a DB with an equivalent load of 90 kW. This module allows the student to go through the program once and to familiarise themselves with tools provided in the package as well as the method of design.

In assess 2, the student has to complete a sizeable design of 2 MVA electrical installations with two incoming busbars, one emergency busbar and one stand-by generator. A 3-D view and a typical floor plan of a seven-level flatted factor will be displayed. On each level, there are four tenant DBs, one landlord DB and one emergency DB. As level 1 to level 7 are identical, the student only needs to complete the design for one level and the package will make identical copies for all other six levels. At the end of the design, the student will be prompted to determine breaker type and size for each incoming circuit. The student is required to verify the earth fault protection. At the end of the module, the student's performance is evaluated and given in an overall score summary.

## I3. Visual User Interface

VipTein utilizes all standard Window facilities such as pull down menus, pop-up windows, symbolic icons and various visually interactive dialogue boxes, etc. It is arranged such that all the menus, icons and dialogue boxes are self-documented. At run time, the student may simply click the Hint label to view the relevant formulae or the Legend label for the relevant description. Warning and guiding messages such as cable or breaker under size or oversize will be displayed accordingly whenever the student makes a mistake and all the relevant data such as load description, cable specification, etc will also be listed for the student to make the right selection. For each test, in the first attempt, if the answer given by the student is wrong, the relevant formulae will be given. In the second attempt, if the answer is still wrong, VipTein will show the student's wrong answer together with the correct answer. A well-done message will be always prompted whenever the student enters the right answer. To keep the student informed on the performance and status, the student's current cumulated demerit points and the number of outstanding buses are displayed at the beginning of each section. For short circuit analysis, relevant breaker's tripping curves and cable withstand limit are graphically shown. Tools are provided for the student to have an enlarged view on a DB or an overview of the whole project including riser with tap-off and the incoming transformer connection.

### I4. Assessment Criteria and Grading

The evaluation of a trainee's performance focuses on ten categories, namely circuit breaker selection, design current calculation, cable sizing, short circuit analysis, earth fault analysis, motor starting, voltage drop calculation, load connection and load balance. All errors made by the student are logged and evaluated automatically by demerit points. The instructor may adjust the number of demerit points for each type of error and the conversion from the total demerit points to an appropriate grade.

### I5. Dynamic Instructor Control

VipTein provides built-in features for the instructor to specify a total of 28 tests grouped under 10 categories in a test specification database file. It is also structured according to three main options, namely technical college, polytechnic and university. In each option, the instructor may specify the number and identification of each DB in assess 1 and in assess 2. For each DB, the instructor may specify the desired types of test according to the students' capability. In general, the test file for technical college will be easier and that for university will be more difficult and each could be focused on different categories. To eliminate repetitive calculation, for some tests that involve a number of steps, the instructor can specify a step number in the test and the system will give the relevant answer of the previous step and jump to the specified steps to test a student. In this way, although the type of building is identical, the scope, duration and depth of study can be dynamically adjusted.

## I6. Related Publications

[1] Gooi H. B., Teo C. Y., "A Project-oriented Power Engineering Curriculum", IEEE Transactions on Power Systems, Vol. 10, No. 1, PP 27-33, 1995

[2] Teo C. Y., "A New Integrated Tool for Design Exercise of Electrical Installations Using a Microcomputer " Journal of Electric Power Systems Research, Vol. 36, No. 2, PP 81-90, 1996

[3] Teo C Y , " A More Practical Approach to Integrate Low Voltage Distribution System into the Electrical Engineering Curriculum", IEEE Transactions on Power Systems, Vol. 13, No. 4, pp 1199-1204, 1998

[4] Teo C Y and F. Shen, "Application of Artificial Intelligence in the Design of Low Voltage Electrical System", IEEE Winter Meeting 2000

[5] Teo C Y, "Integrated Assessment of Electrical Systems in Buildings Through Simulation Tests" Magazine of Singapore Engineer, pp 31-36, 2003

[6] Teo Cheng Yu, "Teaching of Power Engineering Through E-learning with Laboratory Automated Assessment", ICEE, International Conference on Engineering and Education, March 2009

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