N2 Electrical Trade Theory

WILFRED FRITZ
DEON KALLIS
VERONICA OOSTHUIZEN

Pearson

Pearson South Africa (Pty) Ltd
4th floor, Auto Atlantic Building,
Corner of Hertzog Boulevard and Heerengracht,
Cape Town, 8001

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Module 4

Switchgear and protective devices

What is covered?

Upon completion of this module, students should be able to demonstrate an understanding of the different types of switchgear, the various types of faults that could occur in electrical systems, the devices used to protect against the harmful effects of these faults, and how these protective devices operate.

Learning outcomes

After studying this module, you should be able to:

Unit 1

- State the purpose of electrical switchgear.
- Name the switchgear used for the following functions:
  - isolating
  - control
  - protection.

Unit 2

- Explain the difference between a disconnector and a switch disconnector.

Unit 3

- Explain the operation and application of the following:
  - relays
  - contactors
  - timers
  - day-night switch.

Unit 4

- State the device used to protect against the harmful effects of the following faults:
  - short-circuits
  - overloads and over-currents
  - earth leakage current
  - high-voltage surges
  - lightning discharges
  - transient faults in overhead lines
  - phase imbalance.
- With the aid of labelled diagrams, explain the operation of the devices used to protect against the faults mentioned above.

Unit 1: Switchgear

LEARNING OUTCOMES

- State the purpose of electrical switchgear.
- Name the switchgear used for the following functions:
  - isolating
  - control
  - protection.

Introduction

This module covers the equipment used for the control and protection of the electrical network. The discussion will concentrate on low-voltage (LV) installations and is guided by SANS 10142.

The light in your room is controlled by a switch. This is a basic electrical device that allows you to control the light. There are many more devices like this that allow us to operate the network safely and efficiently. In this unit, we categorise some of these devices according to their functions.

Purpose of electrical switchgear

Switchgear are used in an electrical power system to control, protect and isolate electrical equipment. Switchgear remove electrical energy from a part of the network for purposes of maintenance (isolation), if there is a need to disconnect a part of the load (control), or if a fault condition appears on the network (protection). Switchgear are found at all levels of the system; from generation and transmission, to the distribution substation, to the distribution board in the end user's premises.

Figure 4.1 Switchgear in a distribution substation

Switchgear for particular functions

Isolating

We use isolating switchgear to isolate a part of the network for maintenance or similar operations. The isolating function can be performed by a number of devices, such as:

- disconnectors
- load switches
- switch disconnectors
- circuit breakers.

Control

Control switchgear are used to monitor and control the electrical power network to ensure that the network stays within its designed limits. Most control devices have remote-control capabilities, as technology allows the integration of communication and traditional switchgear. Common control switchgear include:

- relays
- contactors
- timers
- day-night switches.

Protection

Protective switchgear are used to protect both users and the infrastructure against the effects of fault conditions on the network. The following protection switchgear are commonly used:

- circuit breakers, including miniature circuit breakers (MCB).

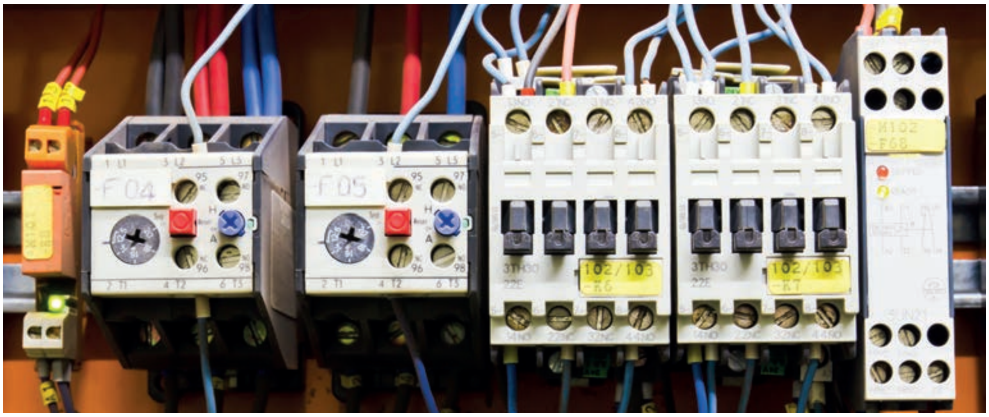


Figure 4.2 A set of single-phase circuit breakers

ACTIVITY 4.1

1. Distinguish between the functions of 'isolating' and 'control'.
2. Where are circuit breakers housed in a home?
3. How many circuit breakers are there in your home?
4. What are the rated currents for each circuit breaker in your home?

Unit 2: Difference between a disconnector and a switch disconnector

LEARNING OUTCOMES

- Explain the difference between a disconnector and a switch disconnector.

Introduction

Disconnectors and switch disconnectors are found in HV, MV and LV electrical networks to isolate sections of the network for maintenance or similar operations.

Disconnectors

A disconnector is a mechanical switching device that:

- for reasons of safety, provides, in the open position, an isolating distance in accordance with specified requirements,
- is capable of opening and closing a circuit either when negligible current is broken or made, or when no significant change in the voltage across the poles of the disconnector occurs, and
- is capable of carrying currents under normal circuit conditions and of carrying, for a specified time, currents under specified abnormal circuit conditions, such as those of short-circuit.[1]

A disconnector is an off-load isolator, since it is not designed to break a circuit under full load, particularly if the load is highly inductive.

Switch disconnectors

A switch disconnector is a switch that, in the open position, satisfies the isolating requirements specified for a disconnector.[2]

A switch disconnector combines the functions of a disconnector (isolation) with that of a load switch. This means that it fulfils the isolating requirements for safe access to the network, while being able to make or break an energised circuit working under normal conditions. It is for this reason that a switch disconnector is also known an on-load isolator.

Difference between a disconnector and a switch disconnector

Both disconnectors and switch disconnectors provide the same function, that is, they both effectively (in compliance with the applicable standard) isolate the source of electrical energy from the load. The difference between the two devices is that disconnectors are not designed to control (switch on or off) a load, particularly if the load is inductive, such as a motor. Therefore, disconnectors cannot be used to control a load. In contrast, switch isolators can be used to control (switch on or off) a load.

[1] 6.25

[2] 6.79.2

If we use a disconnector in a circuit, we have to next connect a switch to control the load. The switch provides the compliant controlling function. If maintenance is required on the circuit, we first use the switch to switch off the load. Next, we use the disconnector to isolate the energy source from the circuit. While it might seem obvious that the switch could be used to isolate the load, the isolating distance between the contacts in the switch will not necessarily be in compliance with the standard. This constitutes a potentially hazardous situation.

ACTIVITY 4.2

1. Give an example of an inductive load.
2. What does 'off-load' mean?
3. What does 'on-load' mean?
4. When will a disconnector be used?
5. Can a disconnector be connected in the neutral line of a load? Explain your answer.
6. If a load motor is energised and running, and if there is a switch disconnector in the circuit, can the switch disconnector be used to de-energise the motor?

Unit 3: Operation and application of relays, contactors, timers, and day-night switches

LEARNING OUTCOMES

- Explain the operation and application of the following:
  - relays
  - contactors
  - timers
  - day-night switches.

Introduction

The devices discussed in this unit fall under the category of LV control switchgear. They provide us with basic control of specified loads to ensure efficiency in network performance.

Operation and application of relays

Function

A relay is an electrically-controlled switch that works on the principle of electromagnetism. It is used when there is the need to control a high-power circuit using an independent low-power control circuit.

Construction

A relay consists of two sections:

- the low-power control circuit comprising an electromagnetic coil, and
- the high-power controlled circuit comprising a sets of contacts.

A basic relay will have a set of contacts to provide normally open or closed connections.

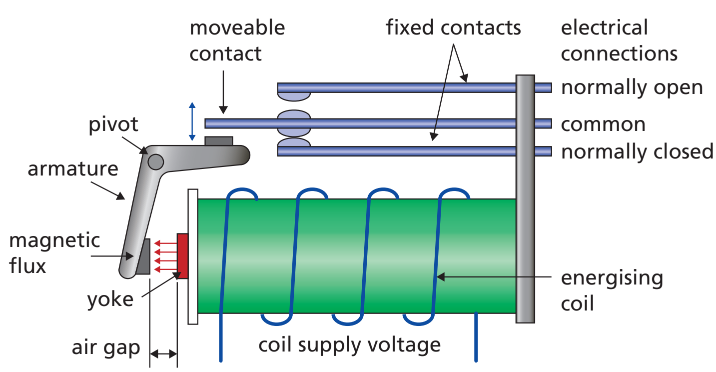


Figure 4.3 Construction of a relay

Figure 4.4 Example of a relay

Operation

In the de-energised state, the common contact is connected to the normally closed contact. When an LV (as specified by the relay type) is applied to the coil, a magnetic field is set up in the core (yoke) that attracts the movable armature. The armature moves the movable contact, thus completing the circuit between the common and normally open contacts.

When the coil voltage is removed, the armature returns to its original position and the movable contact returns to its original position (as the connection between the normally closed and common contact).

Uses

A relay is used when there is a need to control a high-power circuit using a low-power control circuit. Examples include an earth fault trip relay and a starter-motor relay in a vehicle.

Operation and application of contactors

Function

Contactors work on the same principle as a relay, but they are able to control larger high-power currents.

Construction

The basic elements of a contactor are the same as a relay, except for the larger sizes of the components. So, a contactor comprises:

- a control coil (electromagnet)
- a movable armature, and
- a set of fixed and movable contacts.

Contactors are available as single-phase or three-phase units.

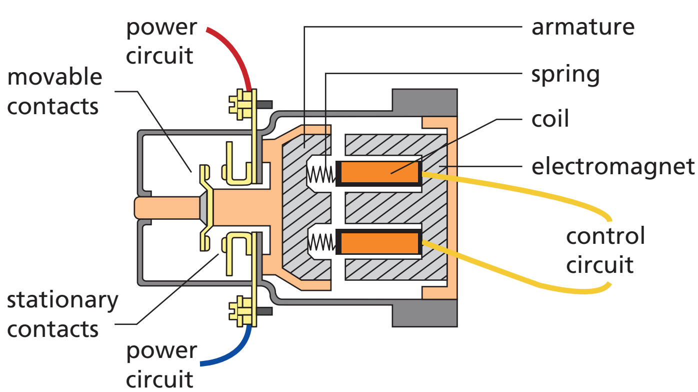


Figure 4.5 Construction of a contactor

Figure 4.6 Example of a contactor

> **NOTE**
> The coil of a relay or contactor generates high back-emf when the coil is switched off. This can damage the controlling circuit and generate electromagnetic interference (EMI). To reduce this risk, we use a flyback diode.
> - DC coil-control signal: we place the flyback diode across the coils.
> - AC coil-control signal: we use varistors (voltage dependent resistor), or snubber networks (series capacitor and resistor).

Operation

In the de-energised state, there is no contact between the movable and stationary contacts. Therefore, the power circuit is an open circuit. When a low-power control voltage is applied to the coil, the armature is attracted toward the electromagnet. This connects the movable contacts to the stationary contacts, providing a closed switch to the power circuit.

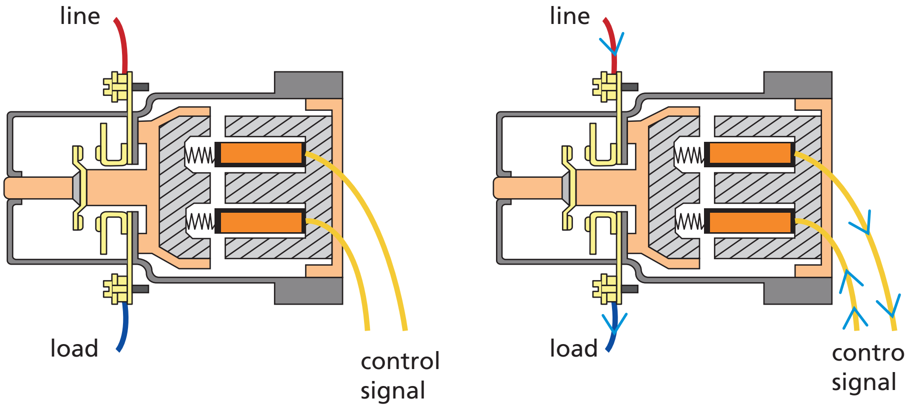


Figure 4.7 Contactors in (a) energised and (b) de-energised states

Uses

We use a contactor when there is the need to control high currents (high power) loads using a lower power control circuit. Examples include: high-power electric motors and high-power lighting (in stadiums and street lighting).

Operation and application of timers

Function

As the name suggests, a timer is an electrically-operated switch that allows for the on-off control of a load, based on the time of day (and day of the month in modern digital time switches).

Figure 4.8 A time switch

Construction

Time switches are based on either mechanical or digital timing control.

In the mechanical time switch, a small electric motor is used to drive a circular clock mechanism. The user sets the on/off times, using slideable tabs that are situated on the perimeter of the clock mechanism. The resolution (shortest on/off time) of these units is typically 30 minutes and the cycle typically repeats every 24 hours.

More advanced time switches have smaller time resolutions and allow for programmable periods of seven days. Digital timers provide even more programming options.

Operation

A mechanical tab, set by the user, closes and opens a small switch, which in turn operates a relay, thus allowing the load to be controlled. The size of the relay determines the size of the load that can be controlled directly from the timer.

Uses

Examples of places where timers are used, include pool pumps and geysers.

Operation and application of day-night switches

Function

A day-night switch allows the on/off control of an electrical load, based on whether it is day or night.

Construction

A day-night switch is constructed using a light sensor (light-dependent resistor, photo-transistor, etc.), an electronic control circuit and a relay. These are all housed in a waterproof enclosure that can be mounted outdoors.

Figure 4.9 A day-night switch

Operation

During daylight, the sensor detects the presence of solar radiation and the control circuit keeps the contacts of the relay open, so that no current flows through the load (load off).

In darkness, the sensor detects the absence of solar radiation and the control circuit closes the relay contacts, thus switching the load on.

Uses

Examples of places where day-night switches are used, include lighting, security systems and night-time irrigation systems.

ACTIVITY 4.3

1. What are the main differences between a relay and a contactor?
2. Draw a circuit, showing how a relay can be used to switch on a light.
3. Give an application for the use of a three-phase contactor.
4. Give an application for the use of a timer.
5. Explain the basic operation of a day-night switch.

Unit 4: Protective devices

LEARNING OUTCOMES

- State the device used to protect against the harmful effects of the following faults:
  - short-circuits
  - overloads and over-currents
  - earth leakage current
  - high-voltage surges
  - lightning discharges
  - transient faults in overhead lines
  - phase imbalance.
- With the aid of labelled diagrams, explain the operation of the devices used to protect against the faults mentioned above.

Introduction

An important function of switchgear is to protect humans, animals and buildings, as well as the electrical infrastructure itself, from the effects of fault conditions.

Devices used to protect against the effects of faults

Table 4.1 shows the various protective devices used in electrical networks, as well as the faults they protect against.

Table 4.1 Electrical faults and protective devices

Protective device	Electrical fault it protects against
Circuit breakers	Short-circuits
Circuit breakers and overload relays	Overloads and over-currents
Earth leakage unit[3]	Earth leakage current
Surge protection devices (SPDs)[4]	High-voltage surge
Lightning rods and surge protection devices (SPDs)	Lightning discharges
Valve arrestors for voltage surges due to transient faults on overhead lines	Transient faults in overhead lines
Three-phase circuit breakers and phase monitor relay (also known as a phase failure relay)	Phase imbalance

3 3.31

4 6.7.6.1

In sections that follow, we will discuss various faults and aspects of the construction and operation of protective devices.

Short-circuits

A short-circuit current is the overcurrent that results from a fault of negligible **impedance** in a circuit.[5]

A circuit breaker is a mechanical switching device that is capable of making, carrying and breaking currents under normal circuit conditions and of making, carrying for a specified time, and automatically breaking currents under specified abnormal circuit conditions, such as those of overcurrent.[6]

Circuit breakers come in various physical forms, depending on the magnitude of the currents. The miniature circuit breaker (MCB) is commonly found in LV domestic and office-building environments. It is housed within the distribution board of the facility and is typically rated up to 125 A.

Keyword

impedance the effective resistance of an electric circuit or component to AC (alternating current)

Thermal magnetic circuit breakers

The internal construction of a thermal magnetic MCB is shown in Figure 4.10. Two independent triggering mechanisms are used: a bimetal strip for overload conditions, and a magnetic coil for short circuit conditions.

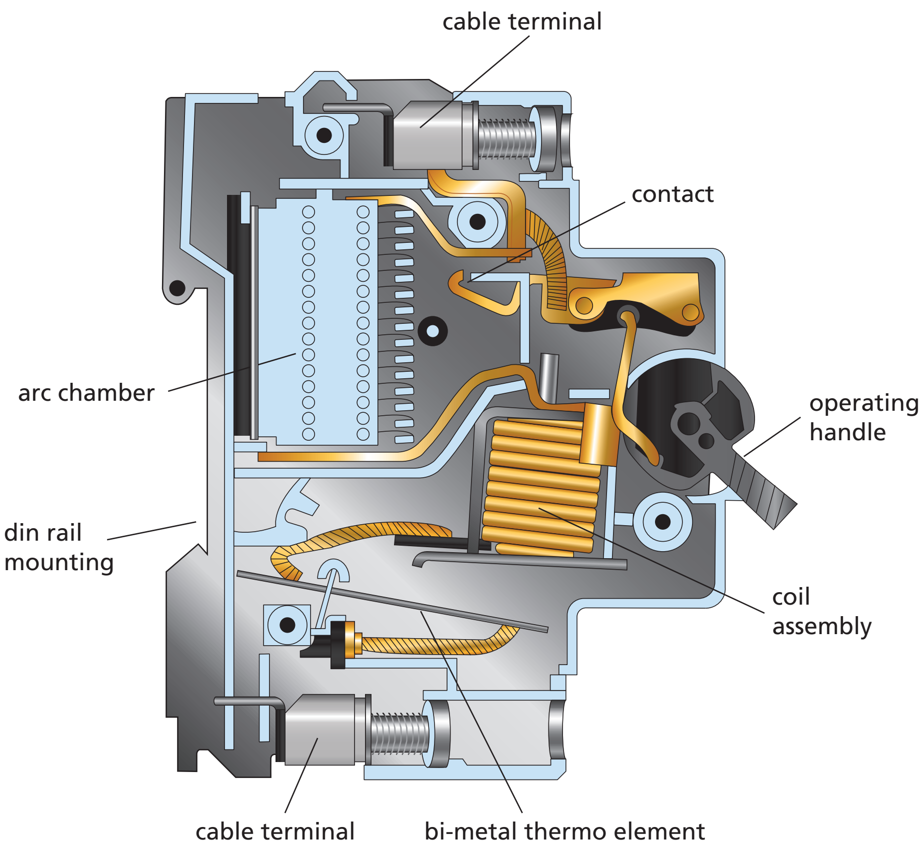


Figure 4.10 Construction of a thermal magnetic circuit breaker

5 3.22.9
6 3.13

Operation

During an overload condition, when the current is higher than the rated value of the circuit breaker, heat is generated in the bimetal strip. This causes the strip to bend and trip the circuit breaker, opening the contacts.

During a short circuit, the sudden and large current generates a magnetic field of sufficient strength in the coil, so that it attracts a movable armature to enable the tripping of the contacts. During overload or short-circuit conditions, the opening of the contacts during tripping creates an arc across the contacts. To prevent damage to the contacts, the arc is guided to the arc chamber, where it is extinguished.

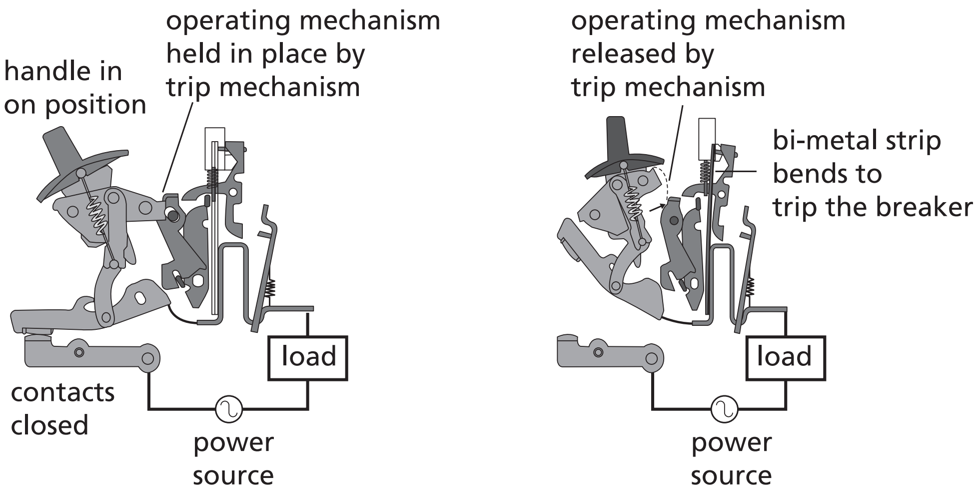


Figure 4.11 The trip operation of a circuit breaker

Inverse time delay

Since the heat generated in the bimetal strip is dependent on the magnitude of the current, the time taken to trip the circuit breaker is inversely related to the magnitude of the current – the larger the current, the shorter the time taken to trip the breaker. This inverse relationship for a typical type-B MCB is shown in Figure 4.12.

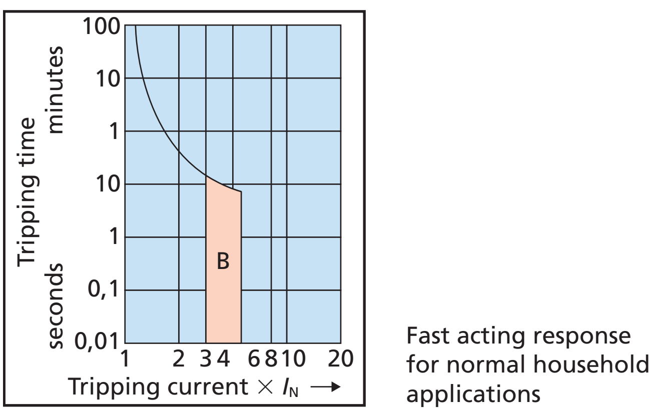


Figure 4.12 Time vs tripping current of a type B circuit breaker

Magnetic-type circuit breakers

In a magnetic-type circuit breaker, the bimetal strip is replaced with a hydraulic-based **damper**. This damper operates in a way similar to that of a shock absorber in vehicles. In Figure 4.13 the damper is shown as an oil-filled tube, containing an iron core and a spring.

Keyword

damper a mechanism to lessen the impact of the armature

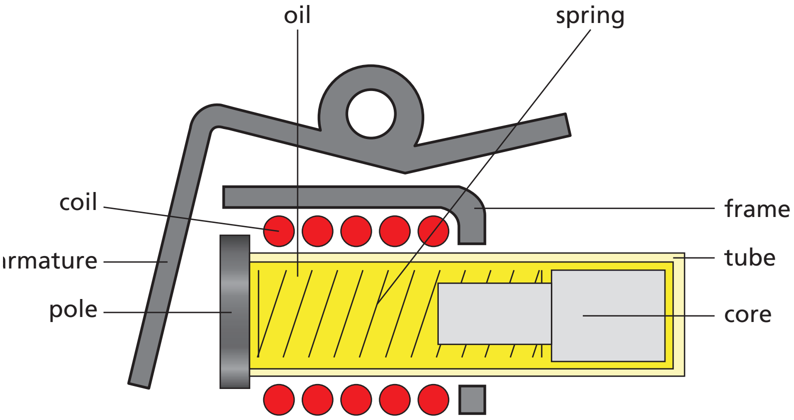


Figure 4.13 Simplified construction of a magnetic-type circuit breaker

Operation

During overload conditions, the magnetic flux generated by the coil attracts the core toward the pole. Once the core reaches the pole, the movable armature is attracted toward the pole and trips the contact mechanism. During short-circuit conditions, the high current generates sufficient magnetic flux to attract the movable armature toward the pole, thereby activating the tripping mechanism.

Required markings

Every MCB must have the following markings on the front:

- Rated current (I_n) in ampere, for example, 20 A
- Suitability for isolation by way of the symbol: —/ ⊢✕
- Indication of the open and closed positions with the symbols I and O.
- Manufacturer's name or trademark.

Overloads and over-currents

We use circuit breakers (see previous section) and overload relays to protect against overloads and over-currents.

Overload relay

We use an overload relay to protect a motor against overloading. Thermal-based (bimetal strip) relays are commonly used for this purpose.

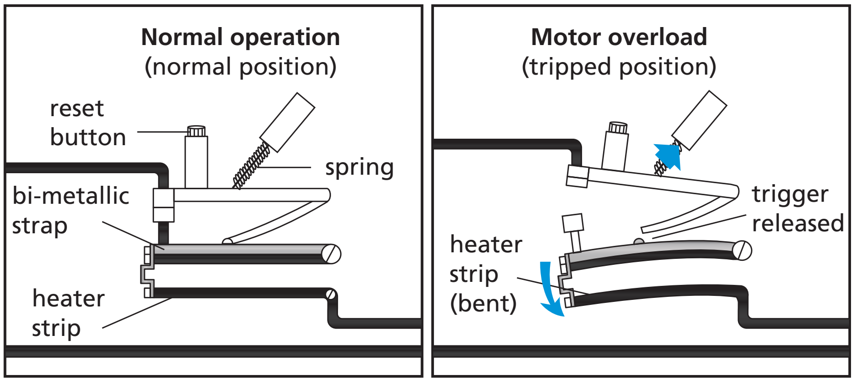


Figure 4.14 The operation of an overload relay

Operation

Under overload conditions, the bimetal strip is heated (due to the high current) and bends. This activates the trigger release system and opens the contacts. The reset control allows the relay to be placed in the normal condition after the fault has been cleared.

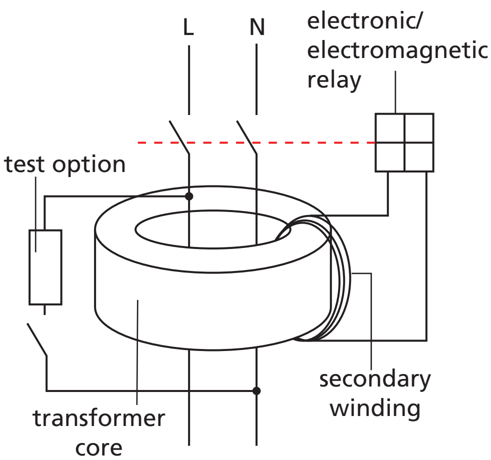


Figure 4.15 An earth leakage unit for a single-phase circuit

Earth leakage current

An earth fault current is a fault current that flows to earth.[7] An earth leakage unit[8] is a device that is used to detect and interrupt (disconnect) the supply, if the earth fault currents exceed a predetermined amount. All installations are required to have an earth leakage protection device.[9]

Figure 4.15 shows a schematic representation of the residual current-type circuit breaker for a single-phase circuit.

- Both live and neutral lines are passed through a transformer core (3), and constitute the primary of a differential current transformer (CT).
- Under normal conditions, the currents in the two conductors are equal in magnitude, but opposite in direction, and the resultant magnetic field in the core will be zero.
- The secondary winding will have no voltage induced in it.
- If an earth fault were to take place, the current in the two conductors would be unequal, resulting in a net magnetic field in the core and a current will be induced in the secondary winding circuit.
- An electronic/electromechanical relay will sense this current and disconnect the contacts, thereby interrupting the supply.
- A test option is provided by connecting a resistor between the lines, creating an imbalance in the core, thereby activating the device.
- A three-phase residual current circuit breaker works on exactly the same principle, except that all three lines and the neutral are connected through the core.

[7] 3.22.2
[8] 3.31
[9] 6.7.5.1

Earth leakage units are designed to disconnect (trip) at a pre-set current. For domestic and personal protection, this level must not exceed 30 mA.

HV surges

Surge protection devices (SPDs)[10] or transient voltage surge suppressors are connected to the installation to protect the infrastructure and equipment from the effects of voltage surges due to lightning, high-power switching or fault conditions. The HV present on the line is shunted to the ground and this function is often performed by a varistor. This is a component with resistance that is dependent on the applied voltage. Under normal conditions, the resistance of the component is high. If the voltage exceeds a certain level, the resistance reduces and the device starts to conduct electricity.

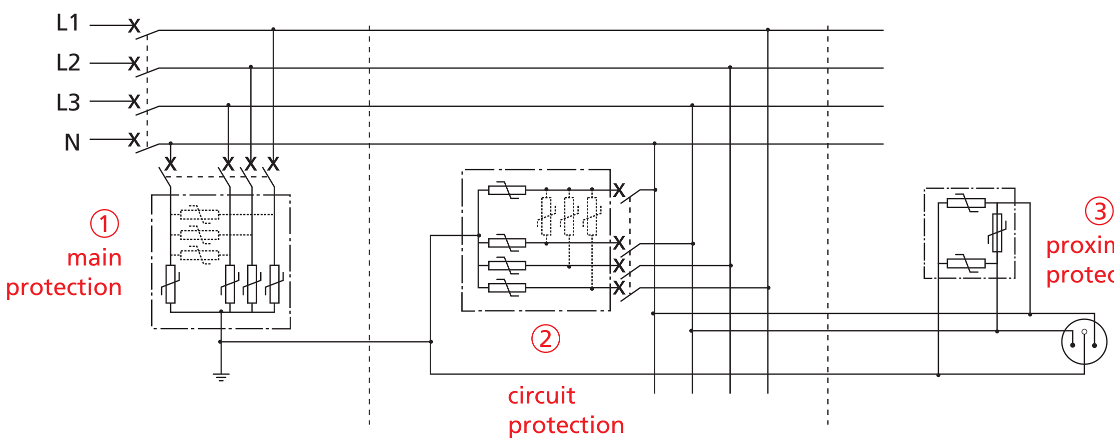


Figure 4.16 Installation diagram for SPDs

As can be seen in Figure 4.16 above, the typical installation of SPDs involves a combination of main protection at the point of supply connection, circuit protection at the distribution board and proximity protection at the appliance.

Lightning discharges

In areas of high lightning activity, the first level of protection involves conducting the lightning bolt to the ground through the use of a solid copper lightning rod (tapered at the top), or other conductive components made from copper, connected to a solid copper ground rod. To enhance the grounding of the rod where soil conductivity is poor, or where a rod cannot be driven into the ground, ground enhancement material (GEM) can be used.

In addition to lightning rods, combined surge protection devices (see Figure 4.17) are also used to protect against the residual effects of a lightning strike.

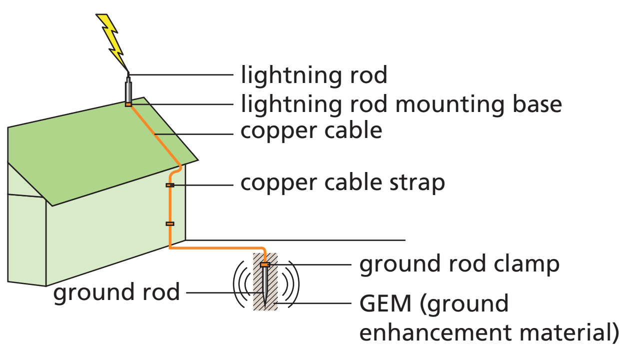


Figure 4.17 Lightning protection for a building

10 6.7.6.1

Transient faults in overhead lines

A transient fault is a fault that is no longer present if power is disconnected for a short time and then restored. This could be as a result of the momentary touching of the conductors, a lightning strike, or bird, animal, or tree contact. The fault does not remain once power is restored.

If a lightning strike causes an HV, a flashover can occur at vulnerable parts of the network. A valve lightning arrester is commonly used to safely conduct the HV before it reaches other parts of the network.

A valve lightning arrester consists of multiple spark gaps connected in series with lower resistance non-linear resistors. High resistance non-linear resistors are placed in parallel across the air gaps. The entire assembly is housed in a sealed porcelain structure and filled with nitrogen gas or sulphur hexafluoride (SF6) gas.

Under normal conditions, the arrester acts as an insulator. When a large voltage occurs across the arrester, current flows in the spark across the air gaps and through the non-linear resistors and down to ground. The arrester returns to normal insulative form, once normal conditions are restored.

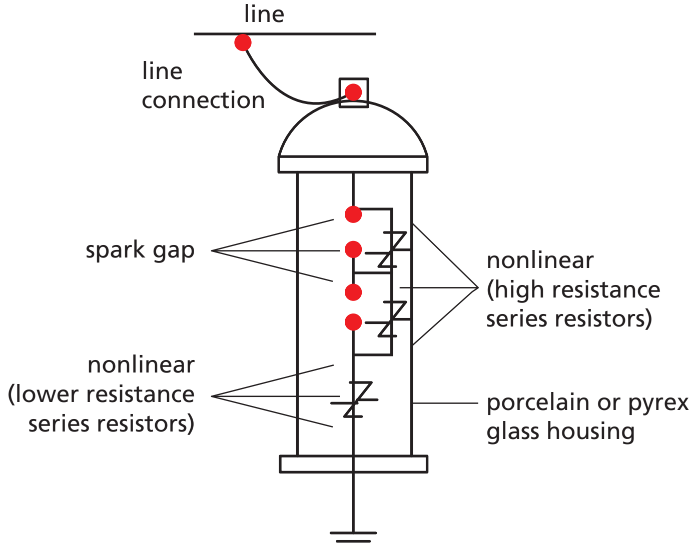


Figure 4.18 An example of a valve lightning arrester

Phase imbalance

Phase imbalance occurs in three-phase systems when there is a loss of one or two of the lines, or if an incorrect single-phase balance installation is made. "In a multiphase installation, the circuits shall be so arranged that the total load is, as nearly as is practicable, balanced between the phases of the supply."[11]

In the case of a three-phase electric motor, if one of the phases were to go open, the motor would still continue to run and deliver its full output power. This condition is known as 'single-phasing' and will lead to damage of the motor. "The overcurrent protective device shall prevent a multiphase motor from continuing to operate under load if single phasing occurs."[12]

Three-phase circuit breakers have coupled contacts, so that if a fault occurs on one line, all three phases are broken.

[11] 6.1.1

[12] 6.16.5.1.3(c)

Operation

A three-phase circuit breaker works on the same principle as a single-phase circuit breaker, except that it has three poles, instead of one as in a single-phase circuit breaker.

Dedicated devices, such as phase monitor relays (also known as phase failure relays), are used to detect and break the supply, should phase abnormalities occur. The principle of operation is based on measuring the current on each line, using a current transformer and comparing them to each other. Any differences in line currents beyond the specified limits are used to trip a relay and break the supply.

ACTIVITY 4.4

1. Draw a neat, labelled diagram, showing the internal construction of a thermal magnetic circuit breaker.
2. Why is there an inverse time delay on a thermal magnetic circuit breaker?
3. What benefit is gained by having an inverse time delay on a circuit breaker?
4. Describe, using a diagram, the operation of a magnetic circuit breaker.
5. What does the test function of an earth leakage unit do?
6. What is the maximum earth fault current that trips an earth leakage unit?
7. Describe the operation of an earth leakage unit.
8. Draw a typical valve arrester.
9. What is single phasing and how can it be avoided?
10. Define the term 'short circuit current'.

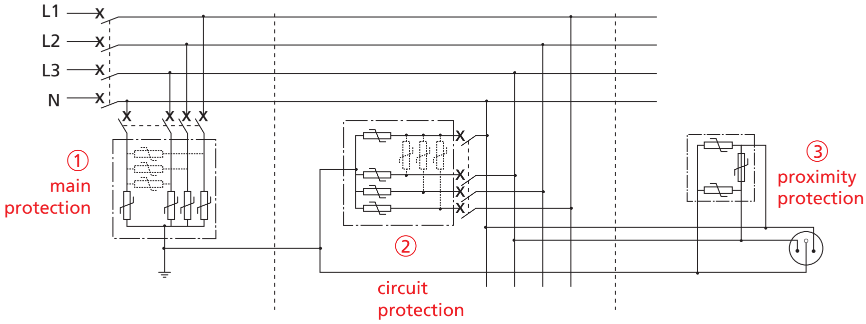
Module summary

- Switchgear are used to remove electrical energy from a part of an electrical network for maintenance (isolate), or if a fault appears on the network (protect), or if we want to disconnect part of the load (control).
  - Isolate: disconnectors, load switches, switch disconnectors, circuit breakers.
  - Control: relays, contactors.
  - Protect: circuit breakers.
- A disconnector is not designed to control (switch on or off) a load, but a switch isolators can be used to control a load.
- We use a relay when we want to control a high-power circuit using an independent low-power control circuit, for example, an earth fault trip relay and a starter-motor relay in a vehicle. A relay comprises a low-power control circuit (electromagnetic coil) and a high-power controlled circuit (a set of contacts).
- Contactors can control larger currents than relays. A contactor comprises a control coil (electromagnet), a movable armature and a set of fixed and movable contacts. Examples: high-power electric motors and high-power lighting (stadiums and street lighting).
- Timers are electrically-operated switches we use for on-off control of a load, based on a specific time, for example, pool pumps and geysers. Mechanical or digital time control.
- Day-night switches allow the on/off control of an electrical load, based on whether it is day or night, for example, lighting and night-time irrigation systems. Comprises a light sensor, an electronic control circuit and a relay, housed in a waterproof enclosure.
- Circuit breakers (magnetic circuit, thermal magnetic) protect against short circuits. In thermal magnetic circuit breakers, the higher the current, the quicker the breaker trips.
- We use circuit breakers and overload relays to protect against overloads and over-currents.
- An earth leakage unit detects and disconnects the supply if the earth fault current (a fault current that flows to earth) is larger than a specific amount. All installations are required to have an ELU.
- Surge protection devices (SPD) protects electrical equipment from the harmful effects of voltage surges, because the high voltage is shunted to the ground by means of a varistor.
- In areas where there is high lightning activity, a solid copper rod is used to conduct the lightning bolt via a solid copper ground rod, into the ground.
- A transient fault is a fault that disappears, once the supply is interrupted and then continued again. Transient faults occur when, for example, conductors touch for a short time, or lightning strikes. Lightning: a valve lightning arrester is used to conduct high voltage before it reaches other parts of the network. Conductors touching:
- Phase imbalance occurs in three-phase systems when there is a loss of one or two of the lines, or if an incorrect single-phase balance installation is made. Three-phase circuit breakers have coupled contacts, so that if a fault occurs on one line, all three phases are broken.

Exam practice questions

1. State the purpose of a circuit breaker. (2)
2. Indicate where, in an electrical circuit, a disconnect switch must be connected. (1)
3. Identify the electrical components below: (3)

a)



b)

c)

4. An MCB of the domestic type operates faster when subjected to an overload current of 400%, as compared to an overload current of 200%. Explain how this difference in operating speed is achieved in the following:
   a) Thermal magnetic MCB (3)
   b) Magnetic MCB. (3)
5. Compare disconnectors, relays and contactors using the following headings and present your answer in a table:
   a) Construction (3)
   b) Uses (3)
6. Explain what happens within a thermal magnetic circuit breaker under the following conditions:
   a) Operation on overload (2)
   b) Operation on short circuit (2)
7. Explain the purpose of a relay. (2)
8. Name two methods to minimise damage caused by arcing in circuit breakers. (2)

9. Compare disconnectors and circuit breakers in a table using the following headings:
   a) Function (2)
   b) Operation (2)
10. Explain how single-phasing is prevented when a three-phase circuit breaker trips. (2)
11. A circuit breaker has an 'inverse time delay'. Explain this terminology. (2)
12. When a breaker begins to open, the current could still flow as a result of arcing. Name three measures manufacturers use to minimise the destructive power of the arc. (3)
13. State how the geyser sub-circuit is identified on the distribution board. (2)
14. State which visual indication informs you that a miniature circuit breaker (MCB) has tripped. (2)
15. Explain why MCBs are factory-sealed. (2)
16. List two electric devices that use a relatively small current to switch on a circuit that has a relatively larger current. (2)
17. Explain the operation of the thermal magnetic-type circuit breaker. (4)
18. Indicate whether the following statements are true or false. Write 'true' or 'false' next to the question number. Correct the statement if it is false. (6)
   a) A disconnector differs from a switch-disconnector because the disconnector cannot carry the on-load current.
   b) Switch-disconnectors are designed to open a highly inductive load at full voltage.
   c) A switch-disconnector must be connected to the neutral point of the supply.
   d) Overload current is defined as the current that flows when a short circuit occurs.
   e) An abnormally low ambient temperature will delay the tripping of thermal magnetic circuit breakers on overload.
   f) A circuit breaker may be used as a disconnector, provided it complies with the standards of the relevant disconnectors.
19. Explain the operation of a relay. (3)
20. State the difference between relays and contactors. (2)
21. State what component of a relay is connected to the relay control circuit. (1)
22. State the purpose of an earth leakage protection device. (2)
23. Explain 'surge protection'. (2)

Total marks: 65