Higher Colleges of Technology

System Protection and Coordination

ELE 4353

CLO # 1: Explain the basics of power system protection and associated equipment

- Explain the objectives of system protection
- Explain the role of CTs and VTs in protection applications
- List relays types and explain their use with CTs and VTs in protection schemes
- List types of CBs and explain factors affecting the breaker selection and ratings
- List fuse types used in protection schemes.

Instructor: Dr. Haris M. Khalid

CLO # 1 Basics of Power System Protection SO # 1.1

1- Introduction

Power system protection is a branch of electrical power engineering that deals with the protection of electrical power systems from faults through the isolation of faulted parts from the rest of the electrical network. The objective of a protection scheme is to keep the power system stable by isolating only the components that are under fault, whilst leaving as much of the network as possible still in operation.

This chapter presents methods for the study of fault protection of radial lines and is generally applicable to radial distribution feeders and radial transmission lines. Radial lines provide an appropriate introduction to fault protection since there is only one source of supply in a radial system. This permits one to become familiar with the characteristics and applications of protective equipment without the distraction and added complexity of loop or network system configurations. The coordination of fault protection equipment in a radial system is interesting and useful study, it provides a good basis for the study of more complex problems.

2- Various Types of Protection

The various types of protections used in the feeders are:

a- Overcurrent protection

Overcurrent protection is protection against excessive currents or current beyond the acceptable current rating of equipment. Short circuit is a type of overcurrent. Magnetic circuit breakers, fuses and overcurrent relays are commonly used to provide overcurrent protection (topic covered in CLO3).

b- Differential protection

Differential protection is a unit-type protection for a specified zone or piece of equipment. It is based on the fact that it is only in the case of faults internal to the zone that the differential current (difference between input and output currents) will be high (topic covered in CLO4).

c- Distance protection

In a distance relay, a voltage and a current are balanced against each other and the relay responds to the ratio of the voltage to the current, which is the impedance of the transmission line from the relay location to the point of interest. The impedance may be used to measure distance along a transmission line, hence the name distance relay (not covered here)

d- Pilot relaying protection.

Pilot relaying refers to the communication network implemented on the high voltage transmission line to transmit “trip or don’t trip” signal to and from between two or more substations. Signal can be sent through the power line, telephone lines, fiber-optic cable or from microwave tower (not covered here)

3- Selective Coordination of Protective Devices

Today, more than ever, one of the most important parts of any installation – whether it is an office building, an industrial plant, a theater, a high rise apartment or a hospital - is the electrical system. Nothing will stop all activity, paralyze production, inconvenience and disconcert people and possibility cause a panic more effectively than a major power failure.A proper coordination between relays must be established as shown in Figure 1.1.

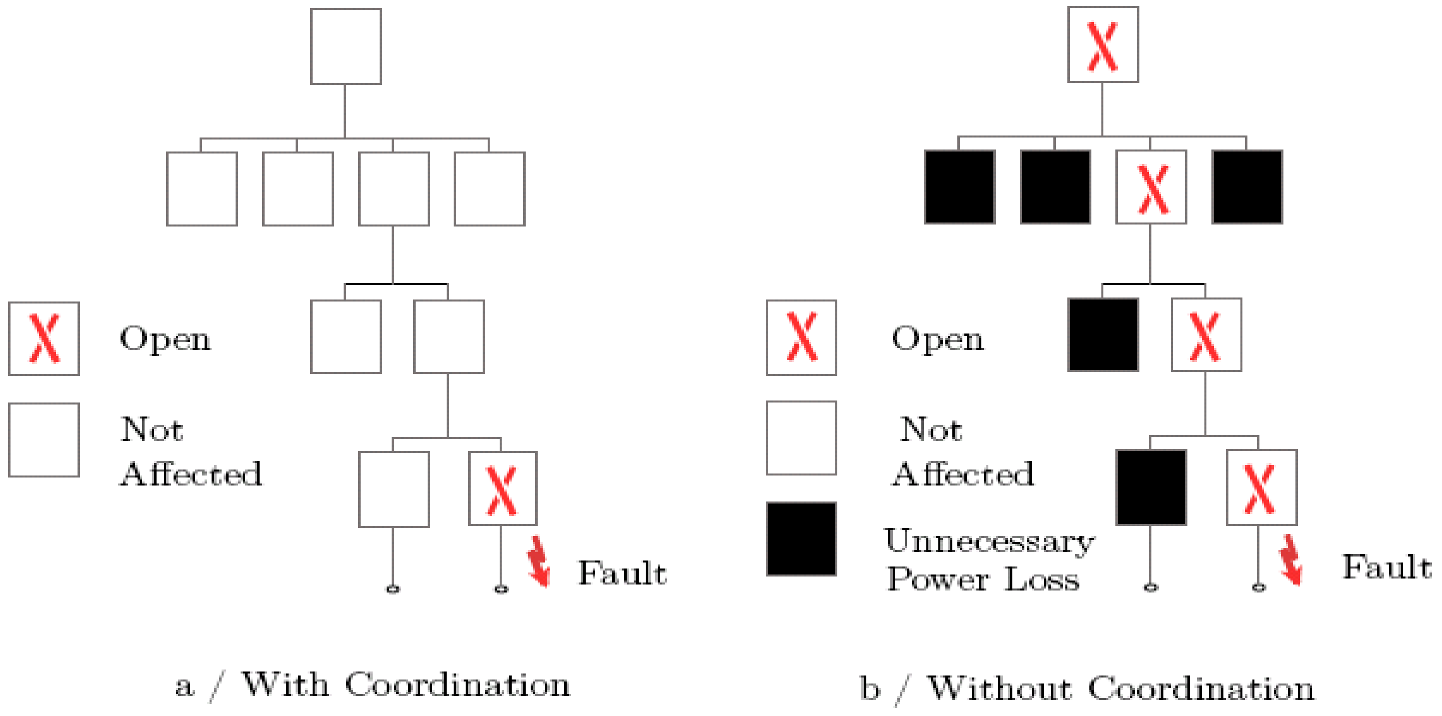

Figure 1.1: Concept of selective coordination

4- Overcurrents (OC)

During the fault, an overcurrent OC is flowing through the line as shown in Figure 1.2. Overcurrents O/C exist when the normal load for a circuit is exceeded. It can either be an:

- An overload O/L condition: any current flowing within the circuit path that is higher than the circuit's normal full load current FLC. It can be 2 to 5 times the magnitude of a circuit's normal operating current.

- An earth fault E/F or short circuit S/C condition as shown in Figure 1.3. A short circuit S/C is an overcurrent condition that leaves the normal current path and which greatly exceeds the normal full load current of the circuit by a factor of tens, hundreds, or thousands. Components and equipment can be damaged by these types of overcurrents.

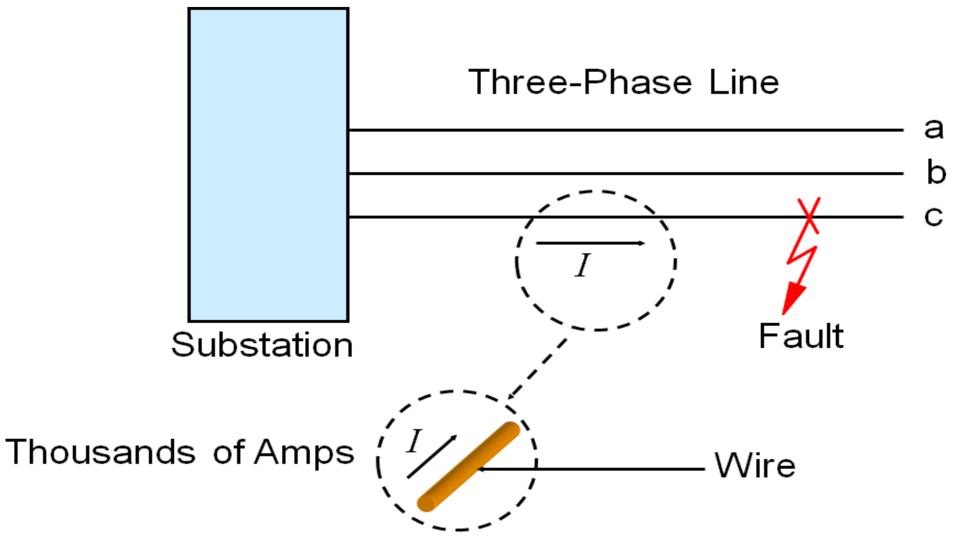

Figure 1.2: Short circuits produce high current

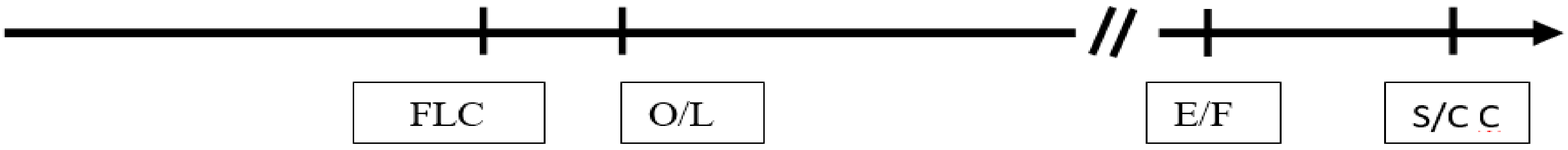

Figure 1.3: Types of over-currents

5- Effects of Short-Circuits

- Thermal; explosion. Heat energy $\propto I^2t$. Excessive heat will soften and melt conductors, melt and ignite insulation, cause overhead conductors to fall down, cause fires, suddenly heat gases and cause explosion

- Mechanical. Forces $\propto I^2$. Excessive forces result in physical damage to equipment see Figure 1.4. High forces can cause rupture of transformers see Figure 1.5., mechanical failure of busbars, etc.

- Safety – Burns, electrocution. Heat from arcs and fires can maim or kill people, excess fault currents can cause local potential rise in the earth and risk of electrocution. See Figure 1.5.

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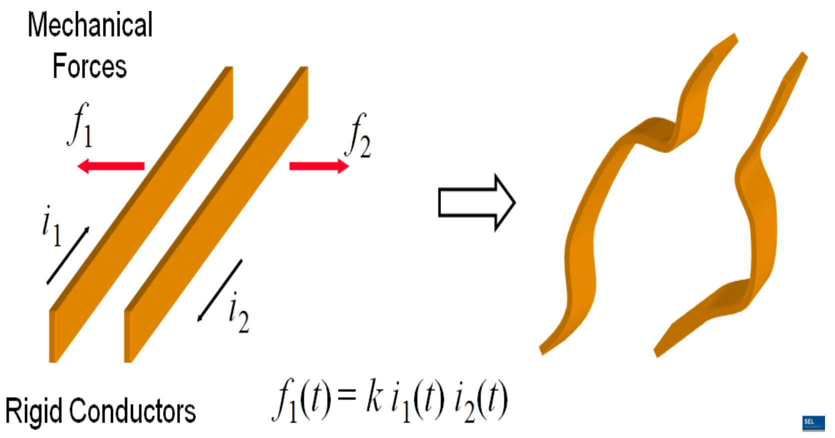


Figure 1.4: Mechanical force exerted on a rigid conductor due high current

Figure 1.5: Damage caused by abnormal conditions

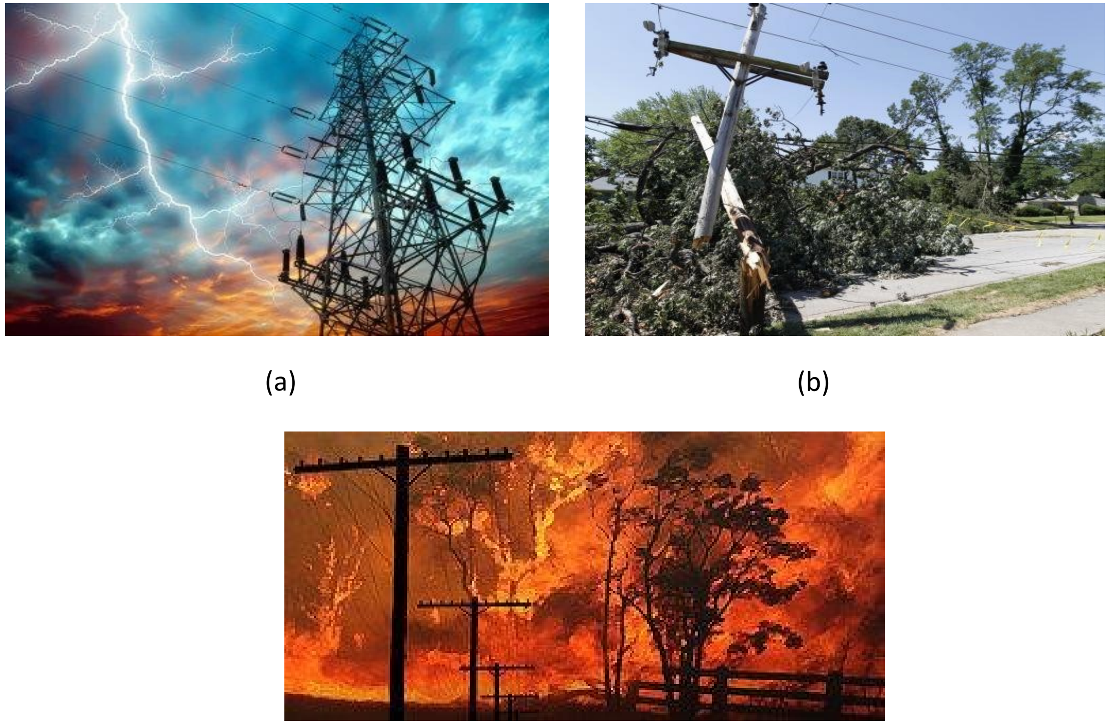
6- The Nature and Causes of Power System Faults

- Failures may occur in each part, such as insulation failure, fallen or broken transmission lines, incorrect operation of circuit breakers, short circuits and open circuits.

- Lightning is one of the major causes of faults on overhead transmissions lines Fig (1.6, a): The insulators on transmission towers are designed to withstand about twice the rated voltage, the lightning strike can momentarily increase the voltage to much higher level.

- Storm damage and other mechanical damage: Severe wind, rain or snow conditions, blown debris, fallen trees, etc see Fig (1.6, b).

- Bush fire: flash over on transmission lines due to the effects of bush fire Fig (1.6, c): sometimes power lines can cause bush fires, so which was the cause and which was the effect?



(c)

Figure 1.6: Electric Power System Exposure to External Agents

8- Power System Protection Design

Severe damage and/or public safety risk (e.g. dangerous voltages, fires, explosions) can result to a power system if a fault remains undetected and uncorrected.

The protection system in all sections of a network must be able to:

- Identify which element of the network is faulty, must only isolate the faulted equipment; leave as much of the healthy system connected **(Selectivity).**

- Be highly reliable, work every time, good design and maintenance (**Reliability).**
- Detect faults, not open a healthy system e.g. operate on the minimum current possible (**Sensitivity)**
- Remain operating under normal transient overload conditions e.g. transformer inrush current (**Stability)**
- Operate as quickly as possible. Remove the faulted element as quickly as is necessary to protect the integrity of the system (**Speed).**

The system once disconnected, must remain disconnected until manual inspection reveals the cause of the fault and its severity and necessary repairs are undertaken.

10- System Protection and Personal Safety

- Power system protection schemes will not prevent electrocution or burns due to inadvertent contact between persons and live wires. System insulation, earthing design and physical barriers will do this.
- O/L and S/C are two separate functions – may need separate devices to adequately address both needs. A S/C is a fault – an O/L is not a fault, rather excess current being drawn
- Power system protection schemes are for short-circuits in the network conductors and plant – do not provide O/L protection for the customers' equipment.
- Note that an open circuit are faulty conditions – may not cause thermal damage to system, but cause problems for customers' equipment. Loss of one phase causes voltage out of balance which can damage motors and generators
- Some overloads are transient and quite normal – e.g. starting current for induction motors, magnetizing inrush for transformers.

- Direct Over Load Current (DOL) starting current for induction motors equals 5 to 6 times normal full-load current, for up to 15 seconds
- Magnetizing inrush for transformers up to 12 × normal FL current for 0.01 second 6 × FL current for 0.1 second.

11- Power System Protection Components

Protection systems usually comprise five components as shown in Figure 1.7:

- Current and voltage transformers VT and CT to step down the high voltages and currents of the electrical power system to convenient levels for the relays to deal with
- Protective relays to sense the fault and initiate a trip, or disconnection. Fuses are capable of both sensing and disconnecting faults.
- Circuit breakers to open/close the system based on relay and auto-recloser commands;
- Batteries to provide power in case of power disconnection in the system.
- Communication channels to allow analysis of current and voltage at remote terminals of a line and to allow remote tripping of equipment.

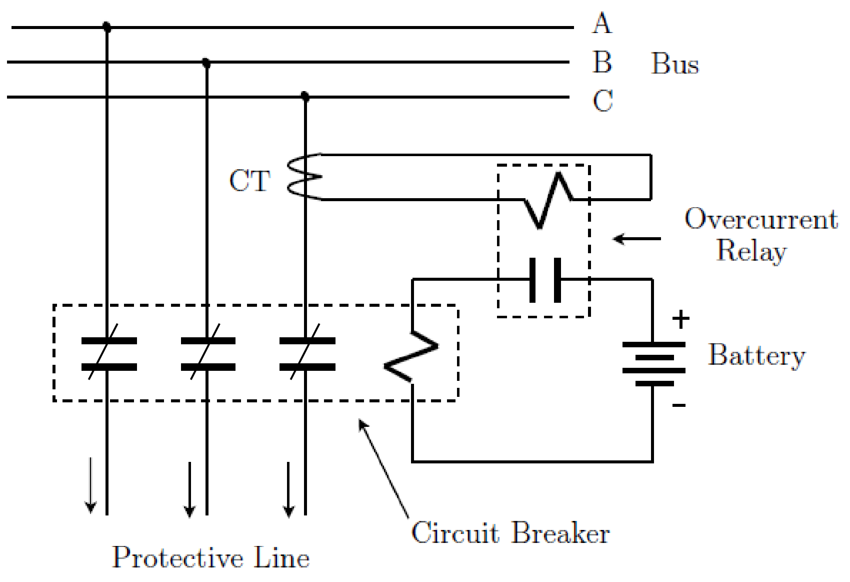


Figure 1.7: CT – O/C Relay – CB Connection

Note: Protective line called also feeder means a connecting link between two circuits. Feeder can be in the form of overhead transmission lines or cables.

12: Protection System Devices

Very High Voltage CT

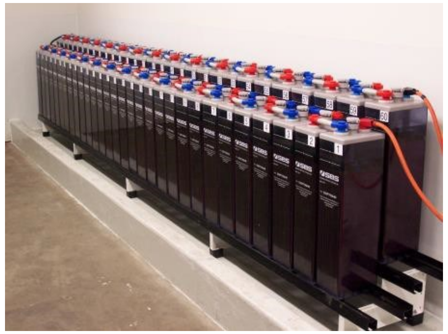
Overcurrent Relay

Circuit Breaker

Cutout Fuse

High Voltage VT

Protective Relays in Substation



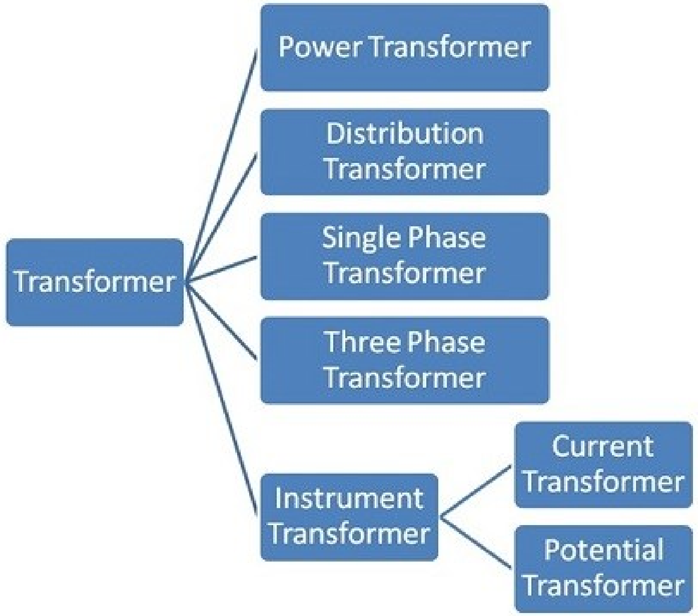
DC Supply System in Substation

HRC Fuse

1- Types of Transformer

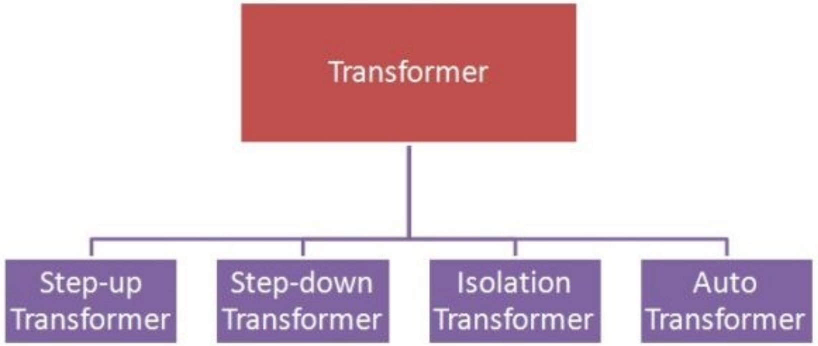
On the basis of **application**, it can be divided into five types:

- Power Transformer
- Distribution Transformer
- Single Phase Transformer
- Three Phase Transformer
- Instrument Transformer



On the basis of **winding** design, there are four types of transformer:

- Step-up Transformer
- Step-down transformer
- Isolation Transformer
- Auto Transformer



2- Introduction to Instrument Transformers

Basic function of **Instrument transformers** is to step down the AC System voltage and current. The voltage and current level of power system is very high. It is very difficult and costly to design the measuring instruments for measurement of such high level voltage and current. Generally measuring instruments are designed for 5 A and 110 V.

Current transformers (CT) and voltage transformers or potential transformers (VT or PT) provide the necessary currents and voltages for:

- **Control:** Activate relays to initiate the alarms, to record faults, to monitor plant system, to control load.
- **Protection :** Activate relays to interrupt the faulty circuit within preset time.
- **Measurement:** Activate relays to measure electrical quantities i.e. voltage, current, power, energy, power factor, frequency.

2- Types of Instrument Transformers

Instrument transformers are of two types, Fig. 1.1:

- Current Transformer (C.T.)
- Potential Transformer (P.T.)

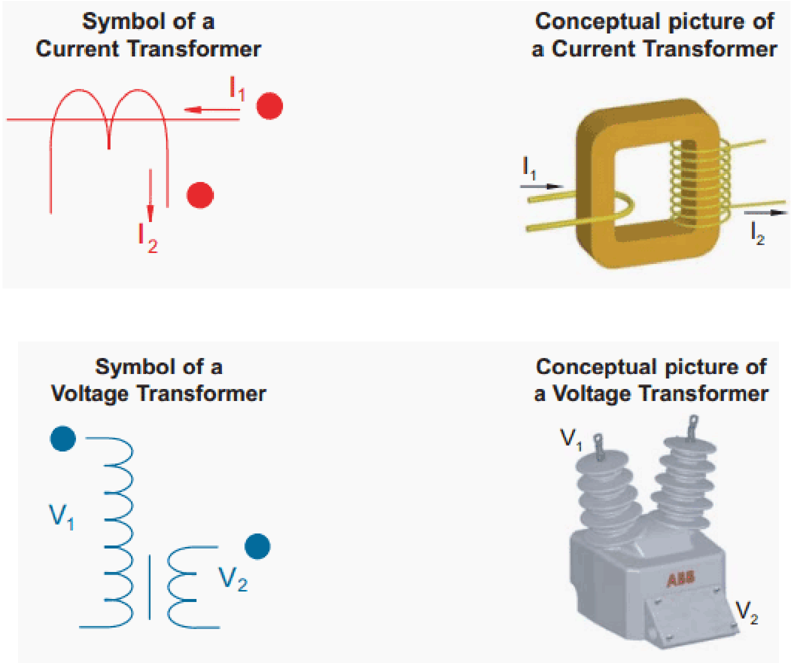


Figure 1.1: CT and PT Symbols, Simplified Concepts

3- Types of Current Transformers

The current transformer has three types, Fig. 1.2:

- Window, ring or bushing type
- Bar type
- Wound type

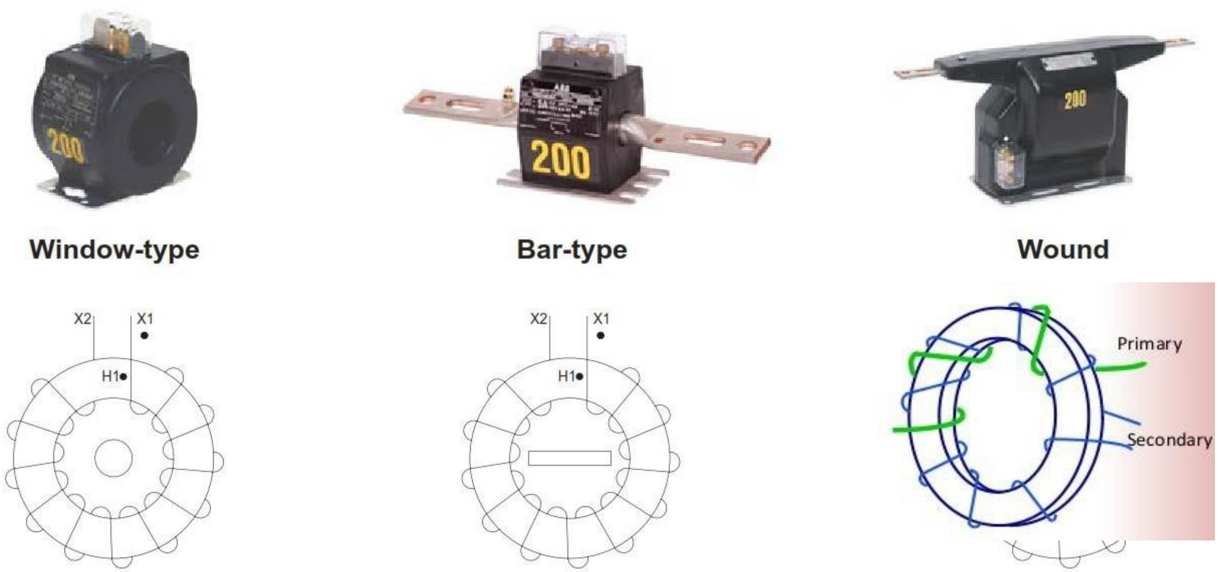


Figure 1.2: CT window, Bar and Wound type

3.1 Current Transformer (C.T.)

Current transformer is used to step down the current of power system to a lower level to make it feasible to be measured by small rating Ammeter (i.e. 5A ammeter). A typical connection diagram of a current transformer measurement type is shown in Figure 1.3.

Primary of C.T. is having very few turns. The secondary is having large no. of turns. Secondary is connected directly to an ammeter. As the ammeter is having very small resistance. Hence, the secondary of current transformer operates almost in short circuited condition.

One terminal of secondary is earthed to reduce the chances of insulation breakdown and also protect the operator against high voltage.

More ever before disconnecting the ammeter, secondary is short circuited through a switch ‘S’ as shown in figure above to avoid the high voltage build up across the secondary.

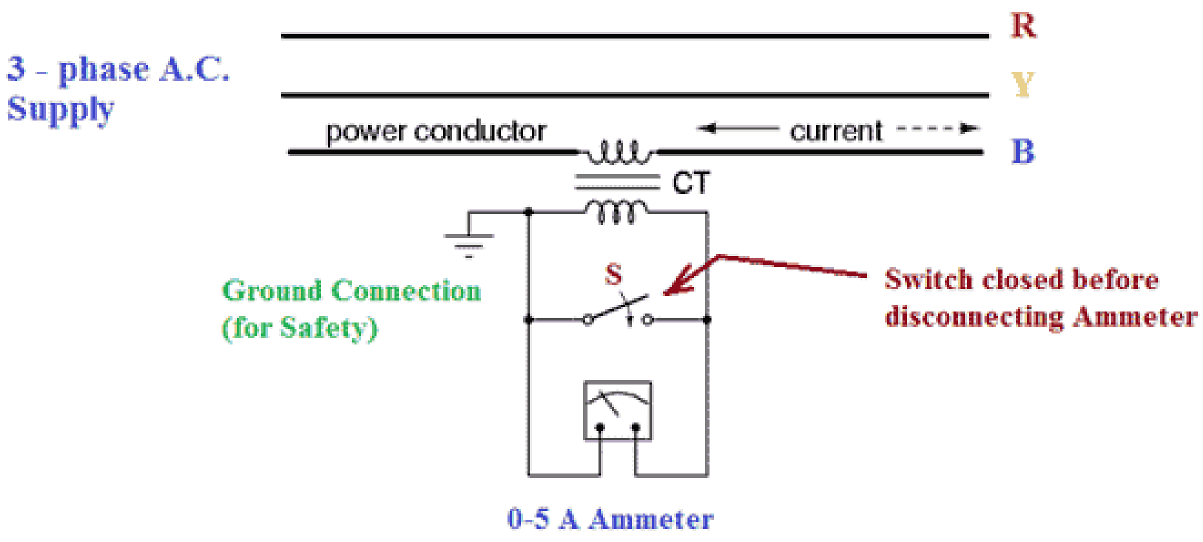


Figure 1.3: Current Transformer CT

3.2- Potential Transformer (P.T.)

Potential Transformer or called also Voltage Transformer VT is used to step down the voltage of power system to a lower level to make is feasible to be measured by small rating voltmeter i.e. 110 – 120 V voltmeter. A typical connection diagram of a potential transformer measurement type is showing Figure 1.4.

Primary of P.T. is having large no. of turns. Primary is connected across the line (generally between on line and earth). Secondary of P.T. is having few turns and connected directly to a voltmeter. As the voltmeter is having large resistance. Hence the secondary of a P.T. operates almost in open circuited condition.

One terminal of secondary of P.T. is earthed to maintain the secondary voltage with respect to earth. Which assures the safety of operators.

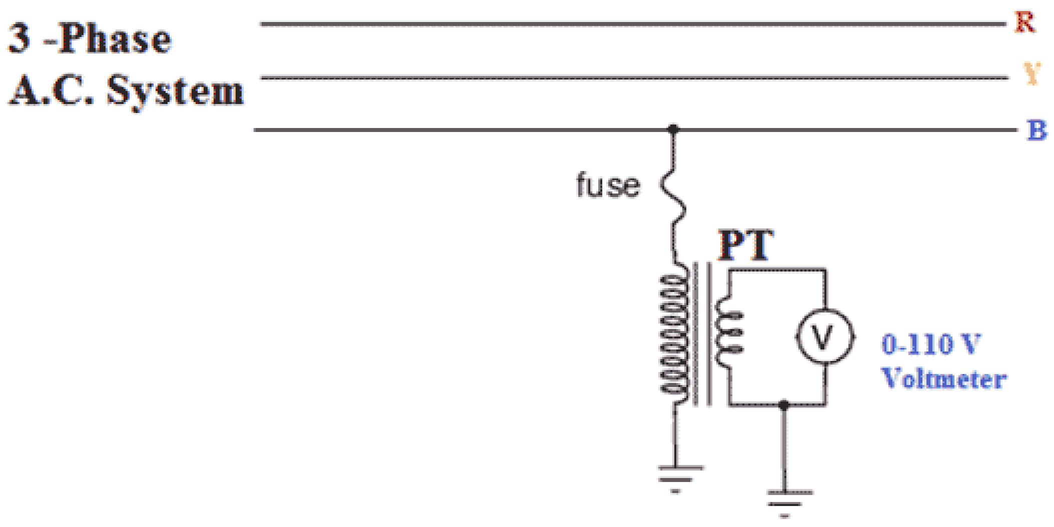


Figure 1.4: Potential Transformer PT

4- Instrument Transformer Polarity

The Primary Terminals of an instrument transformer is marked H1 and H2. The secondary side is marked X1 and X2, see Figure 1.5.

The rule is that whenever the AC wave shape of the H1 is high, then the X1 will also be high.
Some transformers use dots in lieu of characters. In this case H1 and X1 are marked with a dot. H2 and X2 have no marking.

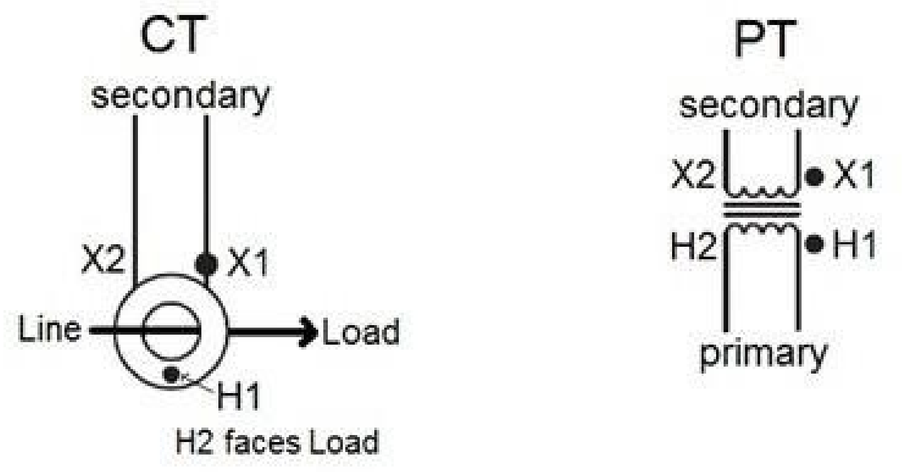


Figure 1.5: CT and PT Polarities

5- Instrument Transformer Network Connection

All electrical measurements and relaying decision are derived from current and voltage transformers as shown in Figure 1.6. These two instrument transformers are necessary because:

- They scale down line currents and bus voltages to fed into the relays or meters

- They are sensors for the relay

- They electrically isolate the relaying system from the apparatus

- Electrical isolation from the primary voltage provides safety for both human personnel and equipment.

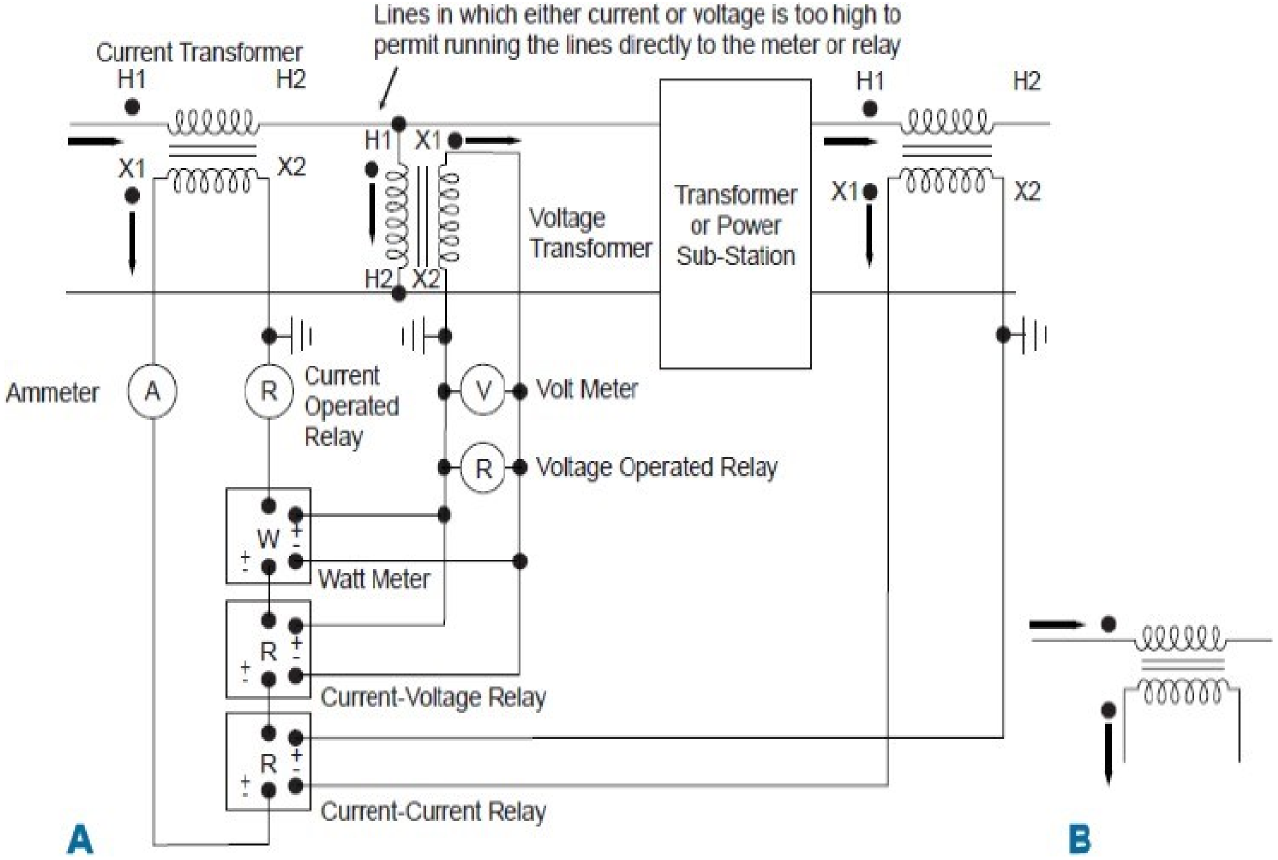


Figure 1.6: Instrument Transformers Connections in the Network

6- Knee Point and CT Magnetizing Curve

- Knee point voltage of a current transformer Figure 1.7 is the magnitude of secondary of current transformer. After or beyond this voltage the linearity between primary and secondary circuit that is the desired property of current transformer does not work anymore. Knee-point voltage Ekn is defined to be the point where a 10% increase in excitation voltage results in a 50% increase in excitation current. Figure

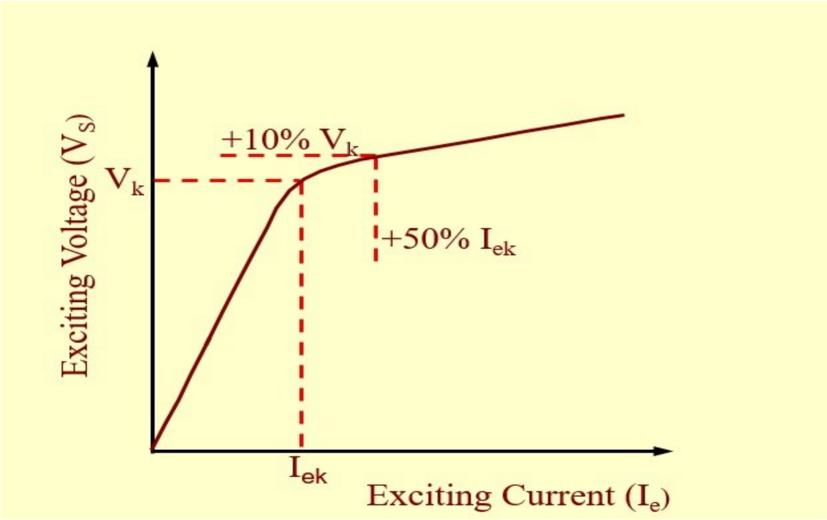


Figure 1.7: CT Knee-point Voltage

- The magnetization curve can be divided into 3 zones as shown in Figure 1.8.

a. Non-saturated zone: Im is low and the voltage Vo (and therefore Is) increases virtually proportionately to the primary current.

b.Intermediary zone: there is no real break in the curve and it is difficult to situate a precise point corresponding to the saturation voltage.

c.Saturated zone: the curve becomes virtually horizontal; the error in transformation ratio is high, the secondary current is distorted by saturation.

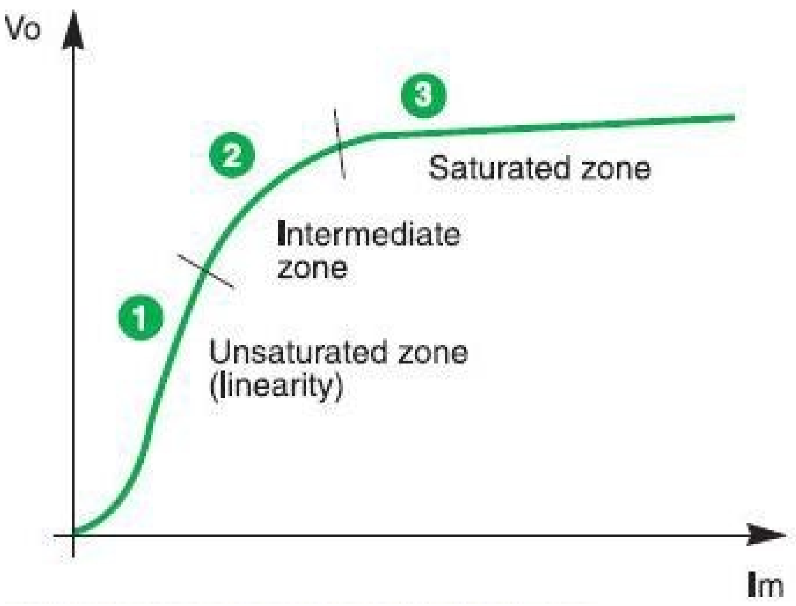


Figure 1.8: CT Magnetizing curve Vo= f(Im)

7- Classification of Current Transformers

The CTs can be classified into following types Figure 1.9:

- Measurement CTs: designed to operate at rated current
- Protection CTs: designed to operate at fault current

Measuring C.T.s
Accurate up to 120% rated current.
Nickel iron alloy core with low exciting current and knee point at low flux density. Low saturation level to protect instruments.

Protection C.T.s
Accuracy not as important as above.
Can operate up to many times rated current (~20x), use grain orientated silicon steel with high saturation flux density.

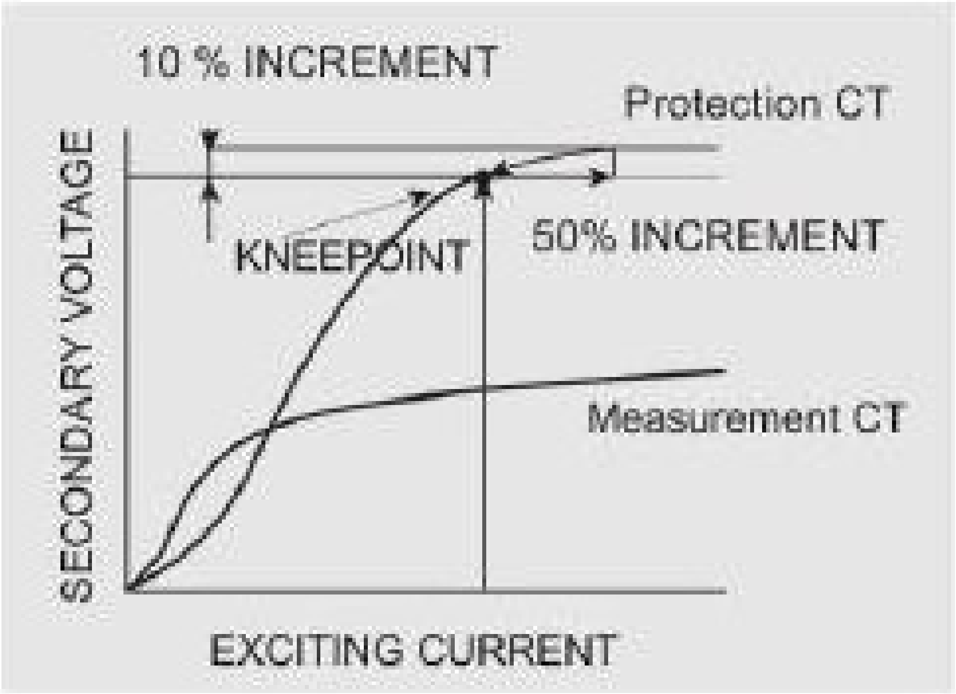


Figure 1.9: Typical magnetizing curves of protective and measurement CTs

8- Current Transformer Ratio

A current transformer, like any other transformer, must satisfy the amp-turn equation, this turns ratio is equal to:

$$\text{CT Ratio} = N_P / N_S = I_S / I_P \text{ from which we get Secondary current} = I_S = I_P \times (N_P / N_S)$$

The current ratio will sets the turn’s ratio and as the primary usually consists of one whilst the secondary can have several hundred turns, the ratio between the primary and secondary can be quite large. For example, assume that the current rating of the primary winding is 100A as shown in Figure 1.10. The secondary winding has the standard rating of 5A. Then the ratio between the primary and the secondary currents is 100A-to-5A (100:5) or 20:1. In other words, the primary current is 20 times greater than the secondary current.

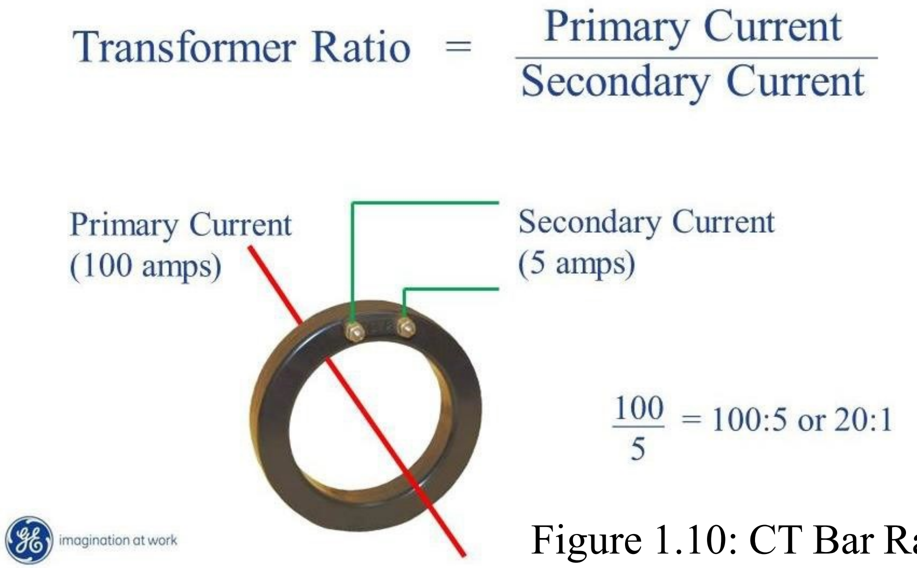


Figure 1.10: CT Bar Ratio

It should be noted that the ratio of 100:5 expresses the “input/output current rating” and not the actual ratio of the primary to the secondary currents I_S / I_P, it is actually the inverse.

Example # 1:

A bar-type current transformer in Figure 1.11 which has 1 turn on its primary and 160 turns on its secondary is to be used with a standard range of ammeters that have an internal resistance of 0.2Ω's. The ammeter is required to give a full scale deflection when the primary current is 800 Amps. Calculate the maximum secondary current and secondary voltage across the ammeter.

Secondary current:

$I_S = I_P \text{ x } (N_P / N_S) = 800 \text{ x } 1/600 = 5A$

Voltage across Ammeter:

$V_S = I_S \text{ x } R_A = 5 \text{ x } 0.2 = 1V$

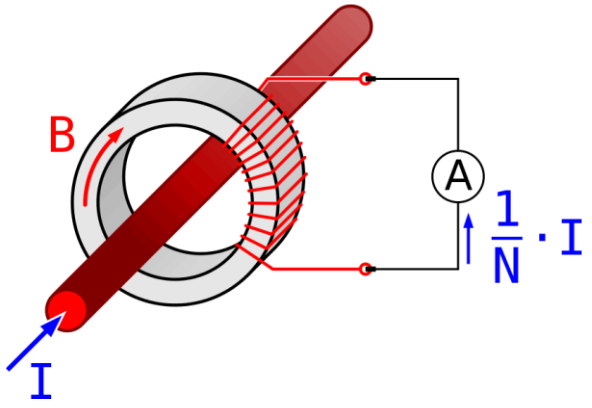


Figure 1.11: CT ring type

We can see above that since the secondary of the current transformer is connected across the ammeter, which has a very small resistance, the voltage drop across the secondary winding is only 1.0 volts at full primary current. If the ammeter is removed, the secondary winding becomes open-circuited and the transformer acts as a step-up transformer resulting in a very high voltage equal to the ratio of: V_P (Ns / Np) being developed across the secondary winding.

16- CT ratio Modification

But relatively large changes in a current transformers turns ratio can be achieved by modifying the primary turns through the CT's window where one primary turn is equal to one pass and more than one pass through the window results in the electrical ratio being modified.

So for example Figure 1.19, a current transformer with a relationship of say, 300/5A can be converted to another of 150/5A or even 100/5A by passing the main primary conductor through its interior window two or three times as shown. This allows a higher value current transformer to provide the maximum output current for the ammeter when used on smaller primary current lines.

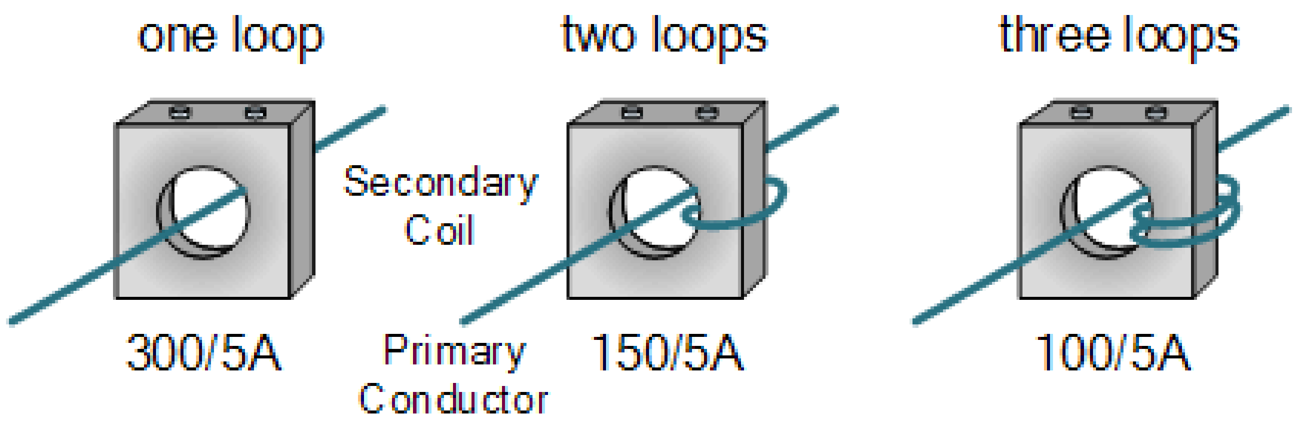


Figure 1.19: One, two and three loops CT ratio

1- Introduction to Protective Relay

Protective relay works in the way of sensing and control devices to accomplish its function. Under normal power system operation, a protective relay ***remains idle*** and serves no active function but when fault or undesirable condition arrives Protective Relay must be operated and function correctly.

A Power System consists of various electrical components like Generator, transformers, transmission lines, isolators, circuit breakers, bus bars, cables, relays, instrument transformers, distribution feeders, and various types of loads.

Faults may occur in any part of power system as a short circuit and earth fault. Fault may be ***Single Line to Ground***, ***Double Line to Ground***, ***Line to Line***, ***three phase short circuit*** etc. This results in flow of ***heavy fault*** current through the system. Fault level also depends on the fault impedance which depends on the location of fault referred from the source side. To calculate fault level at various points in the power system, fault analysis is necessary.

The protection system operates and isolates the faulty section. The operation of the protection system should be fast and selective i.e. it should isolate only the faulty section in the shortest possible time causing minimum disturbance to the system. Also, if main protection fails to operate, there should be a backup protection for which proper relay co-ordination is necessary.
Failure of a protective relay can result in devastating equipment damage and prolonged downtime.

2- Working Principle of Protective Scheme

Protective relaying senses the abnormal condition in a part of power system and gives an alarm or isolates that part from healthy system. Protective relaying is a team work of CT, PT, protective relays, time delay relays, trip circuits, circuit breakers etc.

Protective relaying plays an important role in ***minimizing the faults*** and also in minimizing the damage in the event of faults.

Figure 1.1 shows basic connections of circuit breaker control for the opening operation. The protected ***circuit X*** is shown by dashed line. When a fault occurs in the protected circuit the relay connected to CT and PT actuates and closes its contacts. Current flows from battery in the trip circuit. As the trip coil of circuit breaker is energized, the circuit breaker operating mechanism is actuated and it operates for the opening operation.

Thus the fault is sensed and the trip circuit is actuated by the relay and the faulty part is isolated

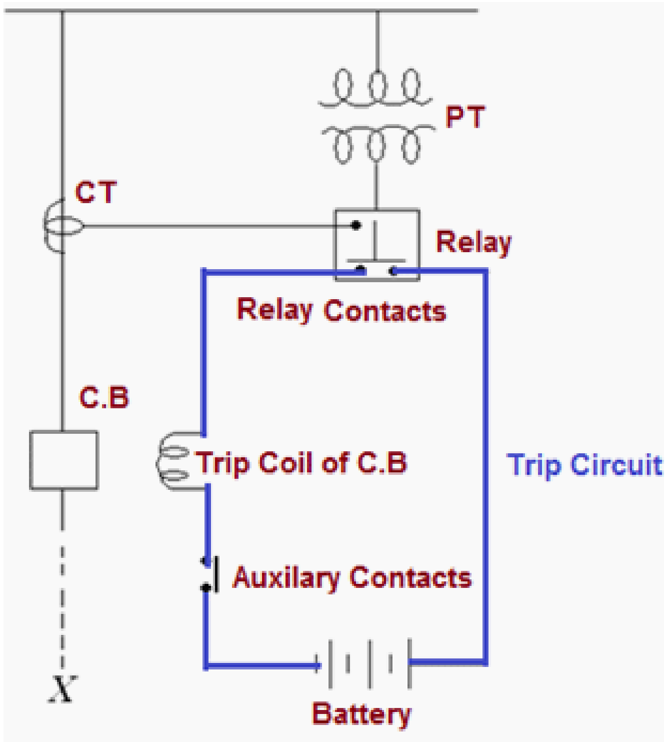


Figure 1.1: CT-Relay-CB circuit diagram connection

https://www.youtube.com/watch?v=bQ6fZrrP0H4

3- What is Relay?

A relay is automatic device which senses an abnormal condition of electrical circuit and closes its contacts.

These contacts in turns close and complete the circuit breaker trip coil circuit hence make the circuit breaker tripped for disconnecting the faulty portion of the electrical circuit from rest of the healthy circuit.

3.1- Functions of Protective Relay

These are the main functions of protective relay:

a. To ***sound an alarm*** or to ***close the trip circuit*** of a circuit breaker so as to disconnect Faulty Section.
b. To ***disconnect*** the abnormally operating part so as to prevent subsequent faults.
c. To ***isolate*** or disconnect faulted circuits or equipment quickly from the remainder of the system so the system can continue to function and to minimize the damage to the faulty part. For example – If machine is disconnected immediately after a winding fault, only a few coils may need replacement. But if the fault is sustained, the entire winding may get damaged and machine may be beyond repairs.

d- To ***localize the effect of fault*** by disconnecting the faulty part from healthy part, causing least disturbance to the healthy system.

e. To disconnect the faulty part quickly so as to improve system stability, service continuity and system performance. Transient stability can be improved by means of improved protective relaying.

f. To minimize hazards to personnel.

4- Desirable Qualities of Protective Relaying

a. Selectivity,
b. Discrimination
c. Stability
d. Sensitivity,
e. Power consumption
f. System Security
g. Adequateness
h. Speed & Time

5- Terminology of protective relay

Pickup level of actuating signal: The value of actuating quantity (voltage or current) which is on threshold above which the relay initiates to be operated. If the value of actuating quantity is increased, the electromagnetic effect of the relay coil is increased and above a certain level of actuating quantity the moving mechanism of the relay just starts to move.

a.Reset level: The value of current or voltage below which a relay opens its contacts and comes in original position.

b.Operating Time of Relay*:* Just after exceeding pickup level of actuating quantity the moving mechanism (for example rotating disc) of relay starts moving and it ultimately close the relay contacts at the end of its journey. The time which elapses between the instant when actuating quantity exceeds the pickup value to the instant when the relay contacts close.

c. Reset time of Relay: The time which elapses between the instant when the actuating quantity becomes less than the reset value to the instant when the relay contacts returns to its normal position.

d- Reach of Relay: A distance relay operates whenever the distance seen by the relay is less than the pre-specified impedance. The actuating impedance in the relay is the function of distance in a distance protection relay. This impedance or corresponding distance is called reach of the relay.

6- History of Protective Relay

The evolution of protective relays begins with the ***electromechanical relays, Table 1.1***. Over the past decade it upgraded from electromechanical to ***solid state technologies*** to predominate use of *microprocessors* or *numerical* relays.

The timeline of the development of protective relays is shown below:

1900 to 1963	1963 to 1972	1972 to 1980	1980 to 1990
Electromechanical Relay	Static Relay	Digital Relay	Numerical Relay
1925=Single Disc Type Relay (Single Input)	1963=Static Relay (All Purpose)	1980=Digital Type Relay (All Purpose)	1990=Numerical Type Relay (All Purpose)
1961=Single Cup Type Relay (Impedance Relay)	1972=Static Relay with self checking (All Purpose)		

Table 1.1: History of protective relay

7 Types of Relays

Types of protection relays are mainly:

1. Based on Characteristic:

a. Definite time Relays.

b. Inverse definite minimum time Relays (IDMT)

c. Instantaneous Relays

c. IDMT with Instantaneous.

d. Stepped Characteristic

e. Programmed Switches

f. Voltage restraint over current relay

7.2 Based on logic:

a. Differential

b. Unbalance

c. Neutral Displacement

d. Directional

e. Restricted Earth Fault

f. Over Fluxing

g. Distance Schemes

h. Bus bar Protection

e. Reverse Power Relays

j. Loss of excitation

k. Negative Phase Sequence Relays etc.

7.3 Based on Actuating parameter:

a. Current Relays
b. Voltage Relays
c. Frequency Relays
d. Power Relays etc

7.4 Based on Applications

1. Primary Relays
2. Backup Relays

5. Based on Operation Mechanism:

a. Electromagnetic Attraction Relay

This Relay Figure 1.2 works on Electromagnetic Attraction Principle.

Figure 1.2: Electromagnetic Relay

- **Measuring Principles**

The electromechanical protective relay converts the voltages and currents to magnetic and electric forces and torques that press against spring tensions in the relay.

- **Function of Relay**

These relays are usually **instantaneous in action**, with no intentional time delay, closing as soon after pickup as the mechanical motion permits. We can add time delay by means of a bellows, dashpot, or a clockwork escapement mechanism.
However, the timing accuracy is considerably less precise than that of induction type relays

- **Operation of Electromagnetic-attraction Relay**

Figure 1.3 shows a typical electromechanical relay. An input voltage is applied to the **coil mechanism.** The input voltage magnetizes the core which pulls the arm towards it. This action causes the output contacts to touch, closing the load circuit.
When the input voltage is removed, the spring lever will push the contacts away from each other, breaking the load circuit connection.

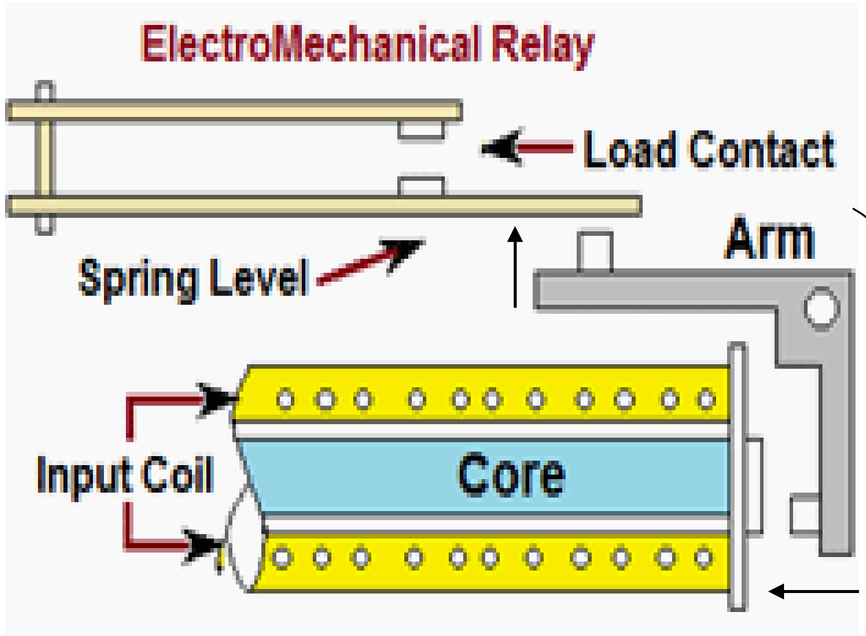


Figure 1.3: Operation of Electromagnetic-attraction Relay

b- Electromagnetic Induction Relay

This Relay works on Electromagnetic Induction Principle

Operation of Electromagnetic-Induction Relay

Induction relays are available in many variations to **provide accurate pickup and time-current responses** for a wide range of simple or complex system.

They are actually like induction motors. On the relay, the moving element (*rotor*) is usually a metal disk as shown in Figure 1.4, although sometimes it's a metal cylinder or cup. The stationary part (*stator*) is one or more integral electromagnets, with current or potential coils inducing currents in the disk, causing it to rotate.

Until the rotational forces are great enough to turn the disk and bring its moving contact against the stationary contact, a spring restrains the disk motion.

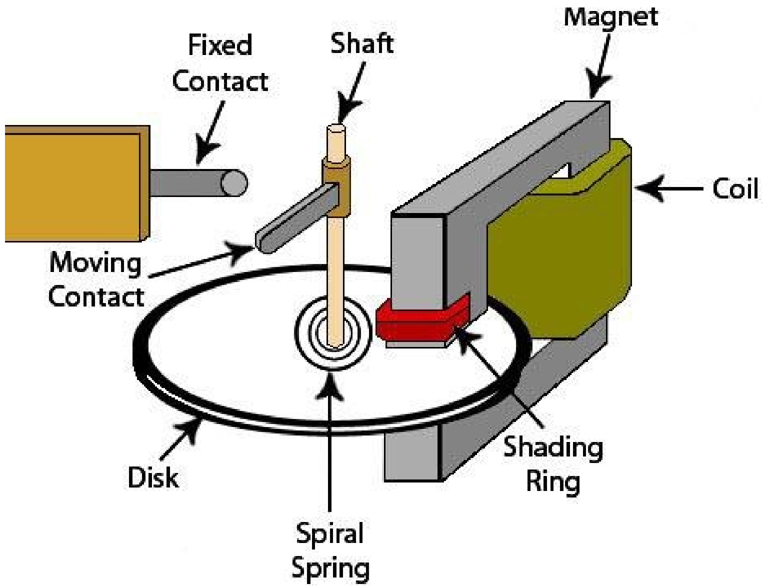


Figure 1.4: Induction-type overcurrent unit, showing the disc rotor and drag magnet

This closes the circuit the relay is controlling. The greater the sensed fault, the greater the current in the coils, and the faster the disk rotates. A calibrated adjustment called the **time dial sets** the spacing between the moving and stationary contacts; this varies the operating time of the relay from fast *(contacts only slightly open) to slow (contacts nearly a full disk revolution apart).*

c- Solid State (Static) Relay

The term ***'static'*** implies that the relay has no moving parts. This is not strictly the case for a static relay, as the output contacts are still generally attracted armature relays. In a protection relay, the term 'static' refers to the absence of moving parts to create the relay characteristic.

- **Analog Relay**: In Analog relays measured ac quantities are converted into lower voltage but similar ac analog signals, which are then combined or compared directly to reference values in level detectors to produce the desired output.

- **Digital Relay**: In Digital relays measured ac quantities are manipulated in analogue form and subsequently converted into square-wave **(binary)** voltages. Logic circuits or microprocessors compare the phase relationships of the square waves to make a trip decision.

- Numerical /Microprocessor Relay

In Numerical relays as shown in Figure 1.5, measured ac quantities are sequentially sampled and converted into **numeric** data form. A microprocessor performs mathematical and/or logical operations on the data to make trip decisions.

Figure 1.5: Numerical Protection Relay

8- Comparison between Protection Relays

Tables 1.2 to 1.4 show the comparison of the four protective relays, electromechanical, static, digital and numerical

Characteristic	El. Mech. Relay	Static Relay	Digital Relay	Numerical Relay
Technology Standard	1st generation relays.	2nd generation relays.	Present generation relays.	Present generation relays.
Operating Principle	They use principle of electromagnetic principle.	In this relays transistors and IC's been used	They use microprocessor. Within built software with predefined values	They use microprocessor. Within built software with predefined values
Measuring elements/ Hardware	Induction disc, electromagnets, induction cup, balance beam	R, L, C, transistors, analogue ICs comparators	Microprocessors, digital ICs, digital dignal processors	Microprocessors, digital ICs, digital signal processors
Measuring method	Electrical qtys converted intomechanical force, torque	Level detects,comparison withreference value in analogue comparator	A/D conversion, numerical algorithm techniques	A/D conversion, numerical algorithm techniques
Surrounding Environment	Depend upon gravitation and the value changes to the surrounding magnetic fields also.	There value may vary with respect to temperature also.		

Characteristic	El. Mech. Relay	Static Relay	Digital Relay	Numerical Relay
Relay Size	Bulky	Small	Small	Compact
Speed of Response	Slow	Fast	Fast	Very fast
Timing function	Mechanical clock works, dashpot	Static timers	Counter	Counter
Time of Accuracy	Temp. dependant	Temp. dependant	Stable	Stable
Reliability	High	Low	High	High
Vibration Proof	No	Yes	Yes	Yes
Characteristics	Limited	Wide	Wide	Wide
Requirement of Draw Out	Required	Required	Not required	Not required
CT Burden	High	Low	Low	Low
CT Burden	8 to 10 VA	1 VA	< 0.5 VA	< 0.5 VA

Comparison between Protection Relays : Continued

Characteristic	El. Mech. Relay	Static Relay	Digital Relay	Numerical Relay
Reset Time	Very High	Less	Less	Less
Auxiliary supply	Required	Required	Required	Required
Range of settings	Limited	Wide	Wide	Wide
Isolation Voltage	Low	High	High	High
Function	Single function	Single function	Multi function	Single function
Maintenance	Frequent	Frequent	Low	Very Low
Resistance	100 mille ohms	10 Ohms	10 Ohms	10 Ohms
Output Capacitance	< 1 Pico Farad	> 20 Pico Farads	> 20 Pico Farads	> 20 Pico Farads

Characteristic	El. Mech. Relay	Static Relay	Digital Relay	Numerical Relay
Deterioration due to Operation	Yes	No	No	No
Relay Programming	No	Partially	Programmable	Programmable
SCADA Compatibility	No	No	Possible	Yes
Operational value indication	Not Possible	Possible	Possible	Possible
Visual indication	Flags, targets	LEDs	LEDs, LCD	LEDs, LCD
Self monitoring	No	Yes	Yes	Yes
Parameter setting	Plug setting, dial setting	Thumb wheel, dual in line switches	Keypad for numeric values, through computer	Keypad for numeric values, through computer
Fault Disturbance Recording	Not possible	Not possible	Possible	Possible

1. Introduction

A circuit breaker is an automatically operated electrical switch designed to protect an electrical circuit from damage caused by an overload or a short circuit. The circuit breaker is a switching device that is used to connect or disconnect circuits in the switchgear. It is used to serves two basic purposes:

a. Switch during normal operation conditions for the purpose of operation and maintenance.
b. Switching during abnormal conditions such as short circuit and interrupting the fault currents.

At normal condition, the contact of the circuit breaker is closed. If the fault occurs as shown in Figure 1.1 , then the current transformer senses this fault current that will activate the relay then the circuit breaker. This activates the circuit breaker opening mechanism, making the circuit breaker open. This isolates the faulty part from rest of the healthy system.

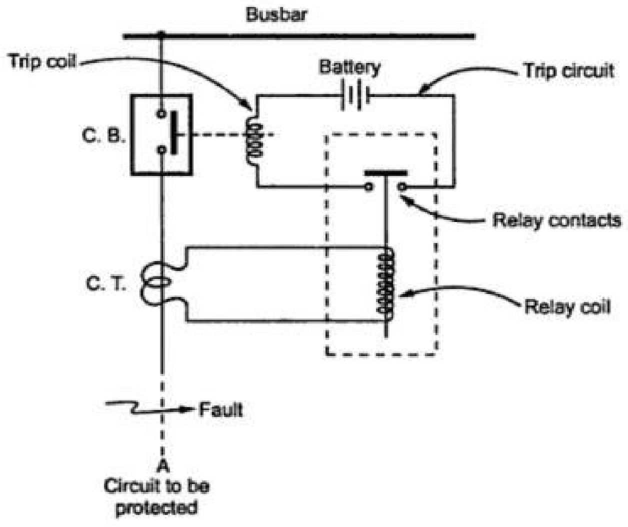


Figure 1.1: Circuit Breaker Operation

Example of circuit breaker operation

Consider Current transformer ratio of100:5 A, Pick up current = 10A, I_{NORMAL} = 100A, I_{FAULT} = 1kA

a. At Normal Condition: Figure 1.2

At normal condition, the secondary current flowing through the relay is less than the pick-up current I_{PU}. The relay is energized but not enough to close its contact. The main contact of the CB remains closed.

$I_{NORMAL} = 100A$, $I_{SEC} = 100 / 20 = 5A$ less than $I_{PU} = 10A$

b. At Faulty Condition: Figure 1.3

When there is a fault current in the line, the secondary current will be greater than the pick-up current and the relay coil gets enough current to open its contact.

$I_{FAULT} = 1kA$, $I_{SEC} = 1000/20 = 50A$more than $I_{PU} = 10A$

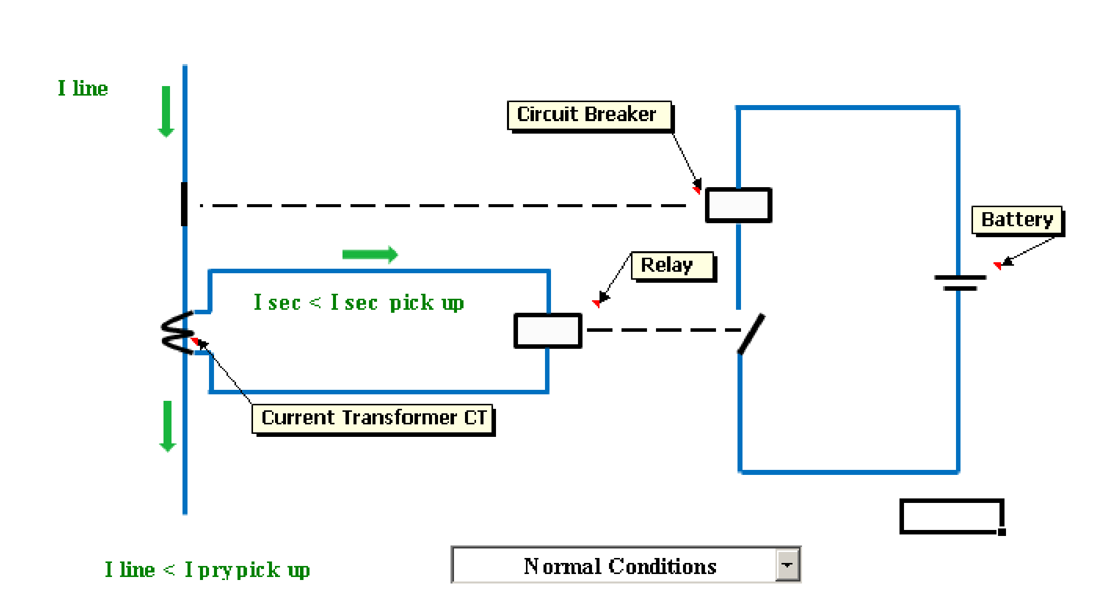


Figure 1.2

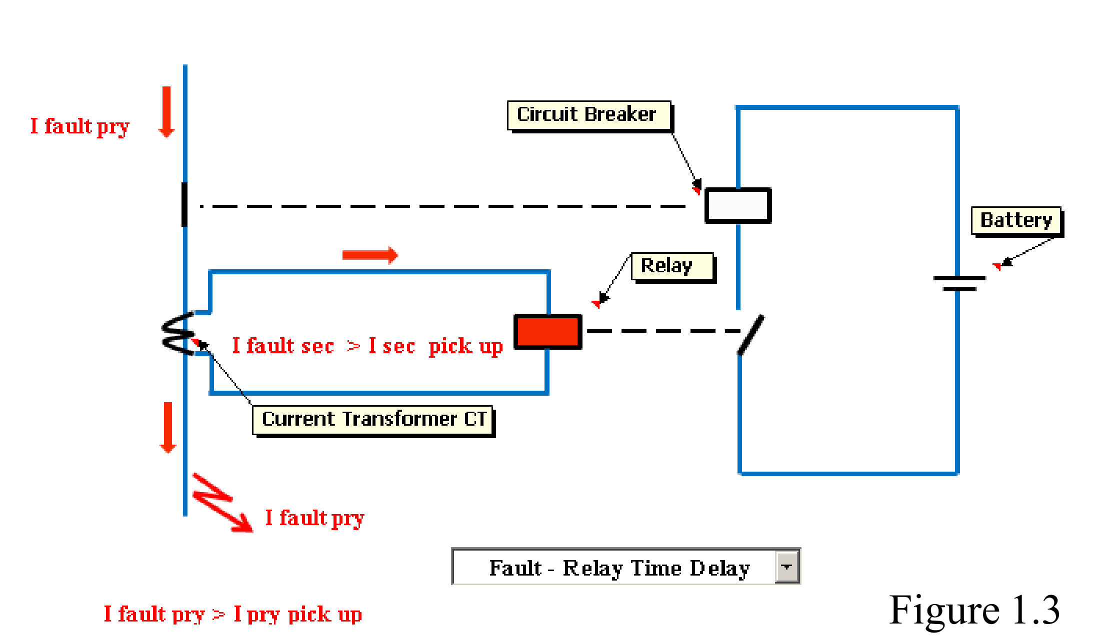


Figure 1.3

c- **Energizing the Circuit Breaker.** Figure 1.4

The relay contact is closed, the circuit breaker coil is energized from the battery.

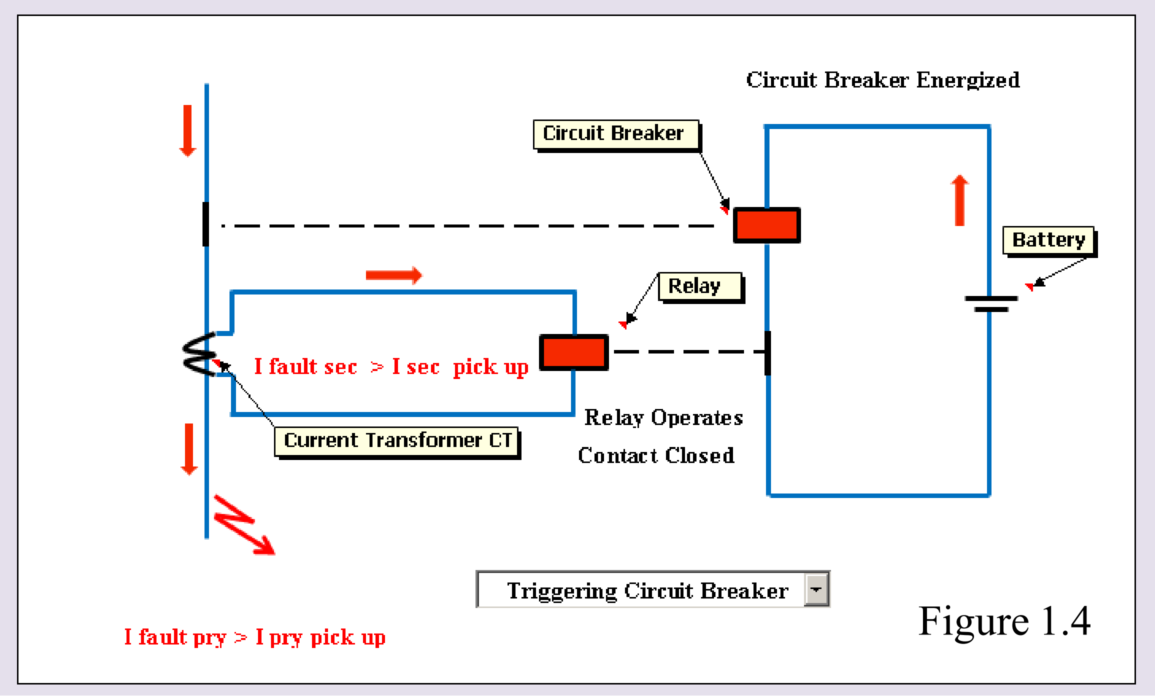


Figure 1.4

d. **Clearing the Fault:** Figure 1.5

The circuit breaker coil opens its main contact; the fault has been cleared. When the fault is isolated, the circuit breaker contact is back closed manually or electrically to restore the power to the system.

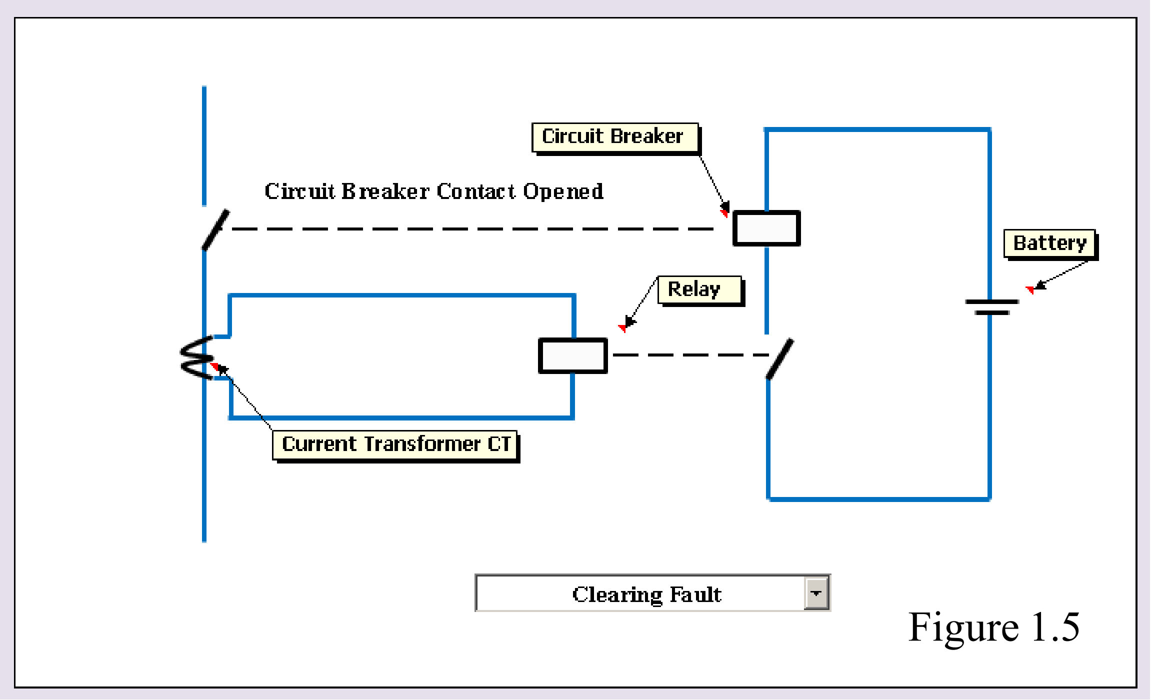


Figure 1.5

2- Arc Phenomenon in Circuit Breaker

-When contacts of circuit breaker start separating Figure 1.6, the contact resistance starts increasing. This increases the (I square r) which is heat produced. During the interruption of the fault this heat energy becomes very high.

-This heat increases the energy of electrons in the contact areas and the ionized particles tries to maintain the current when contacts are separated. This flow of charged particles form one contact to other is called and **arc.**

- The medium surrounding the arc also contains ions.
- Due to this charged particles the arc continues even if the breaker contacts are separated.
- The voltage (potential gradient) across the arc is less and so it continues even for low voltages.

-The arc provides a low resistance path and consequently the current in the circuit remains uninterrupted so long as the arc persists.

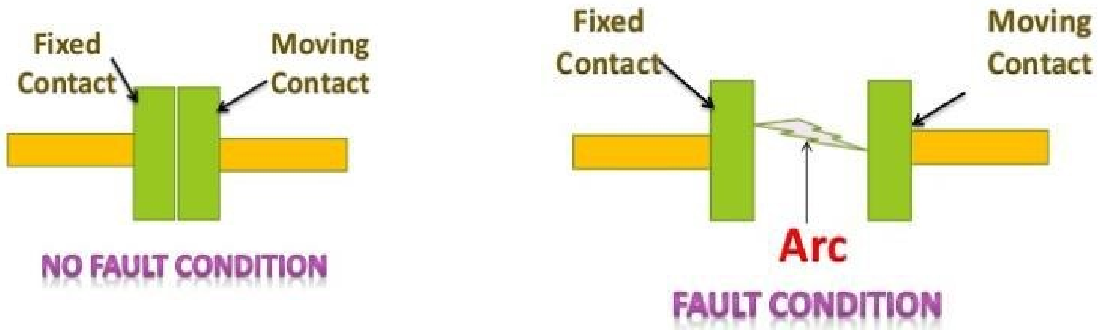


Figure 1.6: Circuit Breaker Arc Phenomenon

https://www.youtube.com/watch?v=VrY_k_pdlCs

3- Circuit Breaker Design and Components

Almost all circuit breakers have five basic components:

A- External Casing : This is the external shell that encases the other parts. Based on the rated current and voltage, they are further divided into three types, Figure 1.7:

Molded Case: Typically used in low voltage circuit breakers

Insulated Case: Used in circuit breakers rated for medium voltage and amperage

Metal Clad: Generally for the higher end of the medium-rated circuit breakers

Molded Case

Insulated Case

Metal Glad

Figure 1.7: CB external casing types

B. Electrical Contacts : There are two contacts in a circuit breaker – a fixed contact and a floating contact (which is controlled by the circuit breaker). When the breaker trips, the floating contact moves away from the fixed contact and disconnects the electricity supply into the circuit.

C.Electrical Arc Extinguishing Mechanism : When the contacts disconnect, electricity can jump through the gap between the last parts in contact. This creates an arc of electricity that can reach very high temperatures. To prevent damage and keep the arc from recreating itself, a circuit breaker uses an arc quenching mechanism to stop these arcs, Figure 1.8.

D.Main Operating Mechanisms : Circuit breakers can use a variety of methods to disconnect power supply. These can include spring-loaded switches, solenoids, hydraulic and pneumatic switches.

E. Trip Elements : Current flowing through a circuit creates heat and a magnetic field. Trip elements are calibrated to use either or both these factors to gauge the current and voltage and trip a switch, in case the maximum ratings are exceeded.

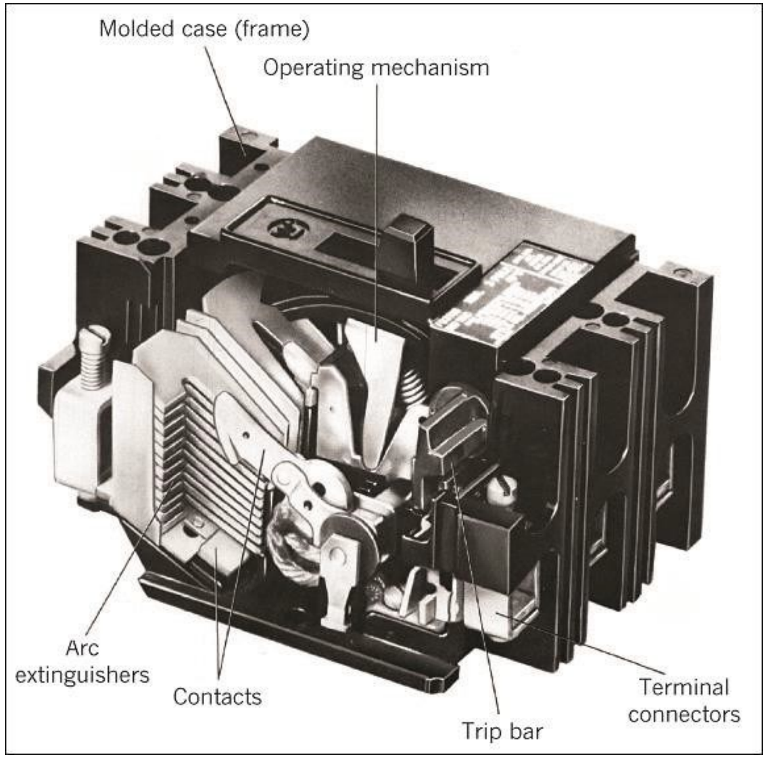


Figure 1.8: Circuit breaker parts

4- Types of Circuit Breakers

There are many types of circuit breaker designs and they can be classified on the basis of voltage (high, medium and low) or other characteristics like their arc quenching media and operating mechanism:

a- Oil-Based Circuit Breaker

In oil-based circuit breakers Figure 1.9, both the contacts are submerged in insulating mineral oil. When the breaker trips and the contacts disconnect, the resulting arc vaporizes the oil, which decomposes and forms a barrier of compressed hydrogen around the arc. This prevents further arcing after the circuit is broken.

Oil-Based Circuit Breaker

b. Air Circuit Breakers:

Air circuit breakers can be used for low-voltage and some medium-voltage circuits too. They operate by increasing the arc voltage, which is the minimum voltage required to maintain an arc. Once it reaches a point greater than the supply voltage, the arc collapses.

Air Circuit Breakers

https://www.youtube.com/watch?v=bDV59jU-hUw

Figure 1.9: Oil and Air CB

c. SF6 Circuit Breakers :

These circuit breakers derive their name from sulfur hexafluoride (SF6) Figure 1.10, which is an excellent insulator that absorbs negative ions. The gas captures the conducting free electrons in the arc to form relatively immobile negative ions. The chamber around the contacts is filled with the gas and electrical arcing causes a chemical reaction that increases the arc voltage.

https://www.youtube.com/watch?v=bDV59jU-hUw

d. Vacuum Circuit Breakers :

During the process the dielectric strength builds up rapidly and the restriking of arc is prevented. The arc interruption takes place in a steel chamber with symmetrically placed ceramic insulators, where a very high vacuum is maintained.

SF6 Circuit Breakers

Vacuum Circuit Breakers

Figure 1.10: SF6 and Vacuum CB

5- Circuit Breaker Rating

a.Breaking capacity: It is the current (r.m.s) that a circuit breaker is capable of breaking at given recovery voltage and under specified conditions. It is expressed in units of MVA. **Breaking capacity =** $\sqrt{3}\times V\times I\times 10^{-6}$ **(MVA)**. Where,V is line voltage in volts and I is the rated breaking current in **Amps**.

b.Making Capacity: The peak value of current (including DC component, Figure 1.11) during the first cycle of current wave after closure of circuit breaker is known as making capacity. Making capacity = 2.55 x symmetrical breaking capacity.

c.Short Time Rating: It is the period for which the CB is able to carry fault current while remaining closed.

d.Normal Current Rating: It is the r.m.s value of current which the CB is capable of carrying continuously at its rated frequency under rated specified conditions.

Example of rated breaking current: A circuit breaker rated at '6 kA' means that the circuit breaker can withstand 6 000 amps of current during the brief time it takes to trip.

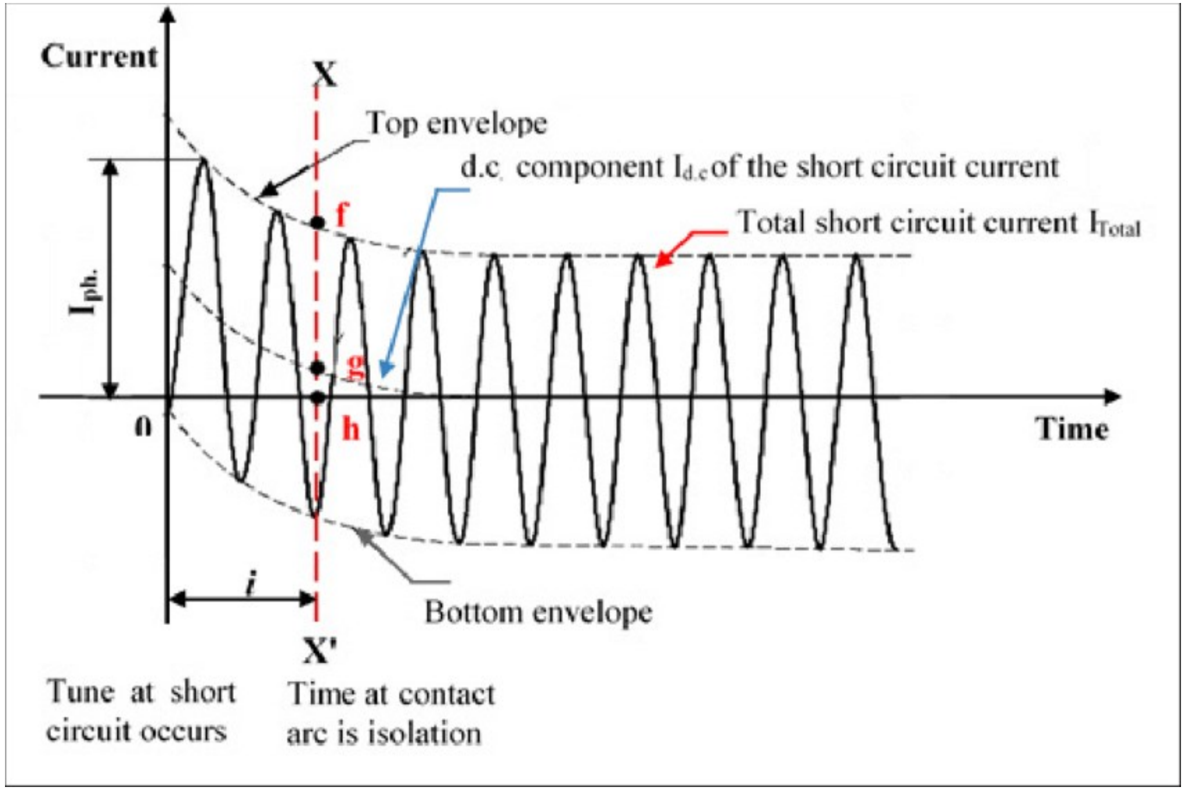


Figure 1.11: CB Fault Current Waveforms

- **6- IEEE Standards for Selection of Circuit Breakers**

- **Step # 1:**

- Calculate the highest value of initial r.m.s current considering symmetrical fault. The current can be obtained by sub-transient reactance of synchronous generators and transient reactance of synchronous motors and induction motors are neglected.
- Following multiplying factors are applied to take into account DC components and decrement of DC components in current. If short circuit kVA exceeds 5000,000, then add 0.1 to the given factors.

Example: If circuit breaker breaking capacity is '6 kA' select 6 x 1.2 = 7.2kA (3 cycle breaker).

8 cycles or slow breaker	1.0
5 cycle breaker	1.1
3 cycle breaker	1.2
2 cycle breaker	1.4

- **Step # 2:**

- To determine the rated momentary current with time 1 sec or less of a breaker. The calculation of highest value of initial rms current can be done as given in step 1 without using sub-transient reactance of all machines including induction motors.
- Multiply the obtain by 1.6.

$$\text{Momentary RMS value of current} = 1.6 \times \frac{v}{xd''}$$

1- Introduction

The fuse is the oldest, simplest and least expensive type of electrical protection device. Its operation is simple: excessive current creates thermal energy, which causes a fuse element to melt, interrupting the path of electrical current flowing through it see Figures 1.1 & 1.2.

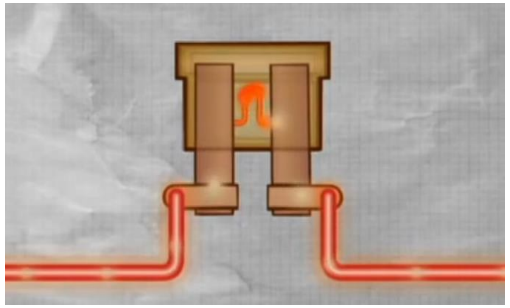


Fig.1.1 fuse under normal condition

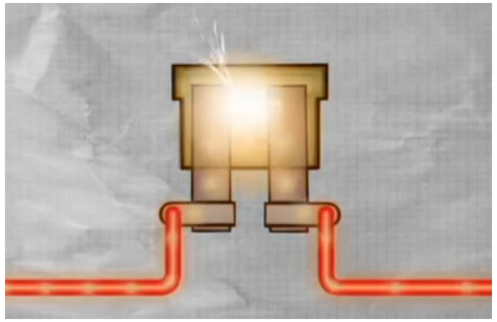


Fig 1.2 Fuse under abnormal condition

https://www.youtube.com/watch?v=2MWwwrOQOUc

2- Fuse properties

- Simple, reliable, economic protection device.
- Combines actions of relays and circuit breakers in one.
-A metallic element melts and physically opens a circuit if current are too high, exceeding the rating current of the fuse.
- Single fuse class has only a single time-current characteristic, which cannot be adjusted.

-Note that once a fuse element has partially melted, the fuse is damaged and will not operate to the correct time characteristic.
- The difference between the curves is the arcing time within the fuse.
- Has an "inverse time" characteristic (i.e. the higher the current, the faster the fuse will blow).
- Fuses cannot be given an external command to trip.
- Usually used on local distributors.
-The time current characteristics of a fuse are represented by two curves: the minimal-melting time curve and the total-clearing time curve. The first the time that the element start to melt, and the second the time the elements have fully melted / vaporized and the arc has been cleared see Figure 1.2.

3- Fuse characteristic

The fuse has an inverse characteristic Figure 1.3 When the fault current is high, the response time is low. At the fault
current If, the fuse starts melting, after a certain time it will get cut. The fault is then cleared.

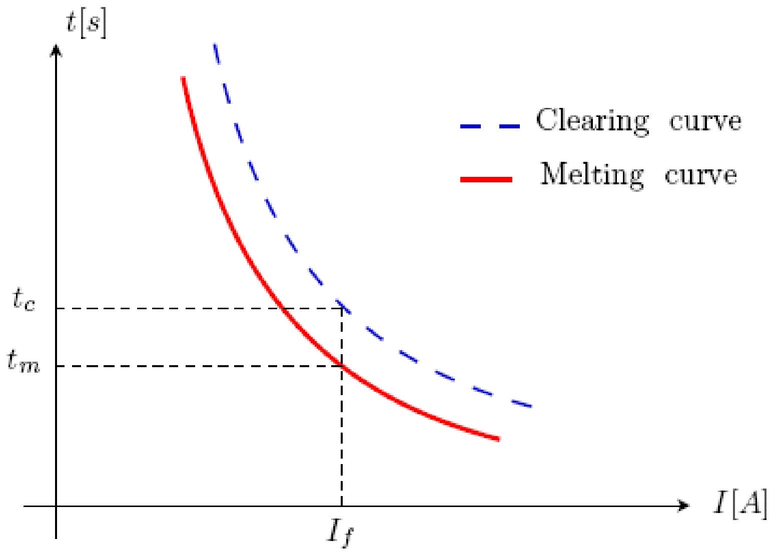


Figure 1.3: Fuse Clearing – Melting Curves

4- Important Terms

The following terms are much used in the analysis of fuses :

- **Current rating of fuse element.**

It is the current which the fuse element can normally carry without overheating or melting. It depends upon the temperature rise of the contacts of the fuse holder, fuse material and the surroundings of the fuse.

- **Fusing current.**

It is the minimum current at which the fuse element melts and thus disconnects the circuit protected by it. Obviously, its value will be more than the current rating of the fuse element. For a round wire, the approximate relationship between fusing current I and diameter d of the wire is

Limitations of a Fuse

- It is difficult to control the time to trip.
- This makes primary backup relay coordination difficult.
- Once fuse melts, it has to be replaced for reenergization of the equipment.
- Thus it is difficult to have remote operation

- **Fusing factor.**

It is the ratio of minimum fusing current to the current rating of the fuse element *i.e.*

Fusing factor = Minimum fusing current / Current rating of fuse

Its value is always more than one. The smaller the fusing factor, the greater is the difficulty in avoiding deterioration due to overheating and oxidation at rated carrying current. For a semi-enclosed or rewirable fuse which employs copper wire as the fuse element, the fusing factor is usually 2. Lower values of fusing factor can be employed for enclosed type cartridge fuses using silver or bimetallic elements.

5- Fuse Types

Three types of fuse are used; the rewireable or semi-enclosed fuse; the cartridge fuse or fuse link; and the high rupturing capacity (HRC) fuse.

a- Semi-enclosed rewireable fuse.

Rewireable fuse is used where low values of fault current are to be interrupted. It consists of a base and a fuse carrier Figure 1.4. The base is of porcelain and carries the fixed contacts to which the incoming and outgoing phase wires are connected.

The fuse carrier is also of porcelain and holds the fuse element (tinned copper wire) between its terminals. The fuse carrier can be inserted in or taken out of the base when desired. This type of fuse was very popular in domestic installations, but less so these days because of their disadvantages.

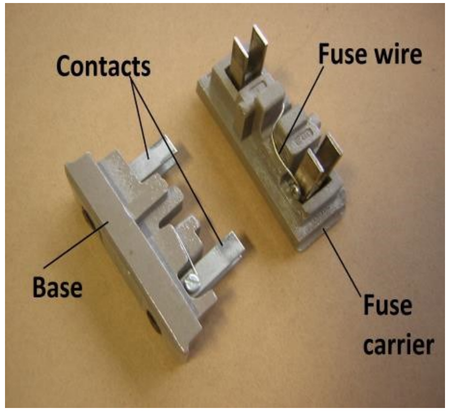


Figure 1.4: Semi-enclosed Fuse

Advantage of semi-enclosed fuses

- They are very cheap compared with other protective devices both to install and to replace.
- There are no mechanical moving parts.
- It is easy to identify a ‘ blown ’ fuse.

Disadvantages of semi-enclosed fuses

- The fuse element may be replaced with wire of the wrong size either deliberately or by accident.
- The fuse element weakens with age due to oxidization, which may result in a failure under normal operating conditions.
- The circuit cannot be restored quickly since the fuse element requires screw fixing.
- They have low breaking capacity since, in the event of a severe fault, the fault current may vaporize the fuse element and continue to flow in the form of an arc across the fuse terminals.
- They are not guaranteed to operate until up to twice the rated current is flowing.

b- Cartridge fuse

The cartridge fuse breaks a faulty circuit in the same way as a semi-enclosed fuse, but its construction eliminates some of the disadvantages experienced with an open-fuse element Figure 1.5. The fuse element is encased in a glass or ceramic tube and secured to end-caps which are firmly attached to the body of the fuse so that they do not blow off when the fuse operates. They may also be filled with quartz sand to absorb and extinguish the energy of the arc when the cartridge is brought into operation.

Figure 1.5: Ceramic tube and Glass type

Advantages of cartridge fuses

- They have no mechanical moving parts.
- The declared rating is accurate.
- The element does not weaken with age.
- They have small physical size and no external arcing which permits their use in plug tops and small fuse carriers.
- Their operation is more rapid than semi-enclosed fuses. Operating time is inversely proportional to the fault current, so the bigger the fault current the quicker the fuse operates.
- They are easy to replace.

Disadvantages of cartridge fuses

- They are more expensive to replace than fuse elements that can be re-wired.
- They can be replaced with an incorrect cartridge.
- The cartridge may be shorted out by wire or silver foil in extreme cases of bad practice.
- It is not possible to see if the fuse element is broken.

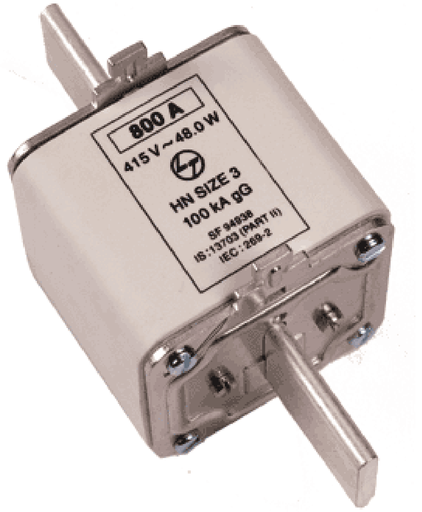
c- High-Rupturing capacity (H.R.C.) cartridge fuse

The primary objection of low and uncertain breaking capacity of semi-enclosed rewireable fuses is overcome in H.R.C. cartridge fuse.

It consists of a heat resisting ceramic body having metal end-caps to which is welded silver current-carrying element Figure 1.6. The space within the body surrounding the element is completely packed with a filling powder. The filling material may be chalk, plaster of paris, quartz or marble dust and acts as an arc quenching and cooling medium.

Typical rupturing capacities:

Re-wirable up to 4 kA
HRC types up to 100 + kA



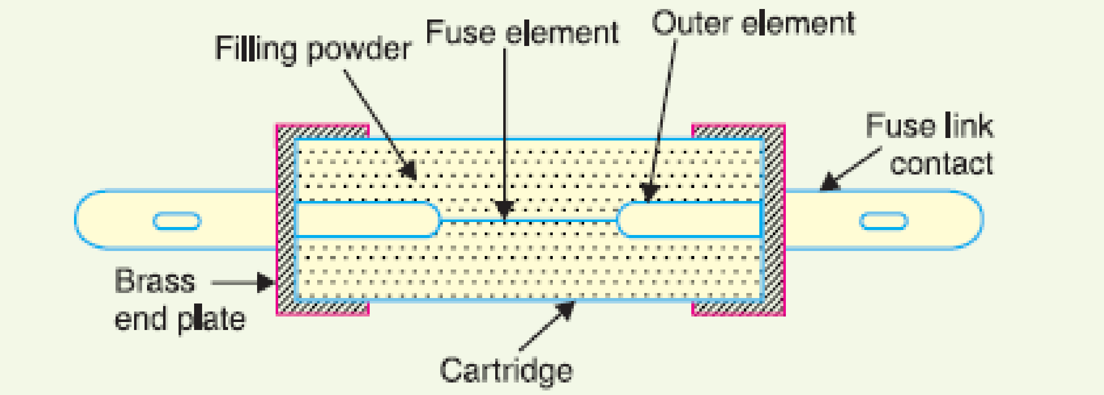


Figure 1.6: High Rupture Capacity Fuse

6- Fuse Rating

It is that value of current which when flows through the element does not melt it. Figure 1.7 shows an HRC fuse specifications.

- Nominal voltages, Vn. the voltage the fuse can operate at. The max voltage is usually Vn +10 %. Care! - max voltage must be matched to max circuit voltage

- Current, In. This will dictate the current-melting time characteristic

- Rated Interruption current. The maximum S/C current the device can safely interrupt, at the rated nominal voltage

- AC or DC

- Fusing factor. The ratio of the current which will just cause the fuse to operate to nominal current.

Note - definitions vary from country to country

Figure 1.7: HRC specifications

7- Fuse Types

A fuse type is indicated by two letters. The first letter indicates the main operating mode and the second letter indicates the object to be protected as shown in Table 1.1.

- **The first letter indicates the main operating mode:**

a: associated fuse. It must be associated to another protective device as it cannot interrupt faults below a specified level. Short circuit protection only.

g: general purpose fuse. It will interrupt all faults between the lowest fusing current (even if it takes 1 hour to melt the fuse elements) and the breaking capacity. Overload and short circuit protection.

- **The second letter indicates the object to be protected:**

G: cable and conductor protection, general
M: motor circuit protection
R: semi conductor protection
S: semi conductor protection
Tr: transformer protection

Note that even for the same fuse rating, operating times for high currents can vary considerably depending on type i.e. whether ’fast’ (e.g. aR, gR) or ’slow’ types (gG, aM). This has grading implications between upstream and downstream fuses,especially if the upstream device is a ’fast’ fuse. Figure 1.8 shows some HRC fuses

Figure 1.8: HRC fuse types gL, gG, Tr, aM

Fuse Type	Typical Industrial Applications	Operating Range
aM	Motor circuits protection against short circuit only	Partial Range
aR	IEC 269-4 fuse for semi conductor protection	
gG	General purpose fuse essentially for conductor protection	Full Range
gM	Motor protection	
gN	North American fast acting fuse for general purpose applications, mainly for conductor protection. As per UL 248 class J and class L fuses.	
gD	North American general purpose time-delay fuse for motor circuit protection and conductor protection (for example: fuse class AJT, RK5 and A4BQ)	
gTR	Transformer protection	
gR, gS	IEC 269-4 semi conductor and conductor protection	
gL, gF, gl	Former type of fuses for conductor protection replaced today by the gG fuses	

Table 1.1: Fuse types

8- IEC Fuse Classifications

We can see the comparison of the time current curve of 4 different IEC1 fuses rated 100A Figure 1.9. Note the use of log-log scales, to accommodate the very wide range in both currents and operating times involved.

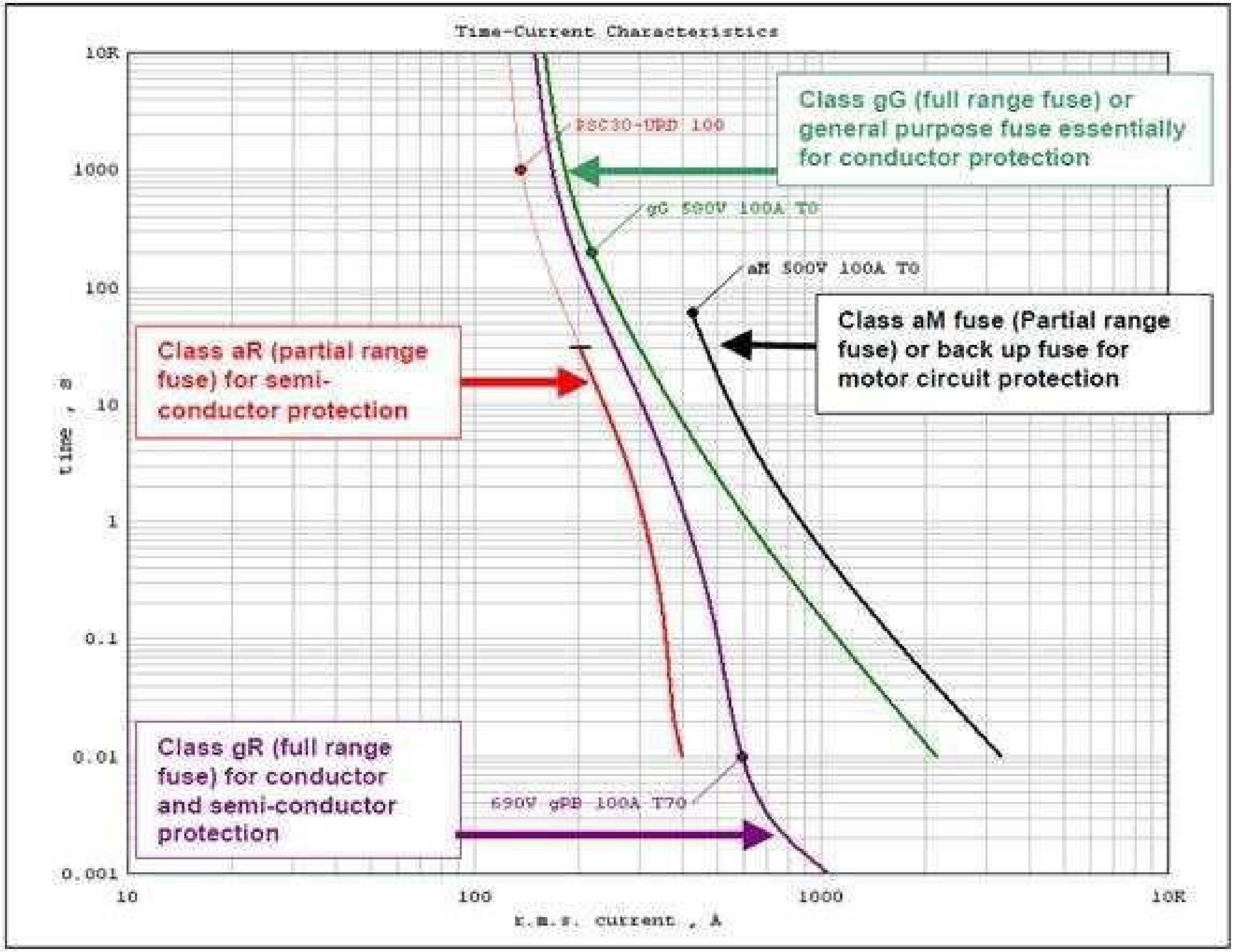


Figure 1.9: Time Current Curve of 4 different EC Fuses Rated 100A

7- Fuse Action

When fault current Figure 1.10 reaches Ic, fuse link melts, see Figure 1.11. This is only for very high current. For lower currents, several cycles will pass before the fuse link gets hot enough to melt. As shown in Figure 1.10, the relationship between the three times is as follow:

Total Clearing Time = Pre-arcing Time + Arcing Time

tt − tp = Arcing Time

Melting Time or Pre-arcing Time : The time taken from the instant the current that causes a break in the fuse wire starts flowing, to instant the arc in initiated.

Arc Time: The time taken from the instant of arc initiation to the instant of arc being extinguished. Total Operating Time: It is the sum of the pre-arcing time and the arcing time.

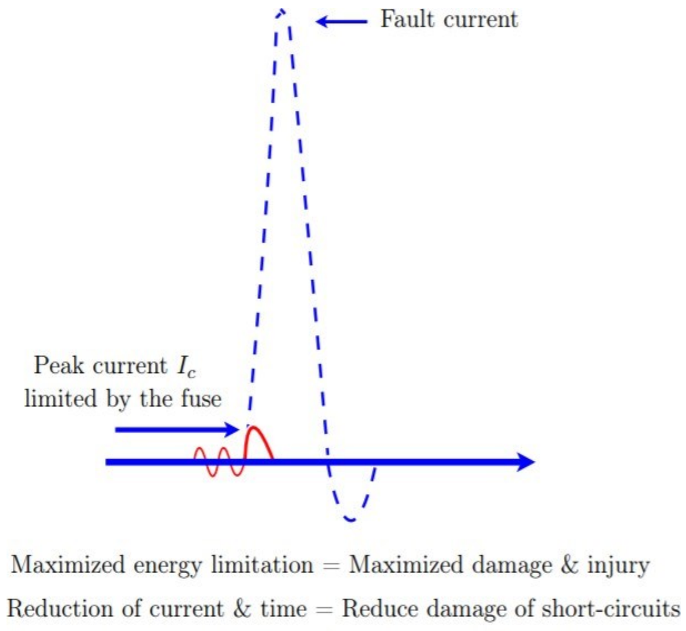


Figure 1.10: Fuse fault current

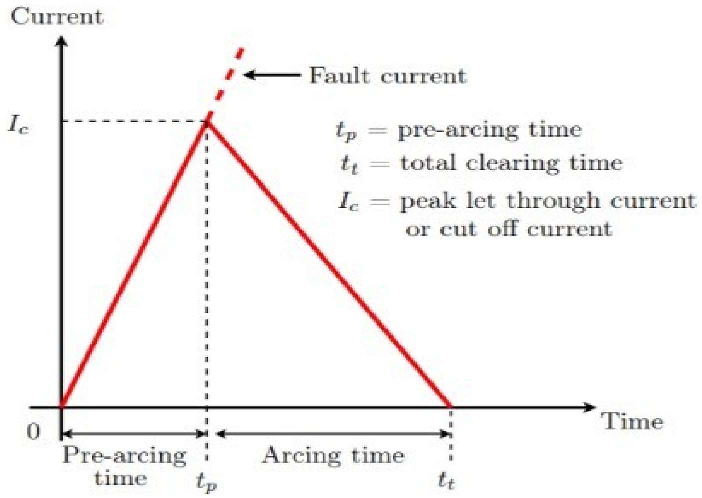


Figure 1.11: Fuse Arcing time

8- Conclusion

The fuse, alone or associated to another protection system is an ideal solution to protect and ensure safely in low voltage and medium voltage distribution circuits, power electronic equipments and DC fed circuit,

Simply Perfect!	
F	**F**ull overcurrent protection, **F**idelity of operation
U	**U**niversal use (gM or gD ideal all-purpose use)
S	**S**electivity, **S**implicity, **S**afely
E	**E**conomical, **E**nergy-limiting, **E**asy-to-use