SELECTION OF FAULT CURRENT FOR A CIRCUIT BREAKER FROM THE LAYOUT OF A TYPICAL SUBSTATION

A thesis submitted to the Department of Electrical and Electronic Engineering, Stamford University of Bangladesh, for the partial fulfillment of the degree of Bachelor of Science in Electrical and Electronic Engineering.

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DECLARATION

This is to certify that this work has been done by us and it has not been submitted elsewhere for the award of any degree.

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Abstract

High-voltage transmission and distribution networks are the backbone of modern power generation and distribution systems. Any type of fault can be very destructive to power system. A great deal of study, development of devices, and design of protection schemes have resulted in continual improvement in the prevention of damage to transmission lines and equipment and interruptions in generation following the occurrence of a fault. The continuity and quality of electricity delivered safely and economically by todays and future's electrical power networks are important for both developed and developing economies. The correct modeling of power system equipment and correct fault analysis of electrical networks are pre-requisite for ensuring safety and they play a critical role in the identification of economic network investments.

Faults on the transmission and distribution system can lead to severe economic losses. Rapid information about the type and the location of the fault can assist the task of repair and maintenance, thereby minimizing the economic effects of power interruption. Usually, faults are considered dangerous because of over current that they create. Circuit breaker is a very unique device which is being used widely for the interruption due to occurrence of a fault in the power system. For the proper selection of circuit breaker it is necessary to find out the maximum fault current that can occur due to a fault in the system.

1.1 Introduction

The continuity and quality of electricity delivered safely and economically by today’s and future’s electrical power networks are important for both developed and developing economies. The correct modeling of power system equipment and correct fault analysis of electrical networks are pre-requisite for ensuring safety and they play a critical role in the identification of economic network investments. Environmental and economic factors require engineers to maximise the use of existing assets which in turn require accurate modeling and analysis techniques.

The fault analysis of a power system is required in order to provide information for the selection of switchgear, setting of relays and stability of system operation. A power system is not static but changes during operation (switching on or off of generators and transmission lines) and during planning (addition of generators and transmission lines).Thus fault studies need to be routinely performed by utility engineers. Faults usually occur in a power system due to insulation failure, flashover, physical damage or human error. These faults may either be three phase in nature involving all three phases in a symmetrical manner, or may be asymmetrical where usually only one or two phases may be involved. Faults may also be caused by either short-circuits to earth or between live conductors, or may be caused by broken conductors in one or more phases. Sometimes simultaneous faults may occur involving both short-circuit and broken conductor faults (also known as open-circuit faults).Balanced three phase faults may be analyzed using an equivalent single phase circuit. With asymmetrical three phase faults, the use of symmetrical components help to reduce the complexity of the calculations as transmission lines and components are by and large symmetrical, although the fault may be asymmetrical. Fault analysis is usually carried out in per-unit quantities (similar to percentage quantities) as they give solutions which are somewhat consistent over different voltage and power ratings, and operate on values of the order of unity.

For the correct application of protection equipment, it is essential to know the fault current distribution throughout the system and the voltages in different parts of the system due to the fault. Further, boundary values of current at any relaying point must be known if the fault is to be cleared with discrimination. The information normally required for each kind of fault at each relaying point is:

i. Maximum fault current
ii. Minimum fault current
iii. Maximum through fault current

To obtain the above information, the limits of stable generation and possible operating conditions, including the method of system earthing, must be known. Faults are always assumed to be through zero fault impedance.

The most important types of faults are as follows:
A. single-phase to earth
B. phase to phase
C. phase-phase-earth
D. three-phase (with or without earth)

The above faults are described as single shunt faults because they occur at one location and involve a connection between one phase and another or to earth.In addition, the Protection Engineer often studies two other types of fault:

1. Single-phase open circuit
2. Cross-country fault

By determining the currents and voltages at the fault point, it is possible to define the fault and connect the sequence networks to represent the fault condition. From the initial equations and the network diagram, the nature of the fault currents and voltages in different branches of the system can be determined. For shunt faults of zero impedance, and neglecting load current, the equations defining each fault (using phase neutral values) can be written down as follows:

a. Single-phase-earth (A-E)

$$\left.\begin{aligned} \bar{I}_b &= 0 \\ \bar{I}_c &= 0 \\ \bar{V}_a &= 0 \end{aligned}\right\}$$

b. Phase-phase (B-C)

$$\left.\begin{aligned} \bar{I}_a &= 0 \\ \bar{I}_b &= -\bar{I}_c \\ \bar{V}_b &= \bar{V}_c \end{aligned}\right\}$$

c. Phase-phase-earth (B-C-E)

$$\left.\begin{aligned} \bar{I}_a &= 0 \\ \overline{V}_b &= 0 \\ \overline{V}_c &= 0 \end{aligned}\right\}$$

d. Three-phase (A-B-C or A-B-C-E)

$$\left.\begin{aligned} \bar{I}_a + \bar{I}_b + \bar{I}_c &= 0 \\ \overline{V}_a &= \overline{V}_b \\ \overline{V}_b &= \overline{V}_c \end{aligned}\right\}$$

It should be noted from the above that for any type of fault there are three equations that define the fault conditions.

In a practical power system, the system regulation is such that the load voltage at any point in the system is within 10% of the declared open-circuit voltage at that point. For this reason, it is usual to regard the pre-fault voltage at the fault as being the open-circuit voltage, and this assumption is also made in a number of the standards dealing with fault level calculations.

2.1 Faults - Types

It is not practical to design and build electrical equipment or networks so as to completely eliminate the possibility of failure in service. It is therefore an everyday fact of life that different types of faults occur on electrical systems, however infrequently, and at random locations. Faults can be broadly classified into two main areas which have been designated “Active” and “Passive”.

Active Faults

The “Active” fault is when actual current flows from one phase conductor to another (phase-to-phase) or alternatively from one phase conductor to earth (phase-to-earth).This type of fault can also be further classified into two areas, namely the “solid” fault and the “incipient” fault.

The solid fault occurs as a result of an immediate complete breakdown of insulation as would happen if, say, a pick struck an underground cable, bridging conductors etc. or the cable was dug up by a bulldozer. In mining, a rock fall could crush a cable as would a shuttle car. In these circumstances the fault current would be very high, resulting in an electrical explosion.

This type of fault must be cleared as quickly as possible, otherwise there will be:

1. Greatly increased damage at the fault location.
   (Fault energy = 1^2 x Rf x t where t is time).
2. Danger to operating personnel (Flash products).
3. Danger of igniting combustible gas such as methane in hazardous areas giving rise to a disaster of horrendous proportions.
4. Increased probability of earth faults spreading to other phases.

The “incipient” fault, on the other hand, is a fault that starts from very small beginnings, from say some partial discharge (excessive electronic activity often referred to as Corona) in a void in the insulation, increasing and developing over an extended period, until such time as it burns away adjacent insulation, eventually running away and developing into a “solid” fault.

Other causes can typically be a high-resistance joint or contact, alternatively pollution of insulators causing tracking across their surface. Once tracking occurs, any surrounding air will ionise which then behaves like a solid conductor consequently creating a “solid” fault

Passive Faults

Passive faults are not real faults in the true sense of the word but are rather conditions that are stressing the system beyond its design capacity, so that ultimately active faults will occur.
Typical examples are:

1. Overloading - leading to overheating of insulation (deteriorating quality, reduced life and ultimate failure).
2. Over voltage - stressing the insulation beyond its limits.
3. under frequency - causing plant to behave incorrectly.
4. Power swings - generators going out-of-step or synchronism with each other.

2.1.1 Types of Faults on a Three Phase System

The types of faults that can occur on a three phase A.C. system are as follows:

(A) Phase-to-earth fault
(B) Phase-to-phase fault
(C) Phase-to-phase-to-earth fault

(D) Three phase fault
(E) Three phase-to-earth fault
(F) Phase-to-pilot fault *
(G) Pilot-to-earth fault *
* In underground mining applications only

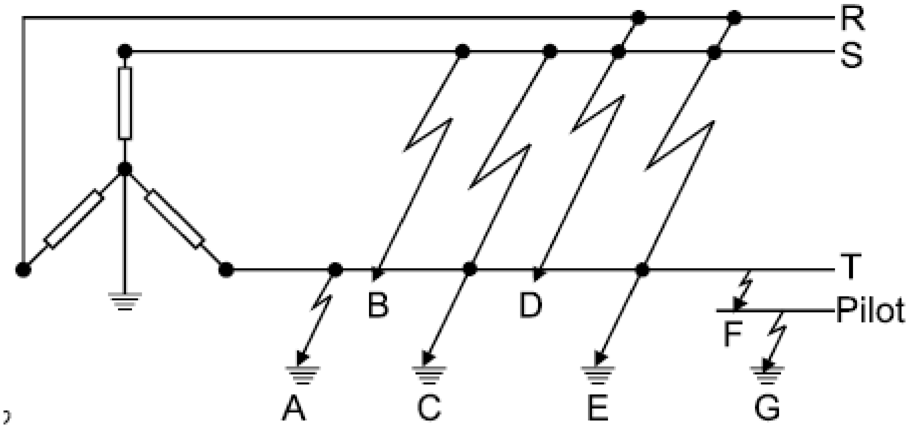


Fig: Types of Fault in 3-Phase System

It will be noted that for a phase-to-phase fault, the currents will be high, because the fault current is only limited by the inherent (natural) series impedance of the power system up to the point of faulty (refer Ohms law).By design, this inherent series impedance in a power system is purposely chosen to be as low as possible in order to get maximum power transfer to the consumer and limit unnecessary losses in the network itself in the interests of efficiency. On the other hand, the magnitude of earth faults currents will be determined by the manner in which the system neutral is earthed. Solid neutral earthing means high earth fault currents as this is only limited by the inherent earth fault (zero sequence) impedance of the system. It is worth noting at this juncture that it is possible to control the level of earth fault current that can flow by the judicious choice of earthing arrangements for the neutral. In other words, by the use of Resistance or Impedance in the neutral of the system, earth fault currents can be engineered to be at whatever level is desired and are therefore controllable. This cannot be achieved for phase faults.

2.1.2 Transient & Permanent Faults

Transient faults are faults which do not damage the insulation permanently and allow the circuit to be safely re-energised after a short period of time.

A typical example would be an insulator flashover following a lightning strike, which would be successfully cleared on opening of the circuit breaker, which could then be automatically reclosed. Transient faults occur mainly on outdoor equipment where air is the main insulating medium.

Permanent faults, as the name implies, are the result of permanent damage to the insulation. In this case, the equipment has to be repaired and reclosing must not be entertained.

2.1.3 Symmetrical & Unsymmetrical Faults

A **Symmetrical** fault is a balanced fault with the sinusoidal waves being equal about their axes, and represents a steady state condition.

We can say the definition of symmetrical fault is that fault on the power system which gives rise to symmetrical currents (equal fault current in the lines with 120 degree displacement) which is called a symmetrical fault.

An **Unsymmetrical** fault displays a d.c. offset, transient in nature and decaying to the steady state of the symmetrical fault after a period of time.

We can say the definition of unsymmetrical fault is that fault on the power system which gives rise to asymmetrical currents (unequal fault current in the lines with unequal phase displacement) which is called unsymmetrical fault.

3.1 Protective Relay

A **Relay** is an electrically operated switch. Electric current through the coil of the relay creates a magnetic field which attracts a lever and changes the switch contacts. The coil current can be on or off so relays have two switch positions and they are double-throw (changeover) switches.

The role of protective relaying in electric-power-system design and operation is explained by a brief examination of the over-all background. There are three aspects of a power system that will serve the purposes of this examination. These aspects are as follows:

A. Normal operation
B. Prevention of electrical failure.
C. Mitigation of the effects of electrical failure.

3.1.1 Function of Protective Relaying

The function of protective relaying is to cause the prompt removal from service of any element of a power system when it suffers a short circuit, or when it starts to operate in any abnormal manner that might cause damage or otherwise interfere with the effective operation of the rest of the system. The relaying equipment is aided in this task by circuit breakers that are capable of disconnecting the faulty element when they are called upon to do so by the relaying equipment.

Circuit breakers are generally located so that each generator, transformer, bus, transmission line, etc., can be completely disconnected from the rest of the system. These circuit breakers must have sufficient capacity so that they can carry momentarily the maximum short-circuit current that can flow through them, and then interrupt this current; they must also withstand closing in on such a short circuit and then interrupting it according to certain prescribed standards.3 Fusing is employed where protective relays and circuit breakers are not economically justifiable. Although the principal function of protective relaying is to mitigate the effects of short circuits, other abnormal operating conditions arise that also require the services of protective relaying. This is particularly true of generators and motors.

A secondary function of protective relaying is to provide indication of the location and type of failure. Such data not only assist in expediting repair but also, by comparison with human observation and automatic oscillograph records, they provide means for analyzing the effectiveness of the fault-prevention and mitigation features including the protective relaying itself.

3.1.2 FUNDAMENTAL PRINCIPLES OF PROTECTIVE RELAYING

Let us consider for the moment only the relaying equipment for the protection against short circuits. There are two groups of such equipment, one which we shall call primary relaying, and the other back-up relaying. Primary relaying is the first line of defense, where as back-up relaying functions only when primary relaying fails.

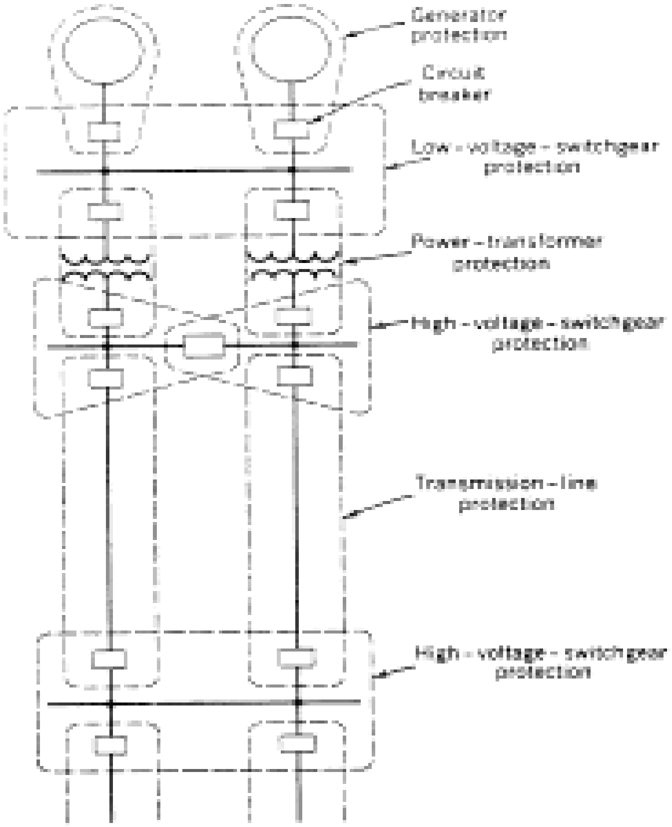


Fig: 1 One-line diagram of a portion of an electric power system illustrating primary relaying.

Figure 1 illustrates primary relaying. The first observation is that circuit breakers are located in the connections to each power element. This provision makes it possible to disconnect only a faulty element. Occasionally, a breaker between two adjacent elements may be omitted, in which event both elements must be disconnected for a failure in either one.

The second observation is that, without at this time knowing how it is accomplished, a separate zone of protection is established around each system element. The significance of this is that any failure occurring within a given zone will cause the tripping (i.e., opening) of all circuit breakers within that zone, and only those breakers. It will become evident that, for failures within the region where two adjacent protective zones overlap, more breakers will be tripped than the minimum necessary to disconnect the faulty element. But, if there were no overlap, a failure in a region between zones would not lie in either zone, and therefore no breakers would be tripped. The overlap is the lesser of the two evils. The extent of the overlap is relatively small, and the probability of failure in this region is low; consequently, the tripping of too many breakers will be quite infrequent. Finally, it will be observed that adjacent protective zones of Fig. 1 overlap around a circuit breaker. This is the preferred practice because, for failures anywhere except in the overlap region, the minimum number of circuit breakers needs to be tripped.

When it becomes desirable for economic or space-saving reasons to overlap on one side of a breaker, as is frequently true in metal-clad switchgear the relaying equipment of the zone that overlaps the breaker must be arranged to trip not only the breakers within its zone but also one or more breakers of the adjacent zone, in order to completely disconnect certain faults. This is illustrated in Fig. 2, where it can be seen that, for a short circuit at X, the circuit breakers of zone B, including breaker C, will be tripped; but, since the short circuit is outside zone A, the relaying equipment of zone B must also trip certain breakers in zone A if that is necessary to interrupt the flow of short circuit current from zone A to the fault. This is not a disadvantage for a fault at X, but the same breakers in zone A will be tripped unnecessarily for other faults in zone B to the right of breaker C. Whether this unnecessary tripping is objectionable will depend on the particular application.

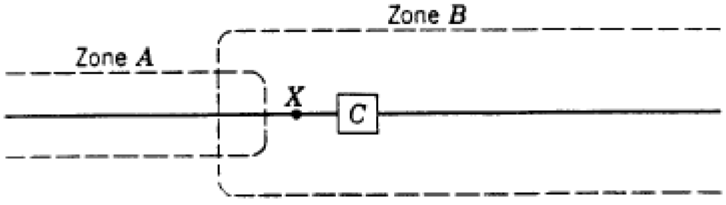


Fig: 2 Overlapping adjacent protective zones on one side of a circuit breaker.

3.1.3 Operation of Protective Relay

All relays used for short-circuit protection, and many other types also, operate by virtue of the current and/or voltage supplied to them by current and voltage transformers connected in various combinations to the system element that is to be protected. Through individual or relative changes in these two quantities, failures signal their presence, type, and location to the protective relays. For every type and location of failure, there is some distinctive difference in these quantities, and there are various types of protective-relaying equipments available, each of which is designed to recognize a particular difference and to operate in response to it more possible differences exist in these quantities than one might suspect. Differences in each quantity are possible in one or more of the following:

A. Magnitude.
B. Frequency.
C. Phase angle.
D. Duration.
E. Rate of change.
F. Direction or order of change.
G. Harmonics or wave shape.

Then, when both voltage and current are considered in combination, or relative to similar quantities at different locations, one can begin to realize the resources available for discriminatory purposes. It is a fortunate circumstance that, although Nature in her contrary way has imposed the burden of electric-power-system failure, she has at the same time provided us with a means for combat.

Aplication of Protective Relay

1. Control a high-current circuit with a low-current signal, as in the starter solenoid of an automobile.
2. To Reduce the effect of fall occurrence By removing faulty section.
3. It gives an Indication about the type of fault
4. It gives an indication about the location of fault.

5. Detect and isolate faults on transmission and distribution lines by opening and closing circuit breakers .
6. Isolate the controlling circuit from the controlled circuit when the two are at different potentials, for example when controlling a mains-powered device from a low-voltage switch.
7. Logic functions.
8. Time delay functions. Relays can be modified to delay opening or delay closing a set of contacts.

4.1 Circuit Breaker

The **Circuit Breakers** are automatic Switches which can interrupt fault currents. The part of the Circuit Breakers connected in one phase is called the pole. A Circuit Breaker suitable for three phase system is called a ‘triple-pole Circuit Breaker. Each pole of the Circuit Breaker comprises one or more interrupter or arc-extinguishing chambers. The interrupters are mounted on support insulators. The interrupter encloses a set of fixed and moving contacts. The moving contacts can be drawn apart by means of the operating links of the operating mechanism. The operating mechanism of the Circuit Breaker gives the necessary energy for opening and closing of contacts of the Circuit Breakers. The arc produced by the separation of current carrying contacts is interrupted by a suitable medium and by adopting suitable techniques for arc extinction.

Circuit breakers are switching devices which according to the American National Standards Association (ANSI) are defined as: "A mechanical device capable of making, carrying and breaking currents under normal circuit conditions and also making, carrying for a specific time and breaking currents under specified abnormal circuit conditions such as those of short circuit."

Historically, as the operating voltages and the short circuit capacities of the power systems have continued to increase, high voltage, high power circuit breakers have evolved trying to keep pace with the growth of the electric power systems. New technologies, primarily those involving the use of advanced interrupting mediums, have been developed and continue to be studied To achieve current interruption some of the early circuit breaker designs simply relied on stretching the arc across a pair of contacts in air. Later, arc chute structures, including some with magnetic blow-out coils were incorporated, while other devices used a liquid medium, including water but more generally oil as the interrupting medium. Some of those early designs have been significantly improved and variations of those types of circuit breakers are still in use, especially in low voltage applications where presently plain air circuit breakers constitute the dominant type of circuit breakers used.

4.1.1 Operation

All circuit breakers have common features in their operation, although details vary substantially depending on the voltage class, current rating and type of the circuit breaker.

The circuit breaker must detect a fault condition; in low-voltage circuit breakers this is usually done within the breaker enclosure. Circuit breakers for large currents or high voltages are usually arranged with pilot devices to sense a fault current and to operate the trip opening mechanism. The trip solenoid that releases the latch is usually energized by a separate battery, although some high-voltage circuit breakers are self-contained with current transformers, protection relays, and an internal control power source.

Once a fault is detected, contacts within the circuit breaker must open to interrupt the circuit; some mechanically-stored energy (using something such as springs or compressed air) contained within the breaker is used to separate the contacts, although some of the energy required may be obtained from the fault current itself. Small circuit breakers may be manually operated; larger units have solenoids to trip the mechanism, and electric motors to restore energy to the springs.

The circuit breaker contacts must carry the load current without excessive heating, and must also withstand the heat of the arc produced when interrupting the circuit. Contacts are made of copper or copper alloys, silver alloys, and other materials. Service life of the contacts is limited by the erosion due to interrupting the arc. Mechanical circuit breakers are usually discarded when the contacts are worn, but power circuit breakers and high-voltage circuit breakers have replaceable contacts.

When a current is interrupted, an arc is generated. This arc must be contained, cooled, and extinguished in a controlled way, so that the gap between the contacts can again withstand the voltage in the circuit. Different circuit breakers use vacuum, air, insulating gas, or oil as the medium in which the arc forms. Different techniques are used to extinguish the arc including:

- Lengthening of the arc
- Intensive cooling (in jet chambers)
- Division into partial arcs
- Zero point quenching[
- Connecting capacitors in parallel with contacts in DC circuits

Finally, once the fault condition has been cleared, the contacts must again be closed to restore power to the interrupted circuit.

4.1.2 Arc interruption

Mechanical low-voltage circuit breakers use air alone to extinguish the arc. Larger ratings will have metal plates or non-metallic arc chutes to divide and cool the arc. Magnetic blowout coils deflect the arc into the arc chute.

In larger ratings, oil circuit breakers rely upon vaporization of some of the oil to blast a jet of oil through the arc.

Gas (usually sulfur hexafluoride) circuit breakers sometimes stretch the arc using a magnetic field, and then rely upon the dielectric strength of the sulfur hexafluoride (SF_6) to quench the stretched arc.

Vacuum circuit breakers have minimal arcing (as there is nothing to ionize other than the contact material), so the arc quenches when it is stretched a very small amount (<2–3 mm). Vacuum circuit breakers are frequently used in modern medium-voltage switchgear to 35,000 volts.

Air circuit breakers may use compressed air to blow out the arc, or alternatively, the contacts are rapidly swung into a small sealed chamber, the escaping of the displaced air thus blowing out the arc.

Circuit breakers are usually able to terminate all current very quickly: typically the arc is extinguished between 30 ms and 150 ms after the mechanism has been tripped, depending upon age and construction of the device.

4.1.3 The Process of Fault Clearing

The Process of Fault Clearing Has The Following Sequence:

1- Fault Occurs. As the fault occurs, the fault impedance being low, the currents increase and the relay gets actuated. The moving part of the relay move because of the increase in the operating torque. The relay takes some time to close its contacts.

2 - Relay contacts close the trip circuit of the Circuit Breaker closes and trip coil is energized.

3 - The operating mechanism starts operating for the opening operation. The Circuit Breaker contacts separate.

4 - Arc is drawn between the breaker contacts. The arc is extinguished in the Circuit Breaker by suitable techniques. The current reaches final zero as the arc is extinguished and does not restrict again.

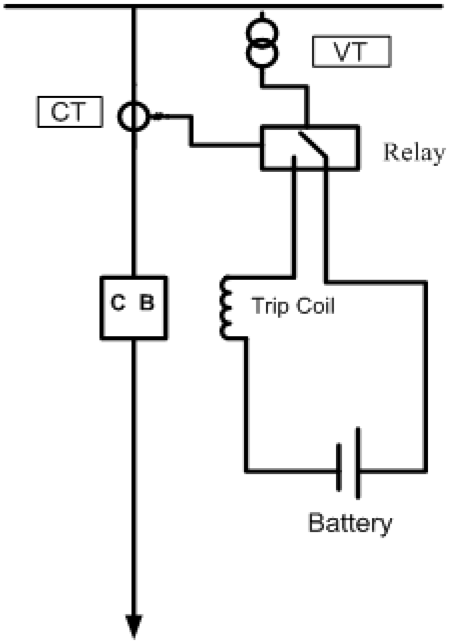


Figure: basic connections of the Circuit Breaker control opening operation.

4.2.1 CIRCUIT BREAKER CLASSIFICATIONS

Circuit breakers can be arbitrarily grouped using many different criteria such as the intended voltage application, the location where they are installed, their external design characteristics, and, perhaps most importantly, by the method and the medium used for the interruption of current.

The type of the circuit breaker is usually identified according to the medium of arc extinction. The classification of the circuit breakers based on the medium of arc extinction is as follows:

(1) Air break circuit breaker
(2) Miniature circuit breaker
(3) Oil circuit breaker
(4) Minimum oil circuit breaker
(5) Air blust circuit breaker
(6) Sulphur hexafluoride(SF_6) circuit breaker
(7) Vacuum circuit breaker
(8) H.V.D.C circuit breaker

4.2.2 Air-Blast Circuit Breaker

Air blast circuit breakers have been applied throughout the complete high voltage range, and until the advent of SF6 circuit breakers, they totally dominated the higher end of the transmission voltage class. In fact, at one time they were the only type of circuit breaker that were available for applications at voltages higher than 345 kV. In reality, air blast circuit breakers should be identified as a specific type of the more generic class of gas blast circuit breakers because air is not necessarily the only gas that can be used to extinguish the arc; other gases such as nitrogen, carbon dioxide, hydrogen, freon and of course SF6 can be used. Furthermore, it is well known, and as is generally agreed, the interrupting process is the same for all gas blast circuit breakers and most of the differences in performance observed between air blast and SF6 circuit breakers are the result of the variations in the cooling capabilities, and therefore in the deionization time constant of each of the gases. When describing the more modern SF6 technology. Because there are some differences in the basic designs of air blast interrupters, and because the newer concepts for gas blast interrupters have evolved from the knowledge gained with the air blast circuit breaker, there are a number of subjects which need to be addressed in this section, if for no other reason than to provide a historical frame of reference.

In all of the designs of air blast circuit breakers the interrupting process is initiated by establishing the arc between two receding contacts and by, simultaneously with the initiation of the arc, opening a pneumatic valve which produces a blast of high pressure air that sweeps the arc column subjecting it to the intense cooling effects of the air flow.

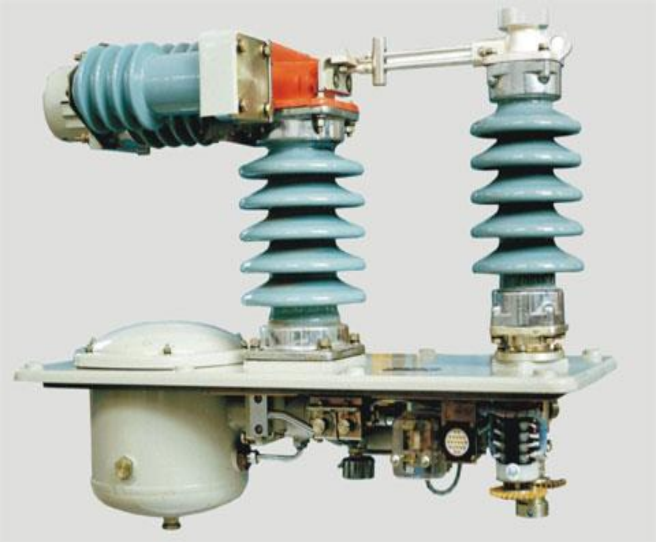


Figure: Air Blast Circuit Breaker

Blast Direction and Nozzle Types

1. Axial blast
2. Radial blast
3. Cross blast

From the three blast types, the axial or the radial type are generally preferred for extra high voltage applications, while the cross blast principle has been used for applications involving medium voltage and very high interrupting currents. To effectively cool the arc the gas flow in an axial blast interrupter must be properly directed towards the location of the arc. Effective control of the gas flow is achieved by using a D'Laval type of a converging-diverging nozzle. These nozzles can be designed either as insulating, or as metallic or conducting nozzles. Additionally and depending on the direction of flow for the exhaust gas, each of the nozzles in these two groups can be either what is called a single or a double flow nozzle.

A conducting single flow nozzle, as shown in Figure, is one where the main stationary contact assembly serves a dual purpose. It carries the continuous current when the circuit breaker is closed and as the circuit breaker opens the arc is initiated across one of its edges and its corresponding mating moving contact. After the gas flow is established, the pneumatic force exerted by the gas on the arc effectively transfers the arc to a stationary arc terminal, or arc catcher, that is disposed longitudinally at the center of the nozzle. It is easily observed that with this design the arc length can be increased considerably and at a faster rate than that which is possible with an insulating nozzle where the arc is initiated directly across a pair of receding arcing contacts. Under these conditions the time needed for the arc to reach its final length is dependent upon the final contact gap and consequently on the opening speed of the circuit breaker contacts that is normally in the range of 3 to 6 meters per second (I 0 to 20 feet per second).

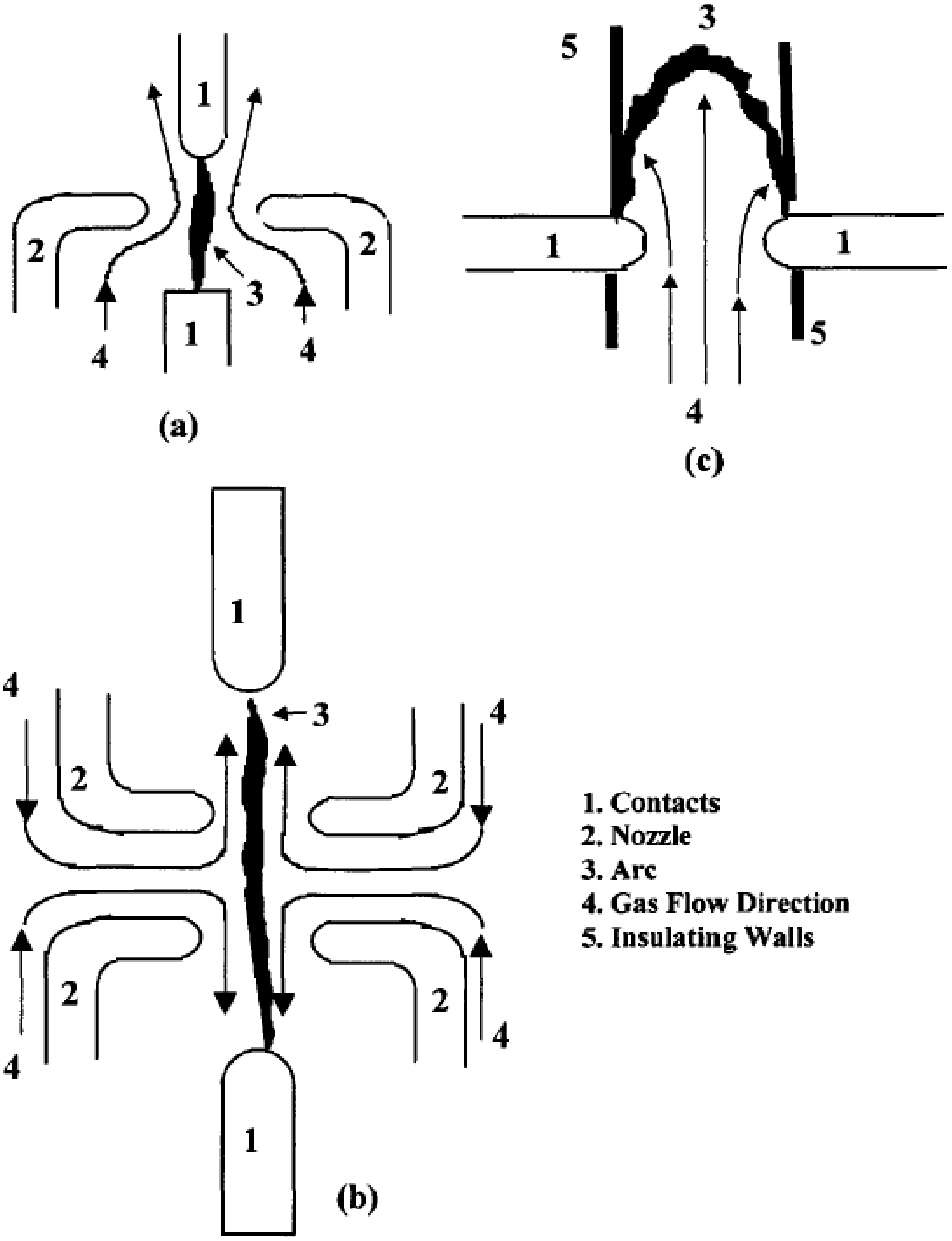


Figure: Air blast direction: (a) axial direction, (b) radial direction, and (c) cross blast or transverse direction.

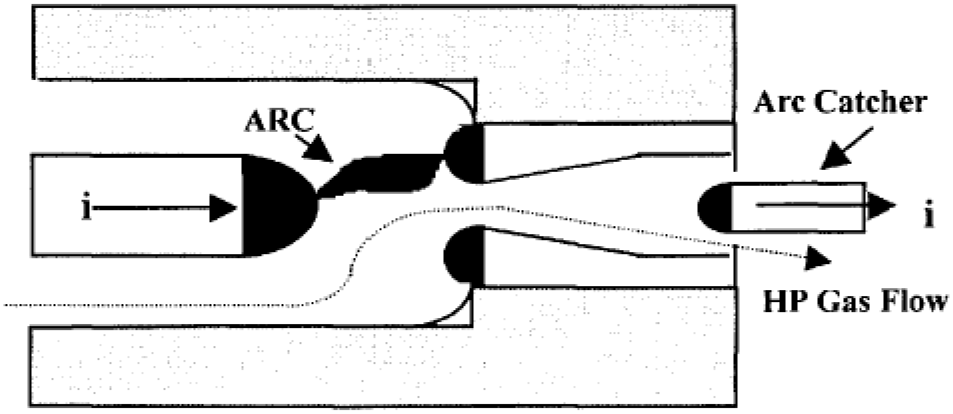


Figure: Outline of a conducting single flow nozzle.

An axial insulating nozzle is geometrically similar to the conducting and as its name implies, the insulating nozzle is made of an insulating material. The material of choice is generally Teflon, either as a pure compound or with some type of filler material. Fillers are used to reduce the rate of erosion of the throat of the nozzle. It should be noted that once the arc is properly attached to the intended arcing contacts, the gas flow characteristics and the interaction between the gas and the arc are the same for both types of nozzles. The cross blast design is among the earliest concepts used on air circuit breakers. As shown schematically in Figure the arc is initiated across a pair of contacts and is subjected to a stream of air that flows perpendicular to the axis of the arc column. It was contended that a considerable amount of heat could be removed from the arc since the whole length of the arc is in contact with the air flow. However, this is not the case, mainly because the core of the arc has a lower density than the surrounding air and therefore at the central part of the arc column there is very little motion between the arc and the gas. Nevertheless, at the regions lying alongside the contacts where the roots of

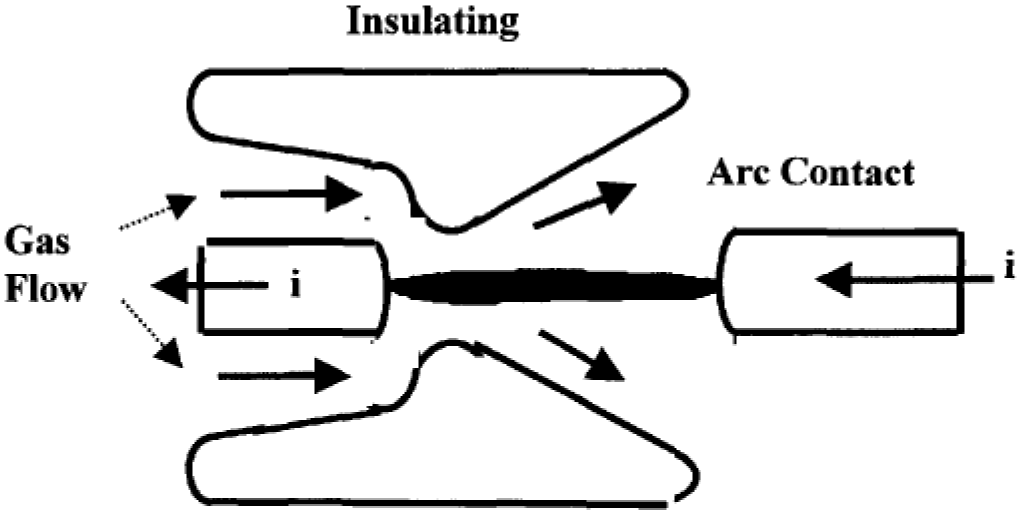


Figure: outline of an axial insulating nozzle.

the arc are being elongated the gas flows in an axial direction and a substantial amount of cooling can be achieved. Most of the circuit breakers that were made using a cross blast were applied only at medium voltages and high currents.

Advantage:

1. There is no fire hazard.
2. The arcing products are completely removed by the blast where as the oil deteriorates with successive operations. The expense of regular of replacement is avoided.
3. The energy supplied for arc extinction is obtained from high pressure air and is independent of the current to be interrupted.
4. Due to lesser arc energy, air blast circuit breakers are very suitable for conditions where frequent operation is required.

4.2.3 Bulk Oil Circuit Breakers

The main distinguishing characteristic of bulk oil circuit breaker types is the fact that these circuit breakers use the oil not only as the interrupting medium but also as the primary means to provide electrical insulation. The original plain break oil circuit breakers obviously belonged to the bulk oil circuit breaker type. Later, the newly developed interrupting chambers were fitted to the existing plain break circuit breakers. Generally this adaptation did not required that any significant modifications be made to the circuit breaker structure and especially to the oil tank. This simple fact, coupled to the good acceptance this type of design had enjoyed, made the bulk oil type concept one of the preferred choices, especially in the US; and the bulk oil circuit breaker simply continued to be fabricated.

Figure: Bulk oil Circuit Breaker

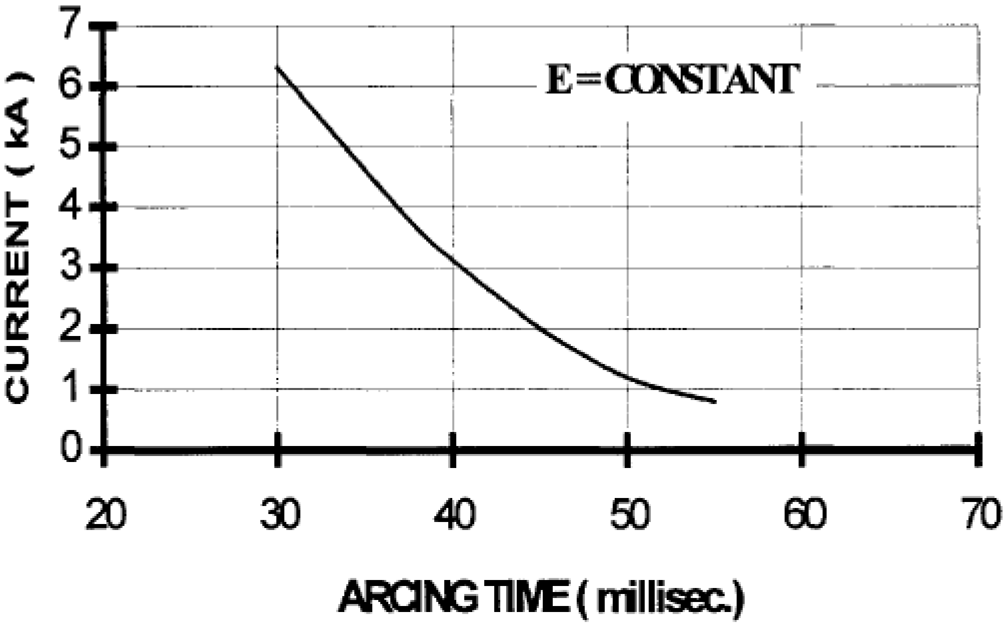


Figure: Oil circuit breaker arcing time as function of current at constant voltage.

In many cases, at voltages that generally extended up to 72.5 kV all three poles were enclosed into a single tank of oil. However, a number of circuit breakers in the medium voltage range had three independent tanks, as did those circuit breakers with voltage ratings greater than 145 kV. The three poles were gang operated by a single operating mechanism.

4.2.4 Minimum Oil Circuit Breakers

Primarily in Europe, because of the need to reduce space requirements and the scarcity and high cost of oil, a type of circuit breaker that used very small volumes of oil was developed. This circuit breaker is the one known by any of the following names: minimum oil, low oil content, or oil poor circuit breaker. The main difference between the minimum oil and the bulk oil circuit breakers is that minimum oil circuit breakers use oil only for the interrupting function while a solid insulating material is used for dielectric purposes, as opposed to bulk oil circuit breakers where oil serves both purposes.

In minimum oil circuit breakers small oil filled, arc interrupting chamber is supported within hollow insulators. These insulators are generally fabricated from reinforced fiberglass for medium voltage applications and from porcelain for the higher voltages The use of insulating supports effectively qualify this design as a live tank circuit breaker. By separating the live parts from ground by means of the insulating support the volume of oil required is greatly decreased as it can be seen in Figure where a typical 15 kV low oil circuit breaker is shown.

Figure: Minimum Oil Circuit Breaker

4.2.5 VACUUM CIRCUIT BREAKERS

Vacuum interrupters take advantage of vacuum because of its exceptional dielectric characteristics and of its diffusion capabilities as an interrupting medium. It should be noted that the remarkable dielectric strength of vacuum is due to the absence of inelastic collisions between the gas molecules which means that there is not an avalanche mechanism to trigger the dielectric breakdown as is the case in gaseous mediums.

Figure: Vacuum Circuit Breaker

Sectional view of a Vacuum Circuit Breaker the most important part is the vacuum interrupter, blown up view of which is given in Figure When the contacts separate, the current to be interrupted initiates a metal vapor arc discharge and flows through this plasma until the next current zero. The arc is then extinguished and the conductive metal vapor condenses on the metal surfaces within a matter of microseconds.

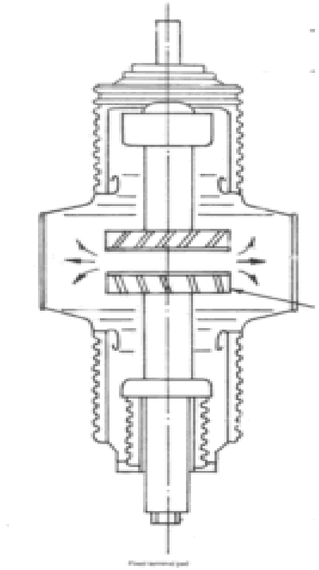


Figure: Blown up view of Vacuum Circuit Breaker

As a result, the dielectric strength in the break builds up very rapidly. The self generated field causes the arc root to travel, thereby preventing local overheating when large currents are being interrupted. Certain minimum current is necessary to maintain the metal vapor arc discharge.

Current of a lesser value is chopped prior to current zero, causing unduly high voltages, as may happen during interruption of no load magnetizing currents of unloaded Transformers.

The rapid build up of the dielectric strength in the break enables the arc to be safely extinguished even if contact separation occurs immediately prior to current zero the maximum arcing time for the last pole to clear is stated to be 15 ms.

Further the arc voltage developed in vacuum interrupter is low (say between 20 to 200 V) due to high conductivity of metal vapor plasma. For there reasons the arc energy developed in the break is very small. High Switching life is claimed on this account. Performance is claimed to be immune to pollution because of interrupters being hermetically sealed.

The manufacturing range Vacuum Circuit Breakers up to rated voltage of 36 kV. Vacuum Circuit Breakers are specially suited in industrial applications, where the Switching frequency is high combined with high degree of pollution.

Advantage:

1. There is no fire hazard.
2. There is no generation of gas during and after operation
3. They have low arc energy.

4.2.6 SULFURHEXAFLUORIDE (SF_6) Circuit Breaker

Sulpherhexafluoride gas is used as the are quenching medium. The SF_6 is an electro negative gas an has a strong tendency to absorb free electrons. The contacts of the breaker are opened in a high pressure flow of SF_6 gas and an arc is struck between them. The conducting free electrons in the arc are rapidly captured by the gas to from relatively immobile negative ions. This loss of conducting electrons in the arc quickly builds up enough insulation strength to extinguish the arc. The SF6 circuit breakers have been found to be very effective for high power and high voltage service.

Construction: It contains of fixed and moving contacts enclosed in a chamber containing SF_6 gas. This chamber is connected to SF_6 gas from the reservoir to flow towards the arc interruption chamber. The fixed contact is also a hollow cylinder with rectangular holes in the sides to permit the SF_6 gas to let out through these holes after flowing along and cross the arc.

Working:

In the closed position of the breaker, the contacts remain surrounded by SF6 gas at a pressure of about 2.8 kg/cm-sq. when the breaker operates the moving contact is pulled apart and an arc is strucked between the contact. The movement of the moving contact is synchronized with the opening of a valve which permits SF6 gas at 14kg/cm ^{2} pressure from the reservoir of the arc interruption chamber. The high pressure flow of SF_6 rapidly absorve the free electron in the arc path to form immobile negative ions which are ineffective as charge carried. After the breaker operation the valve is closed by the action of a set of spring.

Figure: SF_6 Circuit breaker

Advantage:

1. Due to the superior Arc quenching property of SF_6 such circuit breaker have very short arcing time.
2. Since the dielectric strength of SF_6 gas is to 2-3 times that of air, such breaker can interrupt much larger current.
3. The SF_6 circuit breaker gives noiseless operation.
4. There is no risk of fire in SF_6 circuit breaker operation.
5. Since SF_6 circuit breaker are totally enclosed and sealed from atmosphere they are particularly suitable where explosion hazard exist.

Figure: A installed SF_6 Circuit Breaker

4.3 Table: Comparison Between Different Types Of Circuit Breaker

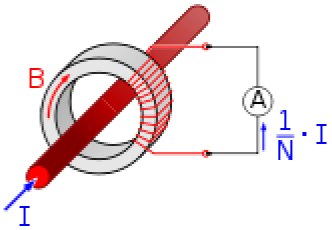
Type	Medium	Voltage-breaking capacity	Design feature	Remark
1.Air-break circuit breaker	Air at atmospheric pressure	430-600 V 5-35MVA	Arc Runner, Arc splitters magnetic coil	1. Used for medium low voltage. 2. Industrial Circuit breaker. 3. Have Current limiting feature.
2.Miniature circuit breaker	Air at atmospheric pressure	430-600V	Small size , current limiting feature	Used low and medium voltages.
3.Bulk-oil circuit breaker	Dielectric oil	12KV, 3.6KV	One tank up to 36KV, 3 tank above 36KV	Getting obsolete used upto 12kv, 500MVA
4.Minimum oil circuit breaker	Dielectric oil	3.6-145 KV	Small size . arc control device used	Used for metal enclosed switch gear up to 36KV. Outdoor between 36 and 145KV
5.Air-blast circuit breaker	Air	245-110KV	Unit type construction	Suitable for all EHV application. Now superseded by SF6 CB for 145 KV and above
6.SF_6 circuit breaker	SF_6 gas($5kg/cm^2$)	145-420KV	One interrupter pole upto 245 kv	Suitable for SF6 switchgear and medium voltage switchgear
7.Vaccum circuit breaker	Vacuum	Up to 36 KV	Verity of design, long life, modest maintenance.	Suitable for a variety of application from 3.6KV to 36KV
8.H.V.D.C circuit breaker	Oil or air-blast	33KV	Artificial current Zero by switching in capacitor	Used for metallic return transfer breaker

4.4 Current Transformer

Practically all electrical measurements and relaying decisions are derived from current and voltage signals. Since relaying hardware works with smaller range of current (in amperes and not kA) and voltage (volts and not kV), real life signals (feeder or transmission line currents) and bus voltages have to be scaled to lower levels and then fed to the relays. This job is done by current and voltage transformers (CTs and VTs). CTs and VTs also electrically isolate the relaying system from the actual power apparatus. The electrical isolation from the primary voltage also provides safety of both human personnel and the equipment. Thus, CT and VTs are the sensors for the relay. CT and VT function like 'ears' and the 'eyes' of the protection system. They listen to and observe all happening in the external world. Relay itself is the brain which processes these signals and issues decision commands implemented by circuit breakers, alarms etc.

In electrical engineering, a current transformer (CT) is used for measurement of electric currents. Current transformers, together with potential transformers (PT), are known as instrument transformers. When current in a circuit is too high to directly apply to measuring instruments, a current transformer produces a reduced current accurately proportional to the current in the circuit, which can be conveniently connected to measuring and recording instruments. A current transformer also isolates the measuring instruments from what may be very high voltage in the monitored circuit. Current transformers are commonly used in metering and protective relays in the electrical power industry.

Like any other transformer, a current transformer has a primary winding, a magnetic core, and a secondary winding. The alternating current flowing in the primary produces a magnetic field in the core, which then induces current flow in the secondary winding circuit. A primary objective of current transformer design is to ensure that the primary and secondary circuits are efficiently coupled, so that the secondary current bears an accurate relationship to the primary current.



The most common design of CT consists of a length of wire wrapped many times around a silicon steel ring passed over the circuit being measured. The CT's primary circuit therefore consists of a single 'turn' of conductor, with a secondary of many hundreds of turns. The primary winding may be a permanent part of the current transformer, with a heavy copper bar to carry current through the magnetic core. Window-type current transformers are also common, which can have circuit cables run through the middle of an opening in the core to provide a single-turn primary winding.

When conductors passing through a CT are not centered in the circular (or oval) opening, slight inaccuracies may occur.

Shapes and sizes can vary depending on the end user or switchgear manufacture. Typical examples of low voltage single ratio metering current transformers are either ring type or plastic moulded case. High-voltage current transformers are mounted on porcelain bushings to insulate them from ground. Some CT configurations slip around the bushing of a high-voltage transformer or circuit breaker, which automatically centers the conductor inside the CT window.

The primary circuit is largely unaffected by the insertion of the CT. The rated secondary current is commonly standardized at 1 or 5 amperes. For example, a 4000:5 CT would provide an output current of 5 amperes when the primary was passing 4000 amperes. The secondary winding can be single ratio or multi ratio, with five taps being common for multi ratio CTs. The load, or burden, of the CT should be of low resistance. If the voltage time integral area is higher than the core's design rating, the core goes into saturation towards the end of each cycle, distorting the waveform and affecting accuracy. Current transformers are used extensively for measuring current and monitoring the operation of the power grid. Along with voltage leads, revenue-grade CTs drive the electrical utility's watt-hour meter on virtually every building with three-phase service, and every residence with greater than 200 amp service.

The CT is typically described by its current ratio from primary to secondary. Often, multiple CTs are installed as a "stack" for various uses. For example, protection devices and revenue metering may use separate CTs; stacking them provides severability while consolidating the high voltage interface. Similarly, potential transformers such as the CVT are used for measuring voltage and monitoring the operation of the power grid. The accuracy of a CT is directly related to a number of factors including:

- Burden
- Burden class/saturation class
- Rating factor
- Load
- External electromagnetic fields
- Temperature and
- Physical configuration.
- The selected tap, for multi-ratio CT's

The CTs can be classified into following types:

1. Measurement CTs

2. Protection CTs

A measurement grade CT has much lower VA capacity than a protection grade CT. A measurement CT has to be accurate over its complete range e.g. from 5% to 125% of normal current. In other words, its magnetizing impedance at low current levels. (and hence low flux levels) should be very high. Note that due to non-linear nature of B-H curve, magnetizing impedance is not constant but varies over the CT's operating range In contrast, for a protection grade CT, linear response is expected up to 20 times the rated current. Its performance has to be accurate in the range of normal currents and upto fault currents. Specifically, for protection grade CT's magnetizing impedance should be maintained to a large value in the range of the currents of the order of fault currents.

When a CT is used for both the purposes, it has to be of required accuracy class to satisfy both accuracy conditions of measurement CTs and protection CTs. In other words, it has to be accurate for both very small and very large values of current. Typically, CT secondary rated current is standardized to 1A or 5A (more common).

4.5 Voltage transformers / Potential Transformer

Voltage transformers (VT) or potential transformers (PT) are another type of instrument transformer, used for metering and protection in high-voltage circuits. They are designed to present negligible load to the supply being measured and to have a precise voltage ratio to accurately step down high voltages so that metering and protective relay equipment can be operated at a lower potential. Typically the secondary of a voltage transformer is rated for 69 V or 120 V at rated primary voltage, to match the input ratings of protection relays.

The transformer winding high-voltage connection points are typically labeled as H_1, H_2 (sometimes H_0 if it is internally grounded) and X_1, X2 and sometimes an X_3 tap may be present. Sometimes a second isolated winding (Y_1, Y_2, Y_3) may also be available on the same voltage transformer. The high side (primary) may be connected phase to ground or phase to phase. The low side (secondary) is usually phase to ground.

The terminal identifications (H_1, X_1, Y_1, etc.) are often referred to as polarity. This applies to current transformers as well. At any instant terminals with the same suffix numeral have the same polarity and phase. Correct identification of terminals and wiring is essential for proper operation of metering and protection relays.

While VTs were formerly used for all voltages greater than 240 V primary, modern meters eliminate the need VTs for most secondary service voltages. VTs are typically used in circuits where the system voltage level is above 600 V. Modern meters eliminate the need of VT's since the voltage remains constant and it is measured in the incoming supply.

5.1 Per-Unit Calculations

The transmission system and several portions of the distribution system are operated at voltages in the kilovolt (kV) range. This results in large amounts of power being transmitted in the range of kilowatts to megawatts, and kilovolt amperes to mega voltamperes. As a result, in analysis, it is useful to scale, or normalize quantities with large physical values. This is commonly done in power system analysis and is referred to as the per-unit system. The calculation of system performance conveniently uses a per-unit representation of voltage, current, impedance, power, reactive power, and apparent power (voltampere). The numerical per-unit value of any quantity is its ratio to the chosen base quantity of the same dimensions. Thus a per-unit quantity is a normalized quantity with respect to a chosen base value.

Historically the per-unit conversion was used to simplify hand calculations. With the advent of the digital computer in power system analysis, this advantage has been eliminated. The conversion however, has several other advantages:

- In the per-unit system of representation, device parameters tend to fall in a relatively fixed range, making erroneous values prominent.
- Ideal transformers are eliminated as circuit elements. This results in a large saving in component representation and reduces computational burden.
- The voltage magnitude throughout a given power system is relatively close to unity in the per-unit system for a power system operating normally. This characteristic provides a useful check on the calculations.

In power system calculations the nominal voltage of lines and equipment is almost always known, so the voltage is a convenient base value to choose. The apparent power (voltampere) is usually chosen as a second base. In equipment this quantity is usually known and makes a convenient base. The choice of these two base quantities will automatically fix the base of current, impedance, and admittance. In a system study, the voltampere base can be selected to be any convenient value such as 100 MVA, 200 MVA, etc.

The same voltampere base is used in all parts of the system. One base voltage in a certain part of the system is selected arbitrarily. All other base voltages must be related to the arbitrarily selected one by the turns ratio of the connecting transformers.

For single-phase systems, or three-phase systems where the term current refers to line current, where the term voltage refers to line to neutral voltage, and where the term kilovoltamperes refers to kilovoltamperes per phase, the following formulae relate the various quantities:

$$\text{Base current , A} = \frac{\text{base, } kVA_{1\phi}}{\text{base voltage , } kV_{LN}} \tag{1}$$

$$\text{Base impedance}\ ,\ \Omega = \frac{\text{base voltage}\ ,\ V_{LN}}{\text{base current}\ ,\ A} \tag{2}$$

$$\text{Base impedance}\ ,\ \Omega = \frac{(\text{base voltage}\ ,\ kV_{LN})^2 \times 1000}{\text{base}\ kVA_{1\phi}} \tag{3}$$

$$\text{Base impedance}\ ,\ \Omega = \frac{(\text{base voltage}\ ,\ kV_{LN})^2}{MVA_{1\phi}} \tag{4}$$

$$\text{Base power}\ ,\ kW_{1\phi} = \text{base}\ kVA_{1\phi} \tag{5}$$

$$\text{Base power}\ ,\ MW_{1\phi} = \text{base}\ MVA_{1\phi} \tag{6}$$

$$\text{Per - unit impedance of an element} = \frac{\text{actual impedance}\ ,\ \Omega}{\text{base impedance}\ ,\ \Omega} \tag{7}$$

In performing per-phase analysis, the bases for the quantities in the circuit representation are kilovoltamperes per-phase, and kilovolts from line to neutral. System specification is usually given in terms of total three-phase kilovoltamperes or megavoltamperes and line-to-line kilovolts. This may result in some confusion regarding the relation between the per-unit value of line-to-line voltage and the per-unit value of phase voltage or line to neutral voltage. In a per-phase circuit, the voltage required for the solution is the line to neutral voltage even though a line-to-line voltage may be specified as a base. The base value of the line to neutral voltage is the base value of the line-to line voltage divided by $\sqrt{3}$. Since this is also the relation between line-to-line and line to neutral voltages of a balanced three-phase system, the per-unit value of a line to neutral voltage on the line to neutral voltage base is equal to the per-unit value of the line-to-line voltage at the same point on the line-to -line voltage base if the system is balanced. Similarly, the three-phase kilovoltamperes is three times the kilovoltamperes per-phase, and the base value of the three-phase kilovoltamperes is three times the base value of the per-phase kilovoltamperes. Therefore, the per-unit value of the three-phase kilovoltamperes on the three-phase kilovoltampere base is identical to the per-unit value of the kilovoltamperes per-phase on the kilovolampere per-phase base.

The following numerical example clarifies the relationships.

$$\text{Base Three Phase Kilovoltampere} = \text{Base } kVA_{3\phi} = 45,000 \ kVA$$

$$\text{Base Line - to - line Voltage} = \text{Base } kV_{LL} = 180 \ kV$$

We then have ,

$$\text{Base per - phase kilovoltampere} = \text{Base } kVA_{1\phi} = \frac{45,000}{3} = 15,000 \ kVA$$

$$\text{Base line to neutral voltage} = \text{Base } kV_{LN} = \frac{180}{\sqrt{3}} = 103.92 \ kV$$

We will now calculate the per-unit quantities for a line-to-line voltage of a 162 kV and a total three-phase power of 24,000 kW.

Line-to-line base

$$\text{Per - unit Voltage} = \frac{162}{180} = 0.90$$

$$\text{Per - unit Power} = \frac{24,000}{45,000} = 0.533$$

Line-to-neutral base

For an actual line-to-line voltage of 162 kV, in a balanced three-phase system, the line to neutral voltage is $162 / \sqrt{3} = 93.5307$ kV, and

$$\text{Per - unit voltage} = \frac{93.5307}{103.92} = 0.90$$

For a total three-phase power of 24,000 kW the power per-phase is 24,000/3 = 8000 kW, and

$$\text{Per - unit power} = \frac{8000}{15000} = 0.533$$

Throughout the above discussion megavoltampere and megawatt may be substituted for kilovoltampere and kilowatt respectively. Conventionally, a given value of base voltage in a three-phase system is a line-to-line voltage, and a given value of base kilovoltamperes or base megavoltamperes is the total three-phase base.

The values of base impedance and base current can be computed from base values of voltage and voltamperes as shown earlier in the section. If the base values of voltamperes and voltage are specified as the voltamperes for the total three phases and voltage from line-to-line in a balanced three phase system respectively, we have

$$\text{Base current , A} = \frac{\text{base } kVA_{3\phi}}{\sqrt{3} \times \text{base voltage , } kV_{LL}} \tag{8}$$

$$\text{Base impedance , } \Omega = \frac{(\text{base voltage , } kV_{LL} / \sqrt{3})^2 \times 1000}{\text{base } kVA_{3\phi} / 3} \tag{9}$$

$$\text{Base impedance , } \Omega = \frac{(\text{base voltage , } kV_{LL})^2 \times 1000}{\text{base } kVA_{3\phi}} \tag{10}$$

$$\text{Base impedance , } \Omega = \frac{(\text{base voltage , } kV_{LL})^2}{\text{base } MVA_{3\phi}} \tag{11}$$

Equations (8)-(11) are identical to Eqs. (1)-(4) respectively, except for the subscripts. The subscripts are used to highlight the distinction between working with three-phase quantities and per-phase quantities.

Example

In the circuit shown in Figure 1, a load having an impedance of 39 + j26Ω is fed from a voltage source through a line having an impedance of 1 + j8Ω. The effective, or rms, value of the source voltage is 220 V.

1. Calculate the load current I_L and voltage V_L .
2. Calculate the average and reactive power delivered to the load.
3. Repeat the above calculation in per-unit choosing a base of 220 V for the voltage, and a base of 1500 VA for the for the voltamperes.
4. Verify the values obtained in c) with those obtained in a), and b).

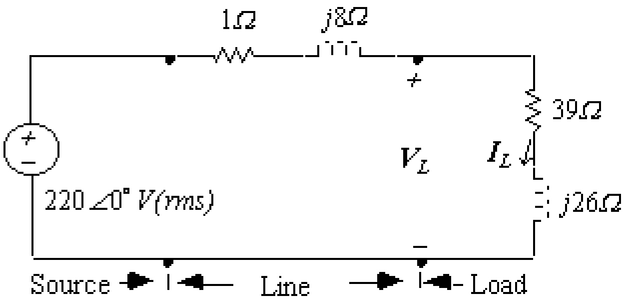


Figure 1.

Solution

1. Since the line and load are in series across the voltage source, the load current equals the voltage divided by the total impedance. Thus

$$I_L = \frac{220 \angle 0^\circ}{40 + j34} = 3.193 - j2.714 = 4.1906 \angle -40.364^\circ A$$

The load voltage is the product of the load current and load impedance:

$$V_L = (39 + j26) I_L = 195.09 - j22.83$$
$$= 196.424\angle -6.674° V$$

1. The average and reactive power delivered to the load is given by

$$S = V_L I_L^* = (195.09 - j22.83)(3.193 + j2.714)$$
$$= 684.889 + j456.592 \ VA$$

1. Voltage Base = 220 V, Voltampere Base = 1500 VA

From Eq. (1) $$\text{Current Base} = \frac{1500}{220} = 6.8181 \ A$$

From Eq. (2) $$\text{Impedance Base} = \frac{220}{6.8181} = 32.267 \ \Omega$$

The circuit diagram in Figure 1 can now be represented in per-unit and the per-unit values of the various quantities are given by

$$V_g = \frac{220\angle 0°}{220\angle 0°} = 1\angle 0° \text{ pu}$$
$$Z_{line} = \frac{1 + j8}{32.267} = 0.03099 + j0.2479 \text{ pu}$$
$$Z_{load} = \frac{39 + j26}{32.67} = 1\ 20867 + j0.805785 \text{ pu}$$

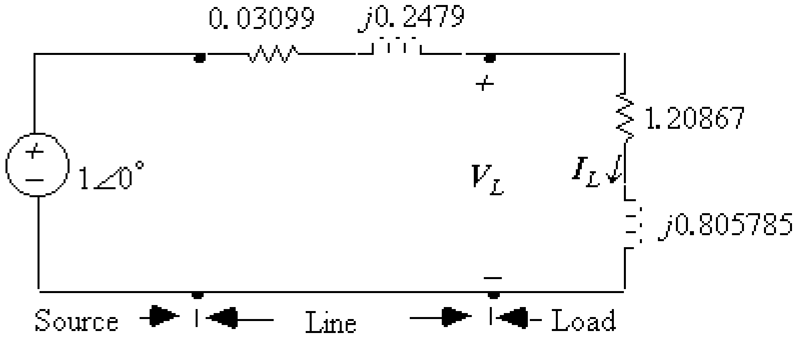


Figure 1.a. Per-Unit Representation

$$I_L = \frac{1\angle 0°}{1.23966 + j1.053685} = 0.614642 \angle -40.364° \text{ pu}$$

$$\boldsymbol{V_L} = (1.20867 + j0.805785)\boldsymbol{I_L} = 0.886805 - j0.103761$$
$$= 0.8928557 \angle -6.674^\circ \text{ pu}$$

$$S = \boldsymbol{V_L}\boldsymbol{I_L}^* = 0.5487866 \angle 33.69^\circ = 0.456618 + j0.3044115 \quad \text{pu}$$

1. In order to verify the per-unit values obtained above, we multiply the per-unit values by their respective base values to obtain the actual value.

$$\boldsymbol{I_L} = 0.614642 \angle -40.364^\circ \times 6.8181 = 4.1906 \angle -40.364^\circ \text{ A}$$

$$\boldsymbol{V_L} = 0.8928557 \angle -6.674^\circ \times 220 = 196.42 \angle -6.674^\circ \text{ V}$$

$$S = (0.456618 + j0.3044115) \times 1500 = 684.899 + j456.592 \text{ VA}$$

These values check with the values obtained in a) and b).

5.1.1 Change of base in per-unit quantities

In most instances, the per-unit impedance of a component is specified on the rated component base which is different from the base selected for the part of the system in which the component is located. When performing calculations, all impedances in any one part of the system must be expressed on the same impedance base. As a result, it is necessary to have a means of converting per-unit impedances from one base to another. Substituting the expression for base impedance given be Eq. (3) or (10) for base impedance in Eq. (7) gives

$$\text{Per-unit impedance} = \frac{(\text{actual impedance}, \Omega) \times (\text{base } kVA)}{(\text{base voltage}, kV)^2 \times 1000} \tag{12}$$

Given a component impedance in per-unit on a specified base, the process of changing this per-unit value of impedance to per-unit on a new base can be done as follows. We shall refer to the base on which the component per-unit value is originally specified as the old base, and the base on which we want to represent it as the new base. From Eq. (12), we can calculate the actual impedance of the component in Ω, given by

$$\text{actual impedance}, \Omega = \frac{(\text{per-unit impedance}_{old}) \times (\text{base voltage}, kV_{old})^2 \times 1000}{(\text{base } kVA_{old})} \tag{13}$$

The per-unit value of the above impedance can now be calculated on the new base by substituting the value of the actual impedance Eq. (13) in Eq. (12) with the choice of the new base for voltage and voltamperes. This gives

$$\text{Per - unit } Z_{new} = \text{Per - unit } Z_{old}\left(\frac{\text{base } kV_{old}}{\text{base } kV_{new}}\right)^2\left(\frac{\text{base } kVA_{new}}{\text{base } kVA_{old}}\right) \quad (14)$$

5.1 Symmetrical fault

Symmetrical fault refers to those conditions in which all three phases of a power system are grounded at the same point. For this reason the symmetrical faults sometimes are also called three-line-to-ground (3LG) faults.

In power engineering, specifically three-phase power, a symmetric, symmetrical or balanced fault is a fault which affects each of the three-phases equally. In transmission line faults, roughly 5% are symmetric. This is in contrast to an asymmetric fault, where the three phases are not affected equally. In practice, most faults in power systems are unbalanced. With this in mind, symmetric faults can be viewed as somewhat of an abstraction; however, as asymmetric faults are difficult to analyze, analysis of asymmetric faults is built up from a thorough understanding of symmetric faults.

Symmetric faults can be analyzed via the same methods as any other phenomena in power systems, and in fact many software tools exist to accomplish this type of analysis automatically (see power flow study). However, there is another method which is as accurate and is usually more instructive.

First, some simplifying assumptions are made. It is assumed that all electrical generators in the system are in phase, and operating at the nominal voltage of the system. Electric motors can also be considered to be generators, because when a fault occurs, they usually supply rather than draw power. The voltages and currents are then calculated for this base case.

Next, the location of the fault is considered to be supplied with a negative voltage source, equal to the voltage at that location in the base case, while all other sources are set to zero. This method makes use of the principle of superposition.

To obtain a more accurate result, these calculations should be performed separately for three separate time ranges:

- subtransient is first, and is associated with the largest currents
- transient comes between subtransient and steady-state
- steady-state occurs after all the transients have had time to settle

5.1.1 Symmetrical Three Phase Fault Analysis

A three phase fault is a condition where either (a) all three phases of the system are shortcircuited to each other, or (b) all three phase of the system are earthed.

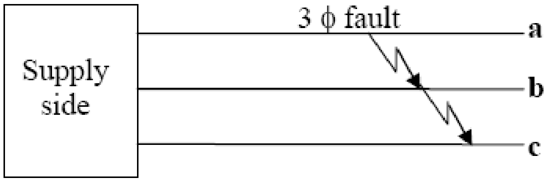


Figure 2.5a – Balanced three phase fault

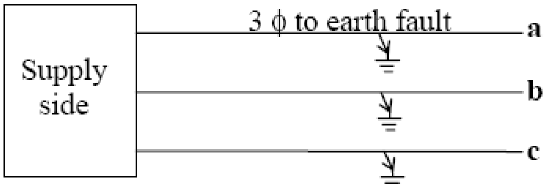


Figure 2.5b – Balanced three phase fault to

This is in general a balanced condition, and we need to only know the positive-sequence network to analyse faults. Further, the single line diagram can be used, as all three phases carry equal currents displaced by 120°.Typically, only 5% of the initial faults in a power system, are three phase faults with or without earth. Of the unbalanced faults, 80 % are line-earth and 15% are double line faults with or without earth and which can often deteriorate to 3 phase fault. Broken conductor faults account for the rest.

5.1.2 Steps for symmetrical fault calculation

3-phase short-circuit faults result in symmetrical fault currents i.e. fault currents in the three phases are equal in magnitude but displayed 120º electrical from one another.Therfore,problems involving such faults can be solved by considering one phase only as the same conditions prevail in the other two phases.The procedure for the solution of such faults involves the following steps:

- Draw a single line diagram of the complete network indicating the rating,voltage and percentage reactance of each element of the network.

- Choose a numerically convenient value of base kVA and convert all percentage reactances to this base value.

- Corresponding to the single line diagram of the network,draw the reactance diagram showing one phase of the system and the neutral,Indicate the % reactances on the base kVA in the reactance diagram.The transformer in the system should be represented by a reactance in series.

- Find the total % reactance of the network upto the point of fault.Let it be X%.
- Find the full-load current corresponding to the selected base kVA and the normal system voltage at the fault point.Let it be I.
- Then various short-circuit calculations are:

Short-circuit current, I_{sc} =I*(100/%X)

Short-circuit kVA =Base kVA*(100/%X)

Example

Consider the power system of Fig. 1 in which a synchronous generator supplies a synchronous motor. The motor is operating at rated voltage and rated MVA while drawing a load current at a power factor of 0.9 (lagging) when a three phase symmetrical short circuit occurs at its terminals. We shall calculate the fault current that flow from both the generator and the motor.

We shall choose a base of 50 MVA, 20 kV in the circuit of the generator. Then the motor synchronous reactance is given by

$$X''_m = 0.2 \times \frac{50}{25} = 0.4 \text{ per unit}$$

Also the base impedance in the circuit of the transmission line is

$$Z_{base} = \frac{66^2}{50} = 87.12 \ \Omega$$

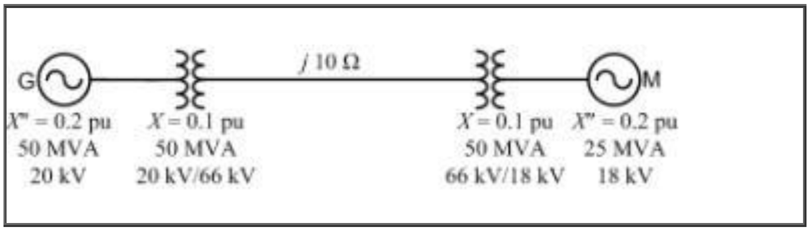


Fig. 1 A generator supplying a motor load though a transmission line.

Therefore the impedance of the transmission line is

$$X_{line} = j\frac{10}{87.12} = j0.1148 \text{ per unit}$$

The impedance diagram for the circuit is shown in Fig. 2 in which the switch S indicates the fault.

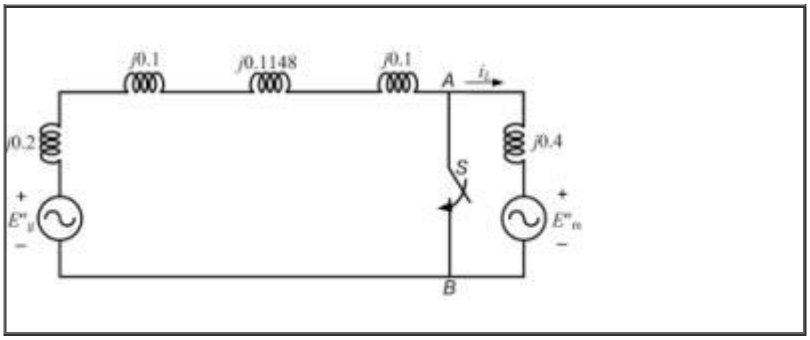


Fig: 2 Impedance diagram of the circuit of Fig. 1

The motor draws a load current at rated voltage and rated MVA with 0.9 lagging power factor. Therefore

$$i_L = 1\angle -\cos^{-1}(0.9) = 0.9 - j0.4359 \text{ per unit}$$

Then the subtransient voltages of the motor and the generator are

$$E''_m = 1.0 - j0.4 \times i_L = 0.8256 - j0.36$$ per unit

$$E''_g = 1.0 + j0.5148 \times i_L = 1.2244 + j0.4633$$ per unit

Hence the subtransient fault currents fed by the motor and the generator are

$$I''_m = \frac{E''_m}{j0.4} = -0.9 - j2.0641$$ per unit

$$I''_g = \frac{E''_g}{j0.5148} = 0.9 - j2.3784$$ per unit

and the total current flowing to the fault is

$$I''_f = I''_g + I''_m = -j4.4425$$ per unit

Note that the base current in the circuit of the motor is

$$I_{base} = \frac{50 \times 10^3}{\sqrt{3} \times 18} = 1603.8$$ A

Therefore while the load current was 1603.8 A, the fault current is 7124.7 A.

5.1.3 Symmetrical Components

Symmetrical Components, first developed by C.L. Fortescue in 1918, is a powerful technique for analysing unbalanced 3 phase systems. Fortescue defined a linear transformation from 3f components to a new set of components called symmetrical components.

The advantage of this transformation is that for balance three phase networks the equivalent circuit obtained for the symmetrical components, called sequence networks, are separated into three uncoupled networks.

Further more, for unbalanced three phase systems, the three sequence networks are connected only at the points of unbalance. As a result, sequence networks for many cases of unbalanced three phase systems are relatively easy to analyse.

The symmetrical component method is basically a modeling technique that permits systematic analysis and design of three phase systems. Decoupling a detailed three phase network into three simpler sequence networks reveals complicated phenomena in more simplistic terms. Sequence network results can then be superimposed to obtain three phase results.

The application of symmetrical components to unsymmetrical fault studies is indespensable.

5.1.4 DEFINITION OF SYMMETRICAL COMPONENTS:

In accordance with Fortescue, the three phase voltages, VR , VY , and V B are resolved into three sets of sequence components:

1. Zero sequence: consisting of three phasors with equal magnitudes and with zero phase displacement.

2. Positive sequence: consisting of three phasors with equal magnitudes, ±120 degree phase displacement and positive sequence.

3. Negative sequence: consisting of three phasors with equal magnitudes, ±120 degree phase displacement and negative sequence.

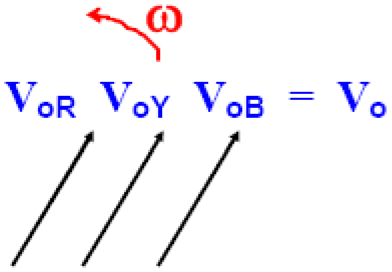


Fig: Zero sequence

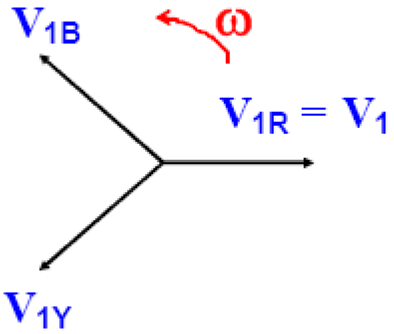


Fig: positive sequence

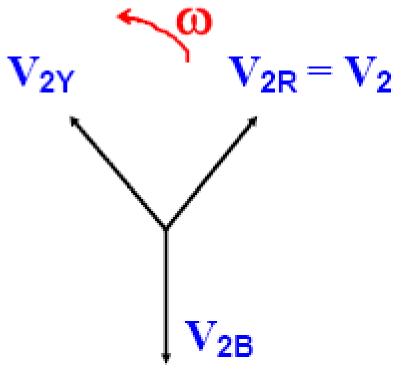
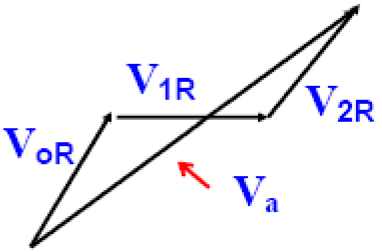


Fig: Negative sequence



$$V_a = V_{oR} + V_{1R} + V_{2R}$$

NOTES:

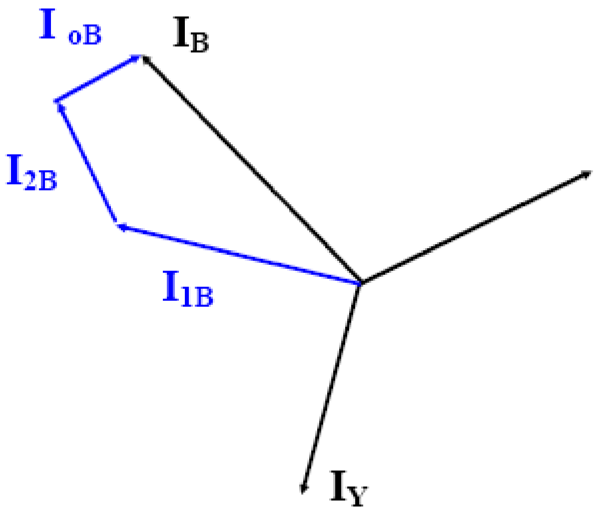
1. The sequence components do not exist as physical quantities in the network.

2. A balanced system has no negative or zero sequence components therefore:
   actual balanced system = positive sequence system

3. The generated emf is balanced, and therefore positive phase sequence only.

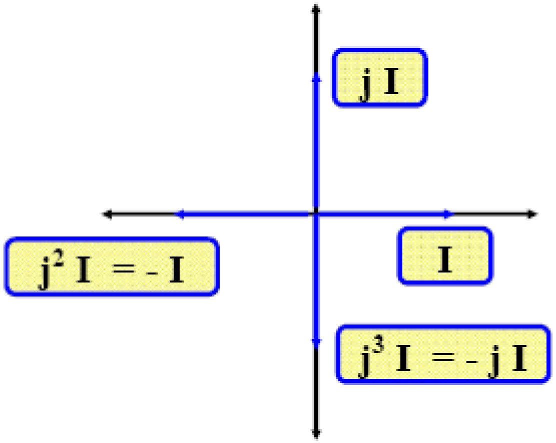
4. In a 3phase 3wire system, there are no zero sequence components, because there is no neutral connection.

ANALYSIS



Notation:

Actual system subscripts	R, Y, B
Positive Phase sequence	1 R, 1Y, 1 B
Negative Phase sequence	2 R, 2 Y , 2 B
Zero Phase sequence	0 R , 0 Y , 0 B



Compare with operator j= √-1
j =1<90˚ =1 <-270˚ = 0 + j1
j 2 =1<1 80˚ =1<-180˚ = - 1+ j 0
j 3 = 1<2 70˚ = 1<- 90˚= 0 - j1
j 4 =1<3 60˚ =1<0˚ =1 + j 0

Multiplication by j = phase shift of + 90˚

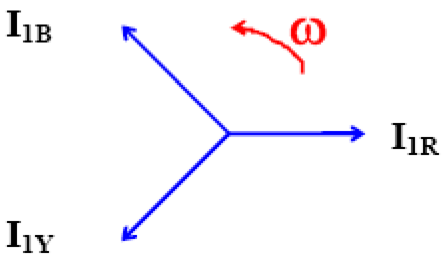
Operator “a” | $I \angle \phi \times "a" \quad = \quad I \angle (\phi + 120^{o})$

For POSITIVE PHASE SEQUENCE

$$I_{1R} = I_{1R}\, e^{j\,0} = \text{reference phasor}$$

$$I_{1Y} = a^2 I_{1R}$$

$$I_{1B} = a \; I_{1R}$$

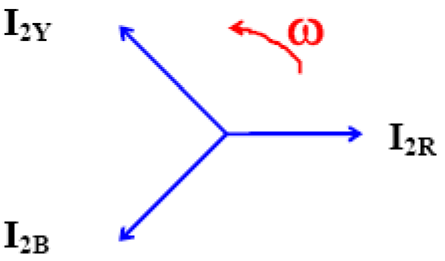


For NEGATIVE PHASE SEQUENCE

$$I_{2R} = reference\ \ phasor$$

$$I_{2Y} = a\ I_{2R}$$

$$I_{2B} = a^2 I_{2R}$$



The UNBALANCED CURRENTS I R, I Y, I B may be expressed as:

$$I_R = I_{1R} + I_{2R} + I_{oR}$$

$$I_Y = I_{1Y} + I_{2Y} + I_{oY} = a^2 I_{1R} + a I_{2R} + I_{oR}$$

$$I_B = I_{1B} + I_{2B} + I_{oB} = a\ I_{1R} + a^2 I_{2R} + I_{oR}$$

All zero sequence components are equal and in phase with I R

In matrix form:

$$\begin{bmatrix} I_R \\ I_Y \\ I_B \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \times \begin{bmatrix} I_{oR} \\ I_{1R} \\ I_{2R} \end{bmatrix}$$

Or inverting the matrix:

$$\begin{bmatrix} I_{oR} \\ I_{1R} \\ I_{2R} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \times \begin{bmatrix} I_R \\ I_Y \\ I_B \end{bmatrix} - Equation\ (1)$$

Similarly for voltage:

$$\begin{bmatrix} V_R \\ V_Y \\ V_B \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \times \begin{bmatrix} V_{oR} \\ V_{1R} \\ V_{2R} \end{bmatrix}$$

And

$$\begin{bmatrix} V_{oR} \\ V_{1R} \\ V_{2R} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \times \begin{bmatrix} V_R \\ V_Y \\ V_B \end{bmatrix} - Equation\ (2)$$

In abbreviated Notation:

$$[I_{RYB}] = [A] \times [I_{120}]$$

$$[I_{120}] = [A]^{-1} \times [I_{RYB}]$$

And similarly for voltages.
Writing Equation (2) as three separate equation:

$$V_{oR} = \frac{1}{3}(V_R + V_Y + V_B) \qquad (i)$$

$$V_{1R} = \frac{1}{3}(V_R + aV_Y + a^2 V_B) \quad (ii)$$

$$V_{2R} = \frac{1}{3}(V_R + a^2 V_Y + aV_B) \quad (iii)$$

Equation (i) shows that there is no zero sequence voltage in a balanced three phase system because the sum of the balanced voltage phasors is zero. In an unbalanced three phase system, line to neutral voltages may have a zero sequence component. But line to line voltages never have a zero sequence component since their sum is always zero.

Likewise from Equation (1) we have that

$$I_{oR} = \frac{1}{3}(I_R + I_Y + I_B) \qquad (iv)$$

Now, in a three phase Y connected system, the neutral current In is the sum of the line currents

$$I_n = I_R + I_Y + I_B$$

Thus,

$$I_n = 3I_o$$

I.e. neutral current equals three times the zero sequence current. Thus in a balanced Y connection, line currents have no zero sequence component, since the neutral current is zero. Also on a three wire system (D connection or ungrounded Y connection),line currents have no zero sequence component.

6.1.1 Unsymmetrical faults

Those faults on the power system which give rise to unsymmetrical currents (unequal fault currents in the lines with unequal phase displacement) are known as unsymmetrical fault.

On the occurrence of an unsymmetrical fault, the currents in the three lines become unequal and so is the phase displacement among them. It may be noted that the term ‘unsymmetry’ applies only to the fault itself and resulting line currents. However, the system impedances and the source voltages are always symmetrical. There are three ways in which unsymmetrical fault may occur in a power system.

1. single line to ground fault (L-G)
2. line to line fault (L-L)
3. double line to ground fault(L-L-G)

The solutions of unsymmetrical fault problems can be obtained by either Kirchhof;s laws or symmetrical components method. The later is preferred because of the following reasons.

1. it is simple method and gives more generality to be given to fault performance studies
2. it provides a useful tool for the protection engineers, particularly in connection with tracing out of fault current.

6.1.2 Analysis of unsymmetrical faults

In the analysis of unsymmetrical faults, the following assumption will be made:

1. The generated e.m.f. system is of positive sequence only.
2. No current flows in the network other than due to fault i.e. load currents are neglected.
3. The impedance of the fault is zero.
4. Phase R shall be taken as the reference phase.

6.1.3 Single-Line-to-Ground Fault

Let a 1LG fault has occurred at node k of a network. The faulted segment is then as shown in Fig where it is assumed that phase-a has touched the ground through an impedance Z_f . Since the system is unloaded before the occurrence of the fault we have

$I_{fb} = I_{fc} = 0$ ……… (1)

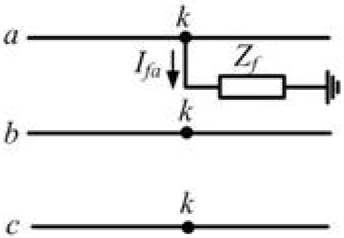


Fig: Representation of 1LG fault

Also the phase-a voltage at the fault point is given by

$V_{ka} = Z_f I_{fa}$ ………(2)

From (1) we can write

$$I_{fa012} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} I_{fa} \\ 0 \\ 0 \end{bmatrix} \quad \text{……………(3)}$$

Solving (3) we get

$$I_{fa0} = I_{fa1} = I_{fa2} = \frac{I_{fa}}{3}$$

This implies that the three sequence currents are in series for the 1LG fault. Let us denote the zero, positive and negative sequence Thevenin impedance at the faulted point as Z_{kk0} , Z_{kk1} and Z_{kk2} respectively.. We can then write

$$V_{ka0} = -Z_{kk0} I_{fa0}$$
$$V_{ka1} = V_f - Z_{kk1} I_{fa1}$$
$$V_{ka2} = -Z_{kk2} I_{fa2} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (4)$$

Then from (4) and (5) we can write

$$V_{ka} = V_{ka0} + V_{ka1} + V_{ka2}$$
$$= V_f - \left(Z_{kk0} + Z_{kk1} + Z_{kk2}\right) I_{fa0} \quad \ldots\ldots\ldots\ldots\ (6)$$

Again since

$$V_{ka} = Z_f I_{fa} = Z_f \left(I_{fa0} + I_{fa1} + I_{fa2}\right) = 3Z_f I_{fa0} \quad \ldots\ldots\ldots\ldots\ (7)$$

We get from (6)

$$I_{fa0} = \frac{V_f}{Z_{kk0} + Z_{kk1} + Z_{kk2} + 3Z_f} \quad \ldots\ldots\ldots\ldots\ldots\ (8)$$

The Thevenin equivalent of the sequence network is shown in Fig.2.

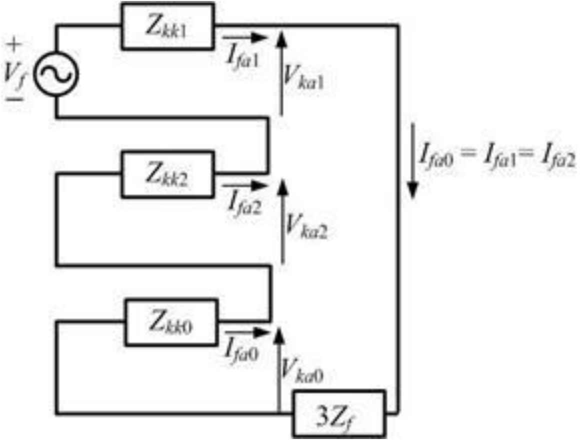


Fig.2 Thevenin equivalent of a 1LG fault.

6.1.4 Line-to-Line Fault

The faulted segment for an L-L fault is shown in Fig where it is assumed that the fault thus occurred at node k of the network. In this the phase's b and c got shorted through the impedance Z_f . Since the system is unloaded before the occurrence of the fault we have

$$I_{fa} = 0 \quad \ldots\ldots\ldots\ldots\ldots\ (1)$$

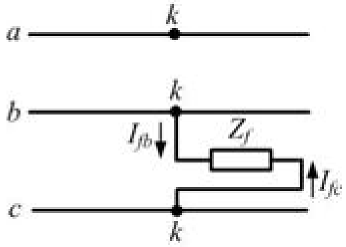


Fig. Representation of L-L fault.

Also since phases b and c are shorted we have

$$I_{fb} = -I_{fc} \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Therefore from (1) and (2) we have

$$I_{fa012} = C\begin{bmatrix} 0 \\ I_{fb} \\ -I_{fb} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 0 \\ \left(a - a^2\right)I_{fb} \\ \left(a^2 - a\right)I_{fb} \end{bmatrix} \ldots\ldots\ldots\ldots\ldots (3)$$

We can then summarize from (3)

$$I_{fa0} = 0$$

$$I_{fa1} = -I_{fa2} \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Therefore no zero sequence current is injected into the network at bus k and hence the zero sequence remains a dead network for an L-L fault. The positive and negative sequence currents are negative of each other. Now from Fig we get the following expression for the voltage at the faulted point

$$V_{kb} - V_{kc} = Z_f I_{fb} \ldots\ldots\ldots\ldots\ldots (5)$$

Again,

$$\begin{aligned} V_{kb} - V_{kc} &= V_{kb0} + V_{kb1} + V_{kb2} - V_{kc0} - V_{kc1} - V_{kc2} \\ &= \left(V_{kb1} - V_{kc1}\right) + \left(V_{kb2} - V_{kc2}\right) \\ &= \left(a^2 - a\right)V_{ka1} + \left(a - a^2\right)V_{ka2} \\ &= \left(a^2 - a\right)\left(V_{ka1} - V_{ka2}\right) \end{aligned} \ldots\ldots\ldots\ldots\ldots (6)$$

Moreover since $I_{fa0} = I_{fb0} = 0$ and $I_{fa1} = -I_{fb2}$, we can write

$$I_{fb} = I_{fb1} + I_{fb2} = a^2 I_{fa1} + aI_{fb2} = \left(a^2 - a\right)I_{fa1} \ldots\ldots\ldots\ldots\ldots (7)$$

Therefore combining (5) - (7) we get

$$V_{ka1} - V_{ka2} = Z_f I_{fa1} \ldots\ldots\ldots\ldots\ldots (8)$$

Equations (5) and (8) indicate that the positive and negative sequence networks are in parallel. The sequence network is then as shown in Fig. 8.6. From this network we get

$$I_{fa1} = -I_{fa2} = \frac{V_f}{Z_{kk1} + Z_{kk2} + Z_f} \quad \text{……………. (9)}$$

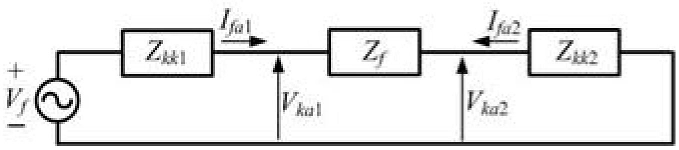


Fig. Thevenin equivalent of an LL fault.

6.1.5 Double- Line -to Ground Fault

The faulted segment for a 2LG fault is shown in Fig where it is assumed that the fault has occurred at node k of the network. In this the phases b and c got shorted through the impedance Z_f to the ground. Since the system is unloaded before the occurrence of the fault we have the same line to line condition as (1) for the phase-a current. Therefore

$$I_{fa0} = \frac{1}{3}\left(I_{fa} + I_{fb} + I_{fc}\right) = \frac{1}{3}\left(I_{fb} + I_{fc}\right)$$
$$\Rightarrow 3I_{fa0} = I_{fb} + I_{fc} \quad \text{............. (1)}$$

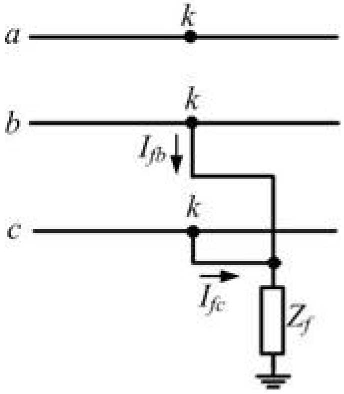


Fig. Representation of 2LG fault.

Also voltages of phases b and c are given by

$$V_{kb} = V_{kc} = Z_f\left(I_b + I_c\right) = 3Z_f I_{fa0} \quad \text{…………… (2)}$$

Therefore,

$$V_{ka012} = C\begin{bmatrix} V_{ka} \\ V_{kb} \\ V_{kb} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} V_{ka} + 2V_{kb} \\ V_{ka} + \left(a + a^2\right)V_{kb} \\ V_{ka} + \left(a + a^2\right)V_{kb} \end{bmatrix} \quad \text{……………. (3)}$$

We thus get the following two equations from (3)

$V_{ka1} = V_{ka2}$ ………………… (4)

$3V_{ka0} = V_{ka} + 2V_{kb} = V_{ka0} + V_{ka1} + V_{ka2} + 2V_{kb}$ ………………. (5)

Substituting (1) and (4) in (5) and rearranging we get

$V_{ka1} = V_{ka2} = V_{ka0} - 3Z_f I_{fa0}$ …………….. (6)

Also since $I_{fa} = 0$ we have

$I_{fa0} + I_{fa1} + I_{fa2} = 0$ ………………. (7)

The Thevenin equivalent circuit for 2LG fault is shown in Fig. From this figure we get,

$$I_{fa1} = \frac{V_f}{Z_{kk1} + Z_{kk2} \| \left(Z_{kk0} + 3Z_f\right)} = \frac{V_f}{Z_{kk1} + \dfrac{Z_{kk2}\left(Z_{kk0} + 3Z_f\right)}{Z_{kk2} + Z_{kk0} + 3Z_f}}$$ ………………… (8)

The zero and negative sequence currents can be obtained using the current divider principle as

$$I_{fa0} = -I_{fa1}\left(\frac{Z_{kk2}}{Z_{kk2} + Z_{kk0} + 3Z_f}\right)$$ ……………… (9)

$$I_{fa2} = -I_{fa1}\left(\frac{Z_{kk0} + 3Z_f}{Z_{kk2} + Z_{kk0} + 3Z_f}\right)$$ …………….. (10)

Example

Consider the network shown in Fig. 8.10. The system parameters are given below

Generator G : 50 MVA, 20 kV, $X'' = X_1 = X_2 = 20\%$, $X_0 = 7.5\%$

Motor M : 40 MVA, 20 kV, $X'' = X_1 = X_2 = 20\%$, $X_0 = 10\%$, $X_n = 5\%$

Transformer T_1 : 50 MVA, 20 kV Δ /110 kVY, X = 10%

Transformer T_2 : 50 MVA, 20 kV Δ /110 kVY, X = 10%

Transmission line: $X_1 = X_2 = 24.2\ \Omega$, $X_0 = 60.5\ \Omega$

We shall find the fault current for when a (a) 1LG, (b) LL and (c) 2LG fault occurs at bus-2.

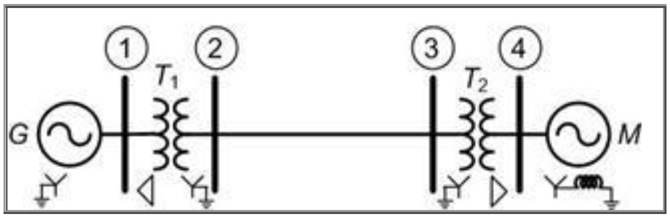


Fig 1. Radial power system

Let us choose a base in the circuit of the generator. Then the per unit impedances of the generator are:

$$X_{G1} = X_{G2} = 0.2, \quad X_{G0} = 0.075$$

The per unit impedances of the two transformers are

$$X_{T1} = X_{T2} = 0.1$$

The MVA base of the motor is 40, while the base MVA of the total circuit is 50. Therefore the per unit impedances of the motor are

$$X_{M1} = X_{M2} = 0.2 \times \frac{50}{40} = 0.25, \quad X_{M0} = 0.1 \times \frac{50}{40} = 0.125, \quad X_n = 0.05 \times \frac{50}{40} = 0.0625$$

For the transmission line

$$Z_{base} = \frac{110^2}{50} = 242\,\Omega$$

Therefore

$$X_{L1} = X_{L2} = \frac{24.2}{242} = 0.1, \quad X_{L0} = \frac{60.5}{242} = 0.25$$

Let us neglect the phase shift associated with the Y/ Δ transformers. Then the positive, negative and zero sequence networks are as shown in Figs. 2-4.

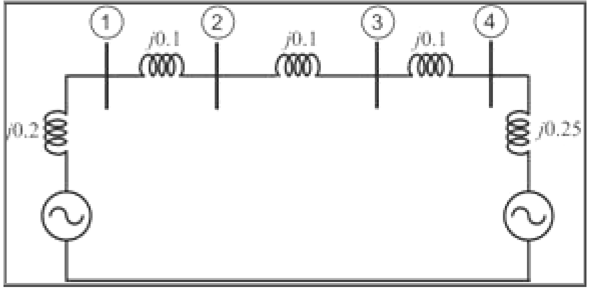


Fig. 2 Positive sequence network of the power system of fig 1

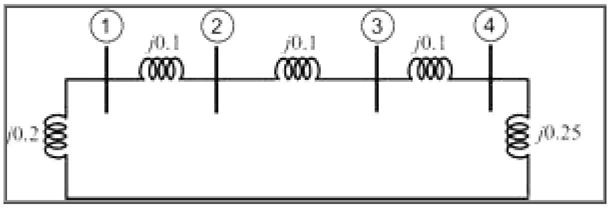


Fig. 3 Negative sequence network of the power system of Fig. 1.

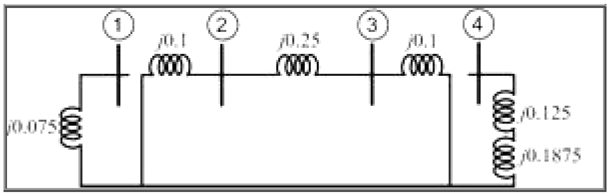


Fig. 4 Zero sequence network of the power system of Fig. 1.

From Figs. 2 and 3 we get the following Y_{bus} matrix for both positive and negative sequences

$$Y_{bus1} = Y_{bus2} = j\begin{bmatrix} -15 & 10 & 0 & 0 \\ 10 & -20 & 10 & 0 \\ 0 & 10 & -20 & 10 \\ 0 & 0 & 10 & 14 \end{bmatrix}$$

Inverting the above matrix we get the following Z_{bus} matrix

$$Z_{bus1} = Z_{bus2} = j\begin{bmatrix} 0.1467 & 0.1200 & 0.0933 & 0.0667 \\ 0.1200 & 0.1800 & 0.1400 & 0.1000 \\ 0.0933 & 0.1400 & 0.1867 & 0.1333 \\ 0.0667 & 0.1000 & 0.1333 & 0.1667 \end{bmatrix}$$

Again from Fig. 4 we get the following Y_{bus} matrix for the zero sequence

$$Y_{bus0} = j\begin{bmatrix} -13.3333 & 0 & 0 & 0 \\ 0 & -14 & 4 & 0 \\ 0 & 4 & -14 & 0 \\ 0 & 0 & 0 & -3.2 \end{bmatrix}$$

Inverting the above matrix we get

$$Z_{bus0} = j\begin{bmatrix} 0.075 & 0 & 0 & 0 \\ 0 & 0.0778 & 0.0222 & 0 \\ 0 & 0.0222 & 0.0778 & 0 \\ 0 & 0 & 0 & 0.3125 \end{bmatrix}$$

Hence for a fault in bus-2, we have the following Thevenin impedances

$$Z_1 = Z_2 = j0.18, \quad Z_0 = j0.0778$$

Alternatively we find from Figs. 2 and 3 that ,

$$\begin{bmatrix} I_{fa} \\ I_{fb} \\ I_{fc} \end{bmatrix} = C^{-1} \begin{bmatrix} 0 \\ I_{fa1} \\ I_{fa2} \end{bmatrix} = \begin{bmatrix} 0 \\ -4.8113 \\ 4.8113 \end{bmatrix}$$

$$Z_1 = Z_2 = j0.3 \| j0.45 = j0.18$$

$$Z_0 = j0.1 \| j0.35 = j0.0778$$

(a) Single-Line-to-Ground Fault

Let a bolted 1LG fault occurs at bus-2 when the system is unloaded with bus voltages being 1.0 per unit. Now we get

$$I_{fa0} = I_{fa1} = I_{fa2} = \frac{1}{j(2\times 0.18 + 0.0778)} = -j2.2841$$ per unit

Now we get

Also I $_{fb}$ = I $_{fc}$ = 0. Now we get the sequence components of the voltages as

$$V_{2a0} = -j0.0778 I_{fa0} = -0.1777$$

$$V_{2a1} = 1 - j0.18 I_{fa1} = 0.5889$$

$$V_{2a2} = -j0.18 I_{fa2} = -0.4111$$

Therefore the voltages at the faulted bus are

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = C^{-1} \begin{bmatrix} V_{2a0} \\ V_{2a1} \\ V_{2a2} \end{bmatrix} = \begin{bmatrix} 0 \\ 0.9061\angle -107.11^\circ \\ 0.9061\angle 107.11^\circ \end{bmatrix}$$

(b) Line-to-Line Fault : For a bolted LL fault, we can write

$$I_{fa1} = -I_{fa2} = \frac{1}{j2\times 0.18} = -j2.7778$$ per unit

Then the fault currents are

$$I_{fa} = 3I_{fa0} = -j6.8524$$ per unit

Finally the sequence components of bus-2 voltages are

$$V_{2a0} = 0$$
$$V_{2a1} = 1 - j0.18 I_{fa1} = 0.5$$
$$V_{2a2} = -j0.18 I_{fa2} = 0.5$$

Hence faulted bus voltages are

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = C^{-1} \begin{bmatrix} V_{2a0} \\ V_{2a1} \\ V_{2a2} \end{bmatrix} = \begin{bmatrix} 1.0 \\ -0.5 \\ -0.5 \end{bmatrix}$$

(c) Double-Line-to-Ground Fault : Let us assumes that a bolted 2LG fault occurs at bus-2. Then

$$Z_{eq} = j0.18 \| j0.0778 = j0.0543$$

Now we get the positive sequence current as

$$I_{fa1} = \frac{1}{j0.18 + Z_{eq}} = -j4.2676$$ per unit

The zero and negative sequence currents are then computed

$$I_{fa0} = -I_{fa1} \frac{j0.18}{j(0.18 + 0.0778)} = j2.9797$$ per unit

$$I_{fa2} = -I_{fa1} \frac{j0.0778}{j(0.18 + 0.0778)} = j1.2879$$ per unit

Therefore the fault currents flowing in the line are

$$\begin{bmatrix} I_{fa} \\ I_{fb} \\ I_{fc} \end{bmatrix} = C^{-1} \begin{bmatrix} I_{fa0} \\ I_{fa1} \\ I_{fa2} \end{bmatrix} = \begin{bmatrix} 0 \\ 6.657\angle 137.11^\circ \\ 6.657\angle 42.89^\circ \end{bmatrix}$$

Furthermore the sequence components of bus-2 voltages are

$$V_{2a0} = -j0.0778 I_{fa0} = 0.2318$$
$$V_{2a1} = 1 - j0.18 I_{fa1} = 0.2318$$
$$V_{2a2} = -j0.18 I_{fa2} = 0.2318$$

Therefore voltages at the faulted bus are

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = C^{-1} \begin{bmatrix} V_{2a0} \\ V_{2a1} \\ V_{2a2} \end{bmatrix} = \begin{bmatrix} 0.6954 \\ 0 \\ 0 \end{bmatrix}$$

7.1 Fault Calculation Of a Typical Indoor Substation

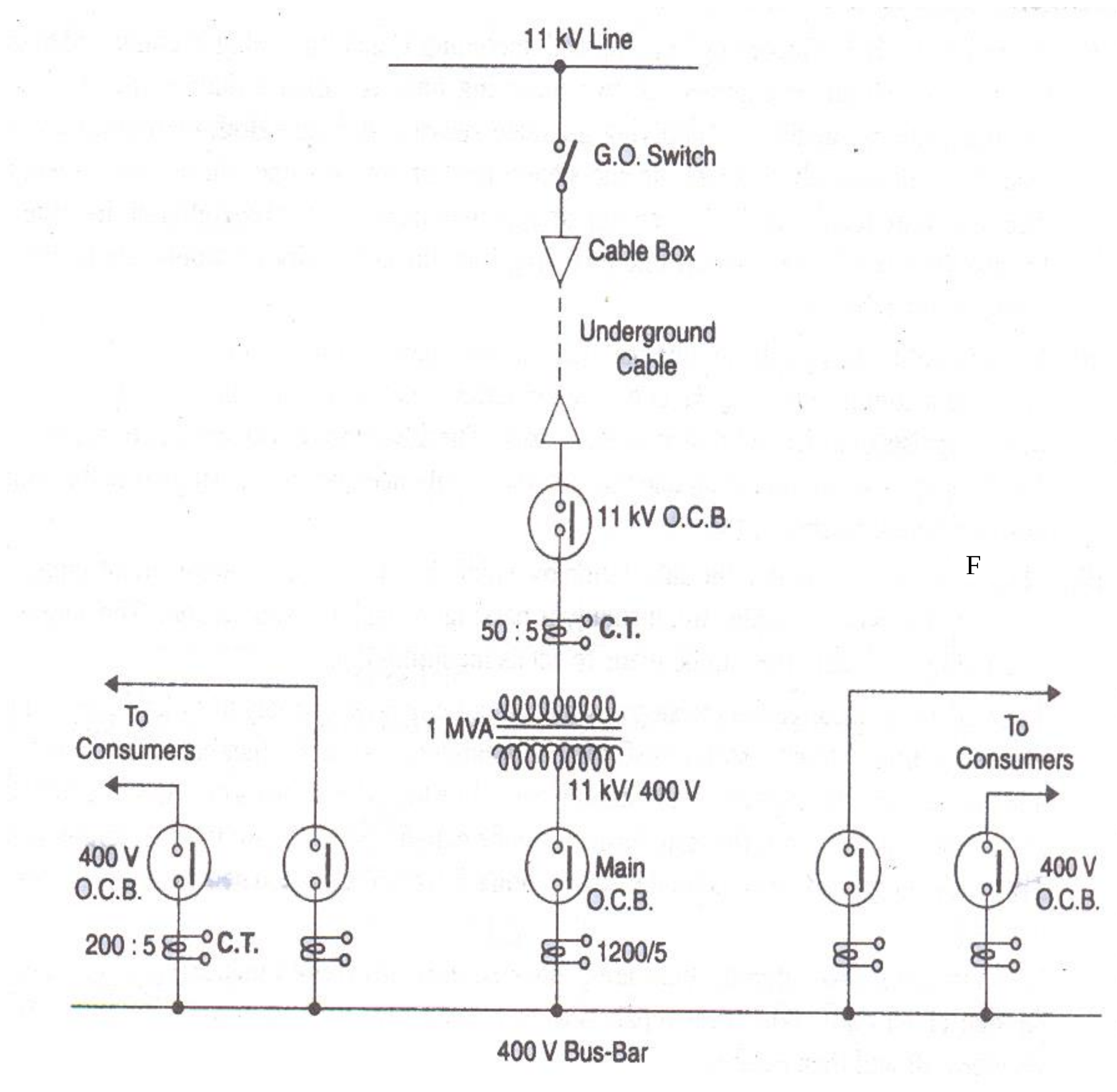


Fig: Layout of a indoor sub-station

The above figure shows the layout of a 11kV/400V indoor sub-station. The rating of the 400V O.C.B is 1500A.Calculate the fault current if

(a) a single line to ground fault occurs at point ‘F’
(b) a double line to ground fault occurs at point ‘F’
(c) a line to line fault occurs a point ‘F’

The base kVA is 1250kVA and base kV is 0.6kV with reactance X1=X2=10%, X0=4% V_f=1(assumed)

Solution:

(a) For single line to ground fault the equivalent sequence networks are connected in series. So

I_{a2}= V_f /(X1+X2+X0)

= (1+j0) / (j0.5+j0.5+j0.2)

= -j0.98 p.u. Amp

$I_{a1} = I_{a2} = I_{a0}$

$I_a = 3I_{a1}$ =3*0.98 p.u.Amp

= 2.94p.u.Amp

Base current in Amp.

=(Base kVA) / (√3*Base kV)

= 1250 / (√3*0.6)

= 1200 Amp.

So the fault current = 1200*2.94

= 3525 Amp.(r.m.s)

As the fault current is greater than the rated current of the circuit breaker, the trip coils of the circuit breaker will be energized and the moving contacts will be pulled apart. This is how the circuit breaker will isolate the faulty section from the system.

(b) For double line to ground fault the Thevenin’s equivalent networks of the three sequence networks will be connected in parallel

$I_{a1} = V_f / [X1+(1/((1/X2)+(1/X0)))$

$= -j15.55$ p.u.

$V_{a1} = V_f – I_{a1}X1$

$= -0.225$ p.u.

$I_{a2} = V_{a1} / X2$

$= +4.5$ p.u.

$I_{a0} = -V_{a1} / X0$

$= j11.00$ p.u.

$I_{a1} = -j15.5$

$I_a = I_{a0} + I_{a1} + I_{a2}$

$= 0$

Fault current I_b for double line to ground fault is

$I_b = I_{a0} + a^2I_{a2} + aI_{a1}$

$= +j11.00 + (-0.5-j0.866)^2(j4.5) + (-0.5+j0.866)(-j15.5)$

$= 22.7$ p.u

$= 22.7*1200 = 27{,}200$ Amp.

In this case the circuit breaker will also activate. But in this type of fault the short-time rating of the circuit breaker must be very low, because the fault current is very high and this amount of high current is very harmful for the system even if it exists for a few seconds.

(c) For a line to line fault the zero sequence network is out of question,it is neglected.The positive sequence networks Thevenin's equivalent and negative sequence network's Thevenin's equivalent are connected in parallel.

$I_{a1} = V_f / (X1 + X2)$

$= -j10$ p.u.Amp

$I_{a2} = -I_{a1} = +j10A$

$I_a = 0+j10-j10$

$= 0$

$I_{a0} = 0$

$I_b = I_{a0} + a^2 I_{a1} + aI_{a2}$

$= -j17.32$ p.u.

$I_c = aI_{a1} + a^2 I_{a2}$

$= j17.32$

Fault current, $I_c = 17.32$ p.u. $= 17.32*1200$

$= 20{,}800$ Amp

So the circuit breaker will be activated as the fault current is greater than the rated current of the circuit breaker.

8.1 Conclusion

The power industry is one of the industries which are growing very fast with thousands of customers being connected to the national grid. This makes the power system to be complex and it becomes difficult to manage. The power system components need to be monitored to make sure that it is adequate to supply the load without breaking down and that customers power is delivered to them in real time and reliably with the frequency and voltage be within the acceptable limits.

Faults on the transmission and distribution system can lead to severe economic losses. Rapid information about the type and the location of the fault can assist the task of repair and maintenance, thereby minimizing the economic effects of power interruption. The planning of future expansion and maintenance of the network requires power fault analysis to be undertaken for adequate decisions to be made.

At present, fault calculation problems in power system are done using digital computers in order to design for protection, transient stability of the system for generators and motors to remain is synchronism under large and small disturbances. For example, DSA is a software developed by Powertech lab(Canada) used for power fault analysis. It contains four packages namely:

1. Voltage Security Assessment Tool (VSAT)
2. Power flow and Short-circuit Assessment Tool (PSAT)
3. Small Signal Assessment Tool (SSAT) and
4. Transient Security Assessment Tool (TSAT).

All this tools focuses on different objectives but yet all are fully integrated to work together. PSAT is used to solve for power flow solution and fault calculations.

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Appendix