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"FAULT LEVEL CALCULATION FROM THE LAYOUT OF A TYPICAL SUBSTATION"

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Lists of symbols

HV/MV/LV high voltage/medium voltage/low voltage
L1, L2, L3 phases of the symmetrical three phase system
R, S, T phases of the symmetrical three phase system
R1, S1, T1 pre-fault measurement
R2, S2, T2 fault measurement
R3, S3, T3 post-fault measurement
SCADA supervision control and data acquisition
1, 2, 0 positive, negative and zero sequence

A total area of the grid, m^2.
C capacitance ,F
C_e phase-to-ground capacitance of the unearthed network
C_o zero-sequence capacitance ,F
D_e equivalent depth of earth return, m
D spacing between parallel conductors, m
D_m maximum distance between any two points on the earth grid, m
D_f current-decrement factor
d diameter of grid conductors, m
E voltage (source), phase voltage ,V
E_m mesh voltage, V
E_s step voltage, V
f frequency ,Hz
h_s surface-layer thickness, m
h depth of earth-grid conductors, m
I current , A
I_C capacitive current , A
I_e earth fault current , A
I_{ef} earth fault current reduced by fault resistance , A
I_f fault current , A
I_L load current , A
I_l current of suppression coil , A
I_P current of the parallel resistor , A
$I_{1,2,0}$ positive, negative and zero sequence current , A
I_f maximum earth-fault current, A
I_r current diverted by overhead earth wires, A
j integer
k load current distribution factor
K_m spacing factor for mesh voltage
K_s spacing factor for step voltage
L inductance
L_C total length of grid conductors, m

L_R total length of earth rods, m
L_r length of earth rods at each location, m
L_p peripheral length of the grid, m
L_M effective buried length of conductors for mesh voltage, m
L_S effective buried length of conductors for step voltage, m
n is the per unit distance between the tap and the fault
n geometric factor composed of factors n_a, n_b, n_c, n_d.
p is the per unit distance between the source and the tap
R resistance, Ω
R_e earthing resistor, Ω
R_f fault resistance, Ω
R_{LE} phase-to-ground resistance of the system
R_P parallel resistor
R_g resistance of the earth grid at IPP station, Ω
r_{gw} resistance of an overhead earth wire, Ω/m
s distance, m
S_f fault current-division factor
t_s duration of shock current, s
$X_{1C,2C,0C}$ positive, negative and zero sequence capacitive reactances
$X_{1l,2l,0l}$ positive, negative and zero sequence line reactances
Y_{in} input admittance of ladder network, 1/Ω
Y total admittance of an overhead earth wire, 1/Ω
Z impedance
$Z_{1,2,0}$ positive, negative and zero sequence impedances
Z_e earthing impedance
Z_f fault impedance
Z_L impedance of the line
Z_T impedance of the transformer
Z_{tap} is the lumped impedance of the tap
Z_{gw} self-impedance of an overhead earth wire, Ω/m
Z_s self-impedance of an overhead earth wire of a tower span, Ω
Z_{tl} impedance of transmission lines, Ω
Z_m mutual impedance between phase conductors and overhead earth wire, Ω
Z_{gm} mutual impedance per metre between phase conductors and overhead earth wire, Ω/m
ω angular frequency
β electric conduction-division factor
ρ_s surface-layer resistivity, Ω-m
ρ_{av} uniform soil resistivity, Ω-m
φ_{Lf} angle between the load and fault current phasors

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Chapter 1

INTRODUCTION

1.1 Introduction:

An electric power system comprises of generation, transmission and distribution of electric energy in the form of alternating current. The electric power is produced at the power stations which are located at favorable places, generally quite away from the consumers. The power houses may be in the midst of population as in the case of steam power houses, the transmission network is inevitable. Long and high voltage transmission lines are necessary to transmit huge blocks of power from the sources of generation to the load centers, to interconnect power houses for increased reliability of supply, greater system stability and lesser standby power plant and hence cheaper electric energy. In between the power houses and ultimate consumers a number of transformation and switching stations have to be created. These are generally known as Substation.

So, Substation is the assembly of apparatus used to change some characteristics such as the conversion from dc to ac, voltage, frequency, power factor of electric supply.

Substation is important part of power system. The continuity of supply depends to a considerable extent upon the successful operation of sub-stations.

Depending on the purpose the Substation are classified as:
Step up Substation, Primary grid Substation, Secondary Substation, Distribution Substation, Bulk Supply and Industrial Substation, Mining Substation, Mobile Substation, Cinematograph Substation.

An electrical substation is a subsidiary station of an electricity generation, transmission and distribution system where voltage is transformed from high to low or the reverse using transformers. Electric power may flow through several substations between generating plant and consumer, and may be changed in voltage in several steps.
A substation that has a step-up transformer increases the voltage while decreasing the current, while a step-down transformer decreases the voltage while increasing the current for domestic and commercial distribution. The word *substation* comes from the days before the distribution system became a grid. The first substations were connected to only one power station where the generator was housed, and were subsidiaries of that power station.

Substations generally contain one or more transformers, and have switching, protection and control equipment. In a large substation, circuit breakers are used to interrupt any short-circuits or overload currents that may occur on the network. Smaller distribution stations may use recloser circuit breakers or fuses for protection of branch circuits. Substations do not (usually) have generators, although a power plant may have a substation nearby. A typical substation will contain line termination structures, high-voltage switchgear, one or more power transformers, low voltage switchgear, surge protection, controls, grounding (earthing) system, and metering.

Other devices such as power factor correction capacitors and voltage regulators may also be located at a substation.

Substations may be on the surface in fenced enclosures, underground, or located in special-purpose buildings. High-rise buildings may have indoor substations. Indoor substations are usually found in urban areas to reduce the noise from the transformers, for reasons of appearance, or to protect switchgear from extreme climate or pollution conditions.

Where a substation has a metallic fence, it must be properly grounded (UK: earthed) to protect people from high voltages that may occur during a fault in the transmission system. Earth faults at a substation can cause ground potential rise at the fault location. Currents flowing in the earth's surface during a fault can cause metal objects to have a significantly different voltage than the ground under a person's feet; this *touch potential* presents a hazard of electrocution.
A transmission substation connects two or more transmission lines. The simplest case is where all transmission lines have the same voltage. In such cases, the substation contains high-voltage switches that allow lines to be connected or isolated for maintenance. A transmission station may have transformers to convert between two transmission voltages, or equipment such as phase angle regulators to control power flow between two adjacent power systems.

1.2 Transmission & Distribution Substations :

Transmission substations can range from simple to complex. A small "switching station" may be little more than a bus plus some circuit breakers. The largest transmission substations can cover a large area (several acres/hectares) with multiple voltage levels, and a large amount of protection and control equipment (capacitors, relays, switches, breakers, voltage and current transformers).

A distribution substation transfers power from the transmission system to the distribution system of an area. It is uneconomical to directly connect electricity consumers to the high-voltage main transmission network, unless they use large amounts of energy; so the distribution station reduces voltage to a value suitable for local distribution.

The input for a distribution substation is typically at least two transmission or subtransmission lines. Input voltage may be, for example, 115 kV, or whatever is common in the area. The output is a number of feeders. Distribution voltages are typically medium voltage, between 2.4 and 33 kV depending on the size of the area served and the practices of the local utility.The feeders will then run overhead, along streets (or under streets, in a city) and eventually power the distribution transformers at or near the customer premises.

Besides changing the voltage, the job of the distribution substation is to isolate faults in either the transmission or distribution systems. Distribution substations may also be the points of voltage regulation, although on long distribution circuits (several km/miles), voltage regulation equipment may also be installed along the line.
Complicated distribution substations can be found in the downtown areas of large cities, with high-voltage switching, and switching and backup systems on the low-voltage side. More typical distribution substations have a switch, one transformer, and minimal facilities on the low-voltage side.

1.3 Fault Calculation Overview

This thesis introduces as main contributions:

- An extended method of fault positions to calculate the fault in the Substation experienced by customers in power distribution networks.
- Analysis of the influence of various network characteristics on experienced by total circuit.
- The calculation is based on by calculating in zero sequence, positive sequence and negative sequence networks.
- Since the faulty part has to be disconnected to protect the certain power system or Substation, some protective device has to be connected to determine the faulty or short circuit over flowed currents.

The thesis consists of a summary with five Chapters and the original papers, which are enclosed as Appendices.

Chapter 2 - General Types of Substation & components of a Substation.

Chapter 3 - General Fault calculation procedures Substation including its Methods.

Chapter 4 - Protection Systems for a different type of fault of Substation applies the developed model and gives examples of calculated and measures.

Chapter 5 - Discussion and Conclusion of the fault calculation of Substation.

Chapter 2

GENERAL TYPES OF SUBSTATION & COMPONENTS

2.1 <u>SINGLE LINE DIAGRAM CONCEPT:</u>

Power systems are extremely complicated electrical networks that are geographically spread over very large areas. For most part, they are also three phase networks – each power circuit consists of three conductors and all devices such as generators, transformers, breakers, disconnects etc. are installed in all three phases. In fact, the power systems are so complex that a complete conventional diagram showing all the connections is impractical. Yet, it is desirable, that there is some concise way of communicating the basic arrangement of power system components. This is done by using Single Line Diagrams (SLD). SLDs are also called One Line Diagrams.

Single Line Diagrams do not show the exact electrical connections of the circuits. As the name suggests, SLDs use a single line to represent all three phases. They show the relative electrical interconnections of generators, transformers, transmission and distribution lines, loads, circuit breakers, etc., used in assembling the power system. The amount of information included in an SLD depends on the purpose for which the diagram is used. For example, if the SLD is used in initial stages of designing a substation, then all major equipment will be included in the diagram – major equipment being transformers, breakers, disconnects and buses. There is no need to include instrument transformers or protection and metering devices. However, if the purpose is to design a protection scheme for the equipment in the substation, then instrument transformers and relays are also included.

There is no universally accepted set of symbols used for single line diagrams. Often used symbols are shown in Fig. 2.1. The variations in symbols are usually minor and are not difficult to understand.

Concept of Bus

Concept of bus in single line diagrams is essentially the same as the concept of a node in an electrical circuit. Just keep in mind that there is one bus for each phase. Buses are shown in SLDs as short straight lines perpendicular to transmission lines and to lines connecting equipment to the buses. In actual substations, the buses are made of aluminum or copper bars or pipes and can be several meters long. The impedance of buses is very low, practically zero, so electrically the whole bus is at the same potential. Of course, there is line voltage between the buses of the individual phases.

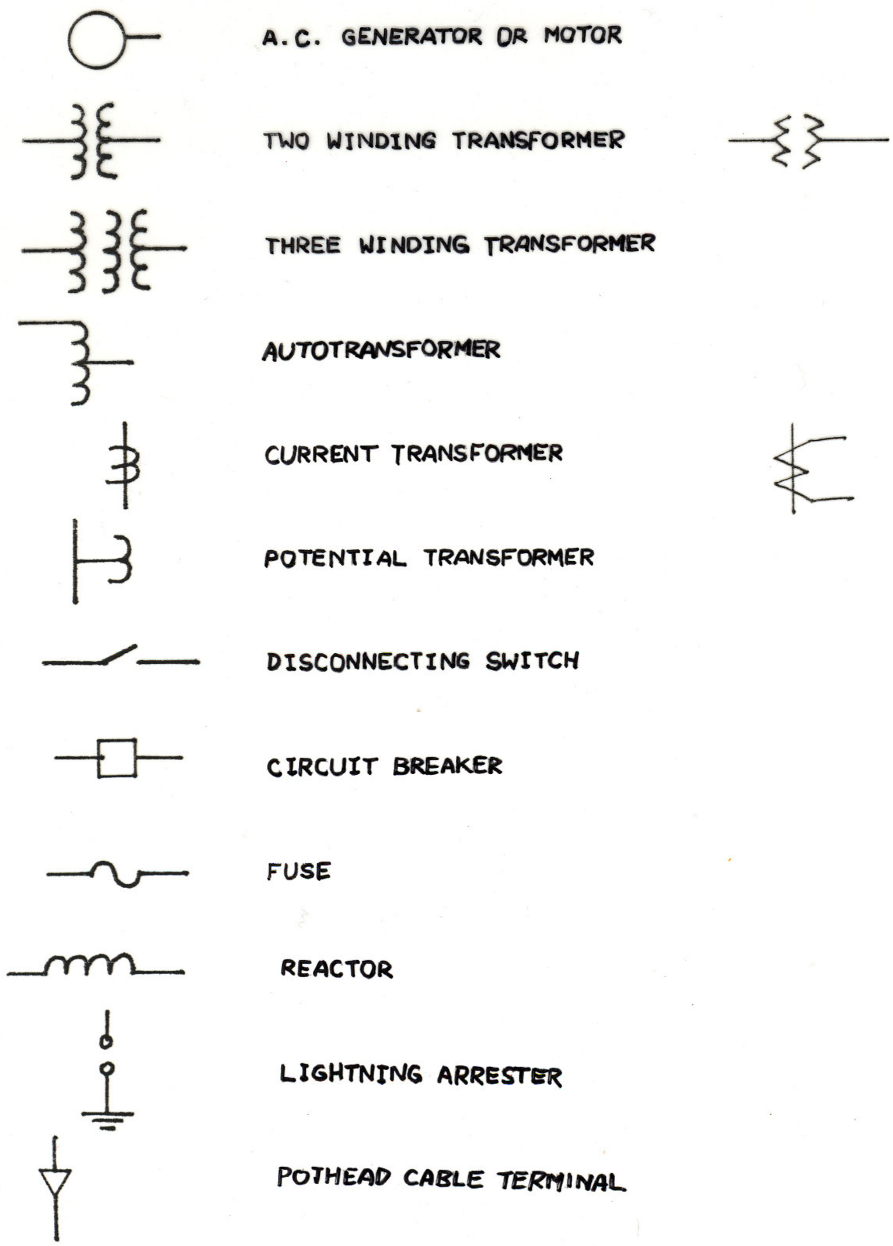


Figure 2.1 – Graphical Symbols for Single Line Diagrams

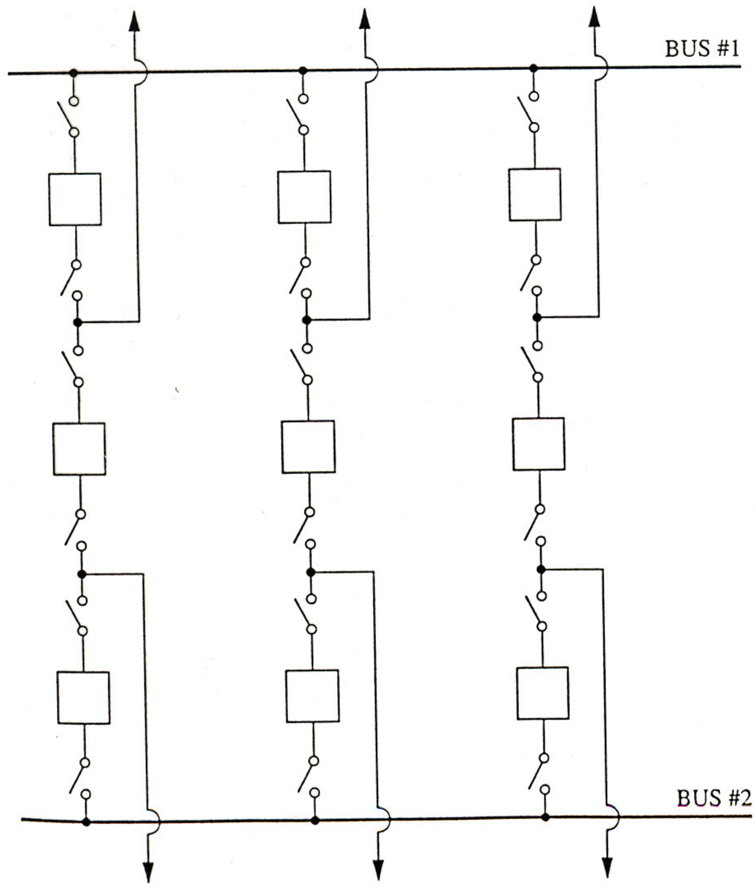


Figure 2.2 – Single Line Diagram showing bus arrangement of a substation.

Single line diagrams like in figure 2 are used to illustrate the layout of buses in a substation. The arrangement of figure two is called a "breaker and a half". There are three breakers for every two connections of lines or transformers to the bus, i.e. 1 ½ breakers per termination.

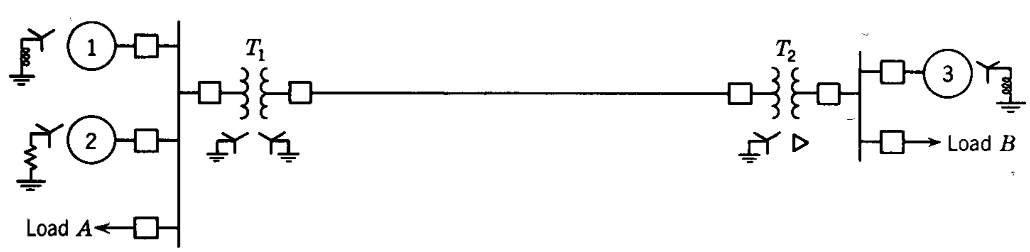


Figure 2.3 – Single line diagram of an electric power system.

2.2 IEC and ANSI/IEEE symbology for some of the main MV protection functions:

Below there is an example of correspondence between IEC and ANSI/IEEE symbology for some of the main MV protection functions.

50 Instantaneous overcurrent relay
A device that operates with no intentional time-delay when the current exceeds a preset value. It can be compared with a protection "I" of a LV release.

51 Time-delayed overcurrent relay
A device that functions when the ac input current exceeds a predetermined value, and in which the input current and operating time are inversely related. It can be compared with a protection "S" of a LV release.

51N or 51G Time-delayed earth fault overcurrent relay: Devices that operate with a definite time-delay when an earth fault occurs. In details:
51N: residual current measured on the CT joint return. This device can be compared with a protection "G" of a LV release.
51G: residual current measured directly either on a CT or on toroidal CT only. This device can be compared with the protection which can be realized, for example, through an homo polar toroid operating a residual current device with adjustable trip times (e.g. a RCQ) or through the function "G" of the protection release supplied by an external toroid.

50N or 50G Instantaneous earth fault overcurrent relay: A device that operates with no intentional time-delay when an earth fault occurs. In details:
50N: residual current measured on the CT common return. It can be compared with a protection "G" with definite time of a LV release.
50G: residual current measured directly either only on a CT or on toroidal CT. It can be compared with a protection which can be realized, for example, through a homo polar toroid.

67 Alternating current directional power relay or directional overcurrent relay: A device that operates at a desired value of power lowing in a predetermined direction, or for overcurrent with power lowing in a predetermined direction. It can be compared with a protection "D" of a LV release.

49 Alternating current thermal relay
A device that operates when the temperature of the machine or of the ac apparatus exceeds a predetermined value. It can be compared with the overload protection "L"

of a LV release, even though a real protection against overload is not provided for MV applications.

Table 1

ANSI/IEEE Code	Function definition	Simbology corresponding to the Standard IEC 60617-7
51	Time-delayed overcurrent	I> ⊢↗⊣
50	Instantaneous overcurrent	I> ⊢=0⊣
51N	Time-delayed earth fault overcurrent	I> ⏚ ⊢↗⊣
50N	Instantaneous earth fault overcurrent	I> ⏚ ⊢=0⊣
67	Directional phase overcurrent	I> ⧫← ⊢=0⊣ ⊢↗⊣
67N	Directional zero-sequence overcurrent	I> ⏚ ⧫← ⊢=0⊣ ⊢↗⊣

Table 1: IEC and ANSI/IEEE symbol for some of the main MV protection functions

2.3 <u>Divisions Of Electrical substations:</u>

An electrical transformer substation consists of a whole set of devices (conductors, measuring and control apparatus and electric machines) dedicated to transforming the voltage supplied by the medium voltage distribution grid (e.g. 15kV or 20kV), into voltage values suitable for supplying low voltage lines with power (400V - 690V).
The electrical substations can be divided into public substations and private substations:
<u>Public substations</u>: These belong to the electricity utility and supply private users in alternating single-phase or three-phase current (typical values of the voltage for the two types of power supply can be 230V and 400V). In turn, these are divided into urban or rural type substations, consisting of a single reduced-size power transformer. Urban substations are usually built using bricks, whereas rural ones are often installed externally directly on the MV pylon.
<u>Private substations</u>: These can often be considered as terminal type substations, i.e. substations where the MV line ends at the point of installation of the substation itself. They belong to the user and can supply both civil users (schools, hospitals, etc.) with power and industrial users with supply from the public MV grid.

These substations are mostly located in the same rooms of the factory they supply and basically consist of three distinct rooms:

- Delivery room: where the switching apparatus of the utility is installed. This room must be of a size to allow any construction of the in-feed/output system which the utility has the right to realize even at a later time to satisfy its new requirements. The take-up point is found in the delivery room, which represents the border and connection between the public grid and the user plant.

- Instrument room: where the measuring units are located. Both these rooms must have public road access to allow intervention by authorized personnel whether the user is present or not.

- User room: destined to contain the transformer and the MV and LV switching apparatus which are the concern of the user. Rooms must normally be adjacent to the other two.

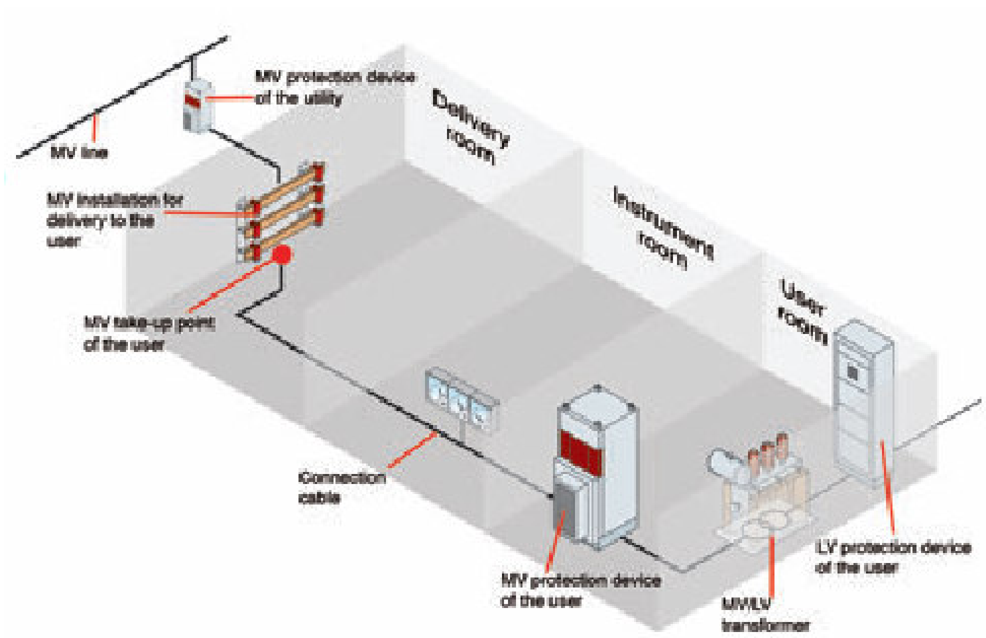


Figure 2.4 – Conceptual diagram of the Substation

Figure shows the typical structure of a substation with division of the rooms as previously described. It is normally expected that the customer use MV/LV transformers with:

- Delta primary winding (Δ), because of this connection type, the third harmonics of the magnetizing currents (distorted due to the non-linearity of the magnetic circuit) and any possible homo polar current are free to circulate through the sides of the delta, without lowing into the network; thus, the magnetic fluxes remain sinusoidal and consequently also the fem induced at the secondary. Besides, in case of unbalanced loads at the secondary winding, the reaction current absorbed by the primary lows only through the corresponding winding (as shown in the figure) without affecting the other two; if this should occur, as in the star connection, the currents in those windings would be magnetizing currents and would cause an asymmetry in the phase voltages. Only when special applications are provided (welding machines, actuators, etc.), the connection can be not of delta type and the choice shall be agreed on with the utility.

- Secondary winding with grounded star point ( ),to make line and phase voltages easily available, but above all for safety reasons, since, in the event of a fault between the MV and LV sides, the voltage at the secondary remains close to the phase value, thus guaranteeing higher safety for people and maintaining the insulation.

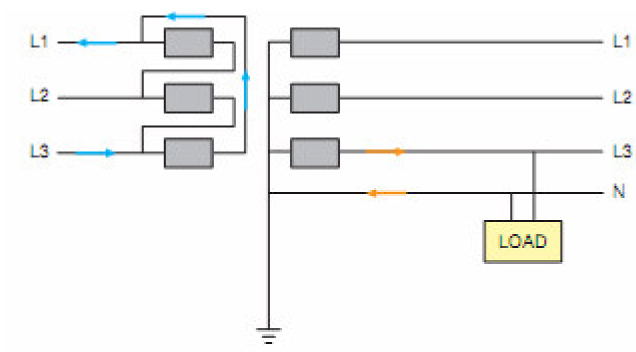


Figure 2.5 – General layout of an (Δ) and connections.

2.4 <u>The main electrical regulations for a MV/LV substation</u>:

The power values allowed are as follows:

- Power not higher than 1600kVA for 15kV networks
- Power not higher than 2000kVA for 20kV networks.

The powers indicated refer to a transformer wit V_k % = 6%. The limit relative to the installable power is also established and, in order not to cause unwanted trips of the Over current protection of the MV line during the putting into service operations of their own plants, the customers cannot install more than three transformers, each of them with size corresponding to the limits previously indicated and with separated LV busbars; otherwise, they shall have to provide suitable devices in their plants in order to avoid the simultaneous energization of those transformers which would determine the exceeding of the above mentioned limits. Moreover, the users cannot install transformers in parallel (voltage busbars connected) for a total power exceeding the mentioned limits so that, in case of a LV short-circuit on the supply side of the LV main circuit-breaker, only the MV circuit-breaker of the user, installed to protect the transformer, and not the line protection device of the utility, trips. In those cases when the customer's plant is not compatible with the aforesaid limitations, it will be necessary to take into consideration other solutions, for example providing power supply through a dedicated line and customizing the settings of the over current protective device. The transformer is connected to the take-up point in the delivery room by means of a copper connection cable which, regardless of the power supplied, must have a minimum cross-section of 95mm^2. This cable is the property of the user and must be as short as possible. The present trend regarding management of the earthing connection of the system is to provide the passage from insulated neutral to earthed neutral by means of impedance. This modification, needed to reduce the single phase earth fault currents which are continually on the increase due to the effect of growingly common use of underground or overhead cables, also implies upgrading the protections against earth faults both by the utility and by the customers. The intention is to limit unwanted trips as far as possible, thereby improving service.

2.5 Different Types OF High-Voltage Substations:

High-voltage substations are points in the power network where power can be pooled from generating sources, distributed and transformed and delivered to the load points. Substations in a grid are interconnected with each other so that the power systems become a meshed network. This increases reliability of the network by providing alternate paths for flow of power to take care of any contingency, so that power delivery to the loads is maintained and the generators do not face any outage. The high-voltage substation is a critical component in the power system, and the reliability of the power system depends upon the substation. Therefore, the circuit configuration of the high-voltage substation has to be selected carefully. Busbars are the part of the substation where all the power is concentrated from the incoming feeders and distributed to the outgoing feeders. That means that the reliability of any high voltage substation depends on the reliability of the busbars present in the power system. An outage of any busbar can have dramatic effects on the power system. An outage of a busbar leads to the outage of the transmission lines connected to it. As a result, the power flow shifts to the surviving healthy lines that are now carrying more power than they are capable of. This leads to tripping of these lines, and the cascading effect goes on until there is a blackout or similar situation. The importance of busbar reliability should be kept in mind when taking a look at the different busbar systems that are prevalent.

2.5.1 Single-busbar scheme (1BB):

The applications of this simple scheme are distribution and transformer substations, and feeding industrial areas (figure 2.6). Because it has only one busbar and the minimum amount of equipment, this scheme is a low-cost solution that provides only limited availability. In the event of a busbar failure and during maintenance periods, there will be an outage of the complete substation. To increase the reliability, a second busbar has to be added.

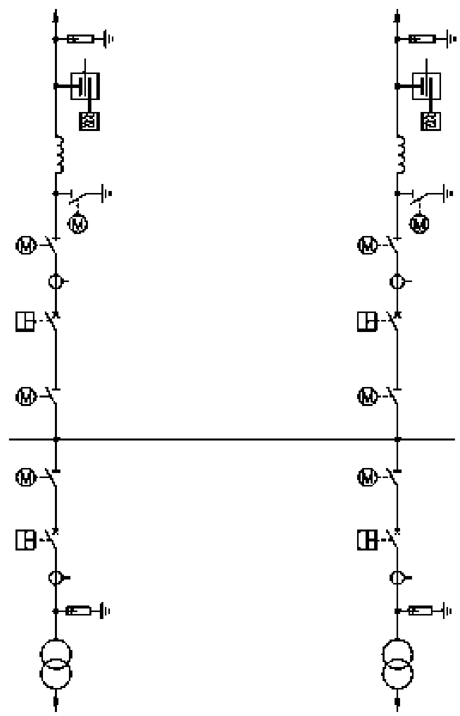


Figure.2.6 – Special single busbar, H-scheme (1 BB)

2.5.2 Double-busbar scheme (2 BB):

The more complex scheme of a double-busbar system gives much more flexibility and reliability during operation of the substation (figure 2.7).

For this reason, the system is used in network nodes of the power system for distribution and transformer substations. It is possible to control the power flow by using the busbars independently, and by switching a feeder from one busbar to the other. Because the busbar disconnections are not able to switch the rated current of the feeder, there will be a short disruption in power flow.

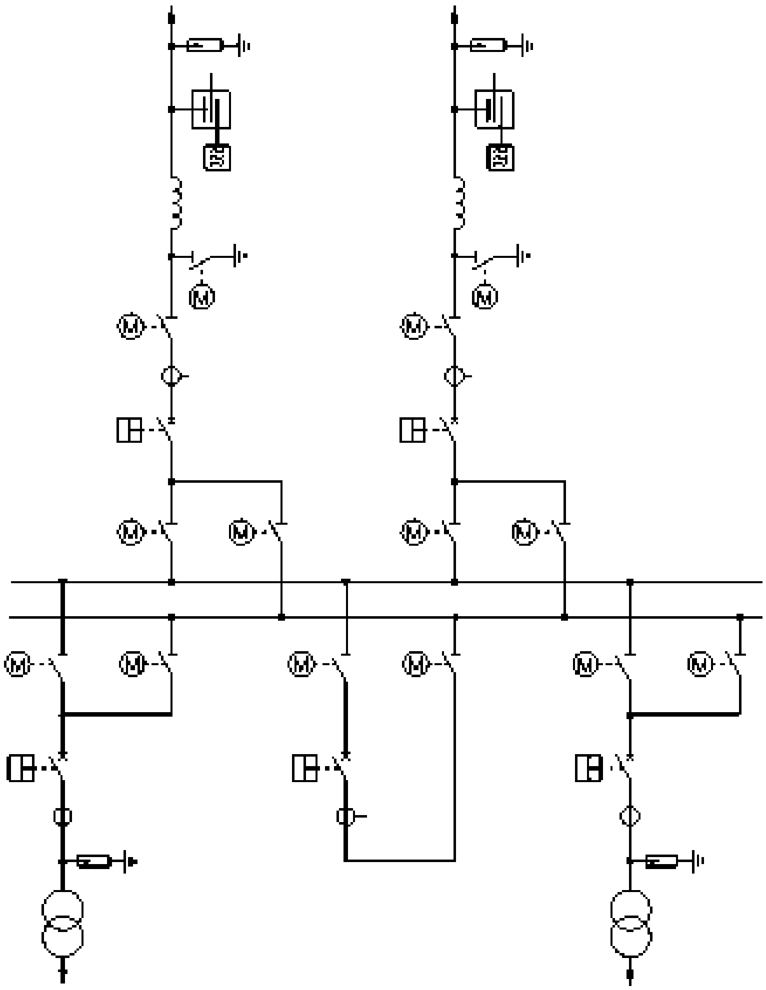


Figure 2.7 – Double-busbar scheme (2 BB)

2.5.3 <u>Double circuit-breaker scheme (2 CB):</u>

To have a load change without disruption, a second circuit breaker per feeder has to be used. This is the most expensive way to solve this problem. In very important feeders, the 2 CB solution will be used (figure 2.8).

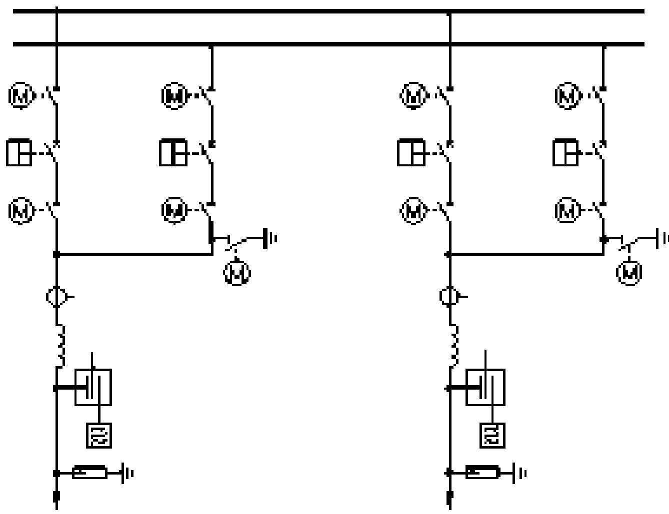


Figure 2.8 – Double circuit-breaker scheme (2 CB)

2.5.4 <u>One circuit-breaker-an-a-half scheme (1.5 CB):</u>

The one circuit-breaker-an-a-half scheme is a compromise between the 2 BB and the 2 CB scheme. This scheme improves the reliability and flexibility because, even in case of loss of a complete busbar, there is no disruption in the power supply of the feeders (figure 2.9).

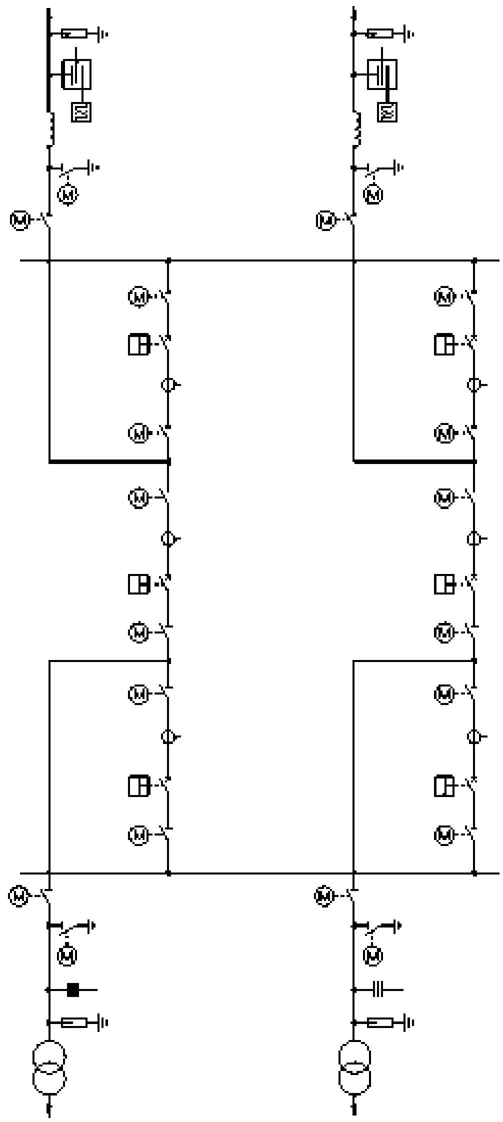


Figure 2.9 – One circuit-breaker-an-a-half scheme (1.5 CB)

2.5.5 <u>3-phase busbar scheme (3 BB):</u>

For important grid stations at transmission network nodes of higher voltage levels, the 3-phase busbar scheme is used. It is a common scheme in Germany, utilized at the 380 kV level (figure 2.10).

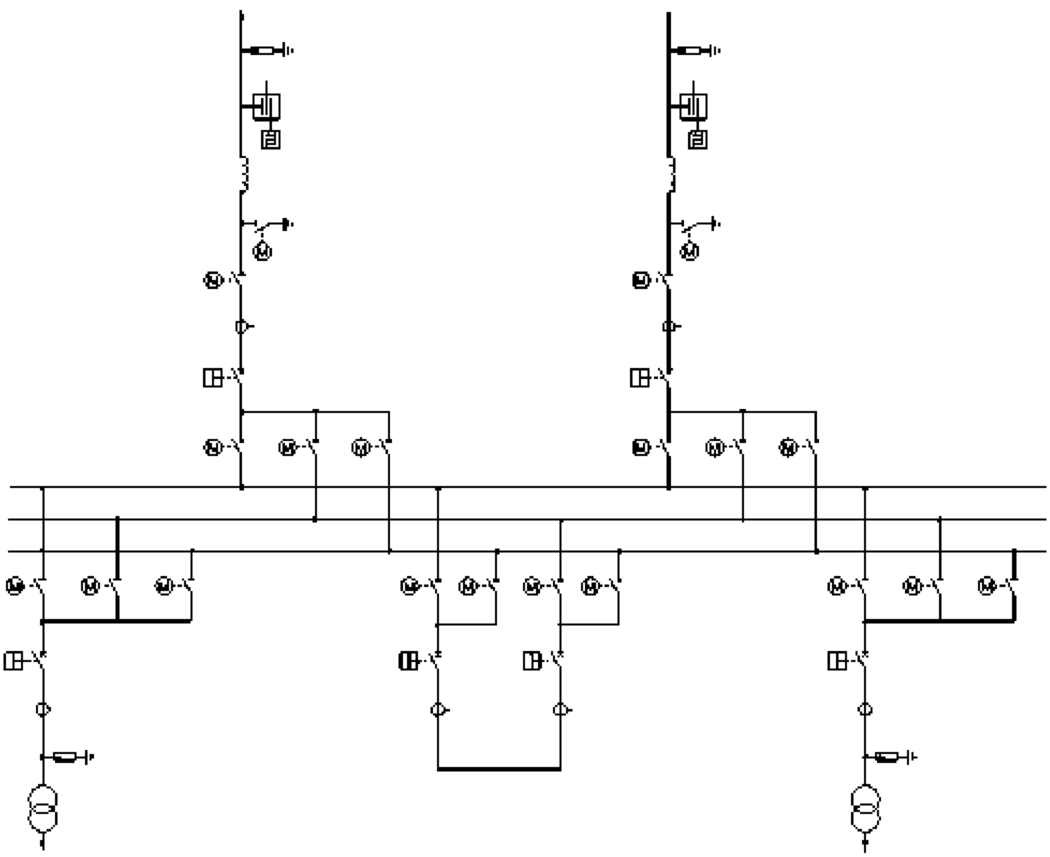


Figure 2.10 – 3-phase busbar scheme (3 BB)

2.5.6 Mesh Substation :

Operation of two circuit breakers is required to connect or disconnect a circuit, and disconnection involves opening of a mesh. Circuit breakers may be maintained without loss of supply or protection, and no additional bypass facilities are required. Busbar faults will only cause the loss of one circuit breaker. Breaker faults will involve the loss of a maximum of two circuits. Generally, not more than twice as many outgoing circuits as infeeds are used in order to rationalise circuit equipment load capabilities and ratings.

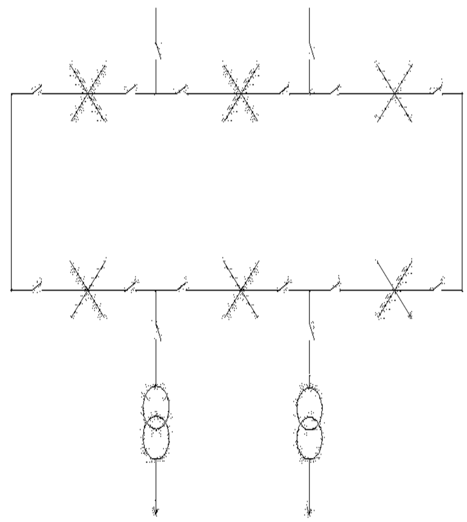


Figure 2.11 – Mesh Substation

2.6 Principle of Substation Layouts:

- Substation layout consists essentially in arranging a number of switchgear components in an ordered pattern governed by their function and rules of spatial separation.

Spatial Separation:

- Earth Clearance: this is the clearance between live parts and earthed structures, walls, screens and ground.
- Phase Clearance: this is the clearance between live parts of different phases.
- Isolating Distance: this is the clearance between the terminals of an isolator and the connections thereto.
- Section Clearance: this is the clearance between live parts and the terminals of a work section. The limits of this work section, or maintenance zone, may be the ground or a platform from which the man works.

2.7 Components of a Substation :

The substation components will only be considered to the extent where they influence substation layout.

2.7.1 Circuit Breakers:

There are two forms of open circuit breakers:

1. Dead Tank - circuit breaker compartment is at earth potential.
2. Live Tank - circuit breaker compartment is at line potential

2.7 2 <u>Current Transformers:</u>

- CT's may be accommodated in one of six manners:
- Over Circuit Breaker bushings or in pedestals.
- In separate post type housings.
- Over moving bushings of some types of insulators.
- Over power transformers of reactor bushings.
- Over wall or roof bushings.
- Over cables.

2.7.3 <u>Isolators:</u>

These are essentially off load devices although they are capable of dealing with small charging currents of busbars and connections. The design of isolators is closely related to the design of substations. Isolator design is considered in the following aspects:

- Space Factor
- Insulation Security
- Standardization
- Ease of Maintenance
- Cost

Some types of isolators include:

- Horizontal Isolation types
- Vertical Isolation types
- Moving Bushing types

2.7.4 <u>Conductor Systems:</u>

- An ideal conductor should fulfill the following requirements:
- Should be capable of carrying the specified load currents and short time currents.
- Should be able to withstand forces on it due to its situation. These forces comprise self weight, and weight of other conductors and equipment, short circuit forces and atmospheric forces such as wind and ice loading.
- Should be corona free at rated voltage.
- Should have the minimum number of joints & should be economical.
- Should need the minimum number of supporting insulators.

2.7.5 <u>Insulation:</u>

- Insulation security has been rated very highly among the aims of good substation design. Extensive research is done on improving flashover characteristics as well as combating pollution. Increased creep age length, resistance glazing, insulation greasing and line washing have been used with varying degrees of success.

2.7.6 <u>Power Transformers:</u>

- EHV power transformers are usually oil immersed with all three phases in one tank. Auto transformers can offer advantage of smaller physical size and reduced losses. The different classes of power transformers are:

- o.n.: Oil immersed, natural cooling
- o.b.: Oil immersed, air blast cooling
- o.f.n.: Oil immersed, oil circulation forced
- o.f.b.: Oil immersed, oil circulation forced, air blast cooling

2.7.7 <u>Overhead Line Terminations:</u>

- Two methods are used to terminate overhead lines at a substation.
- Tensioning conductors to substation structures or buildings
- Tensioning conductors to ground winches.

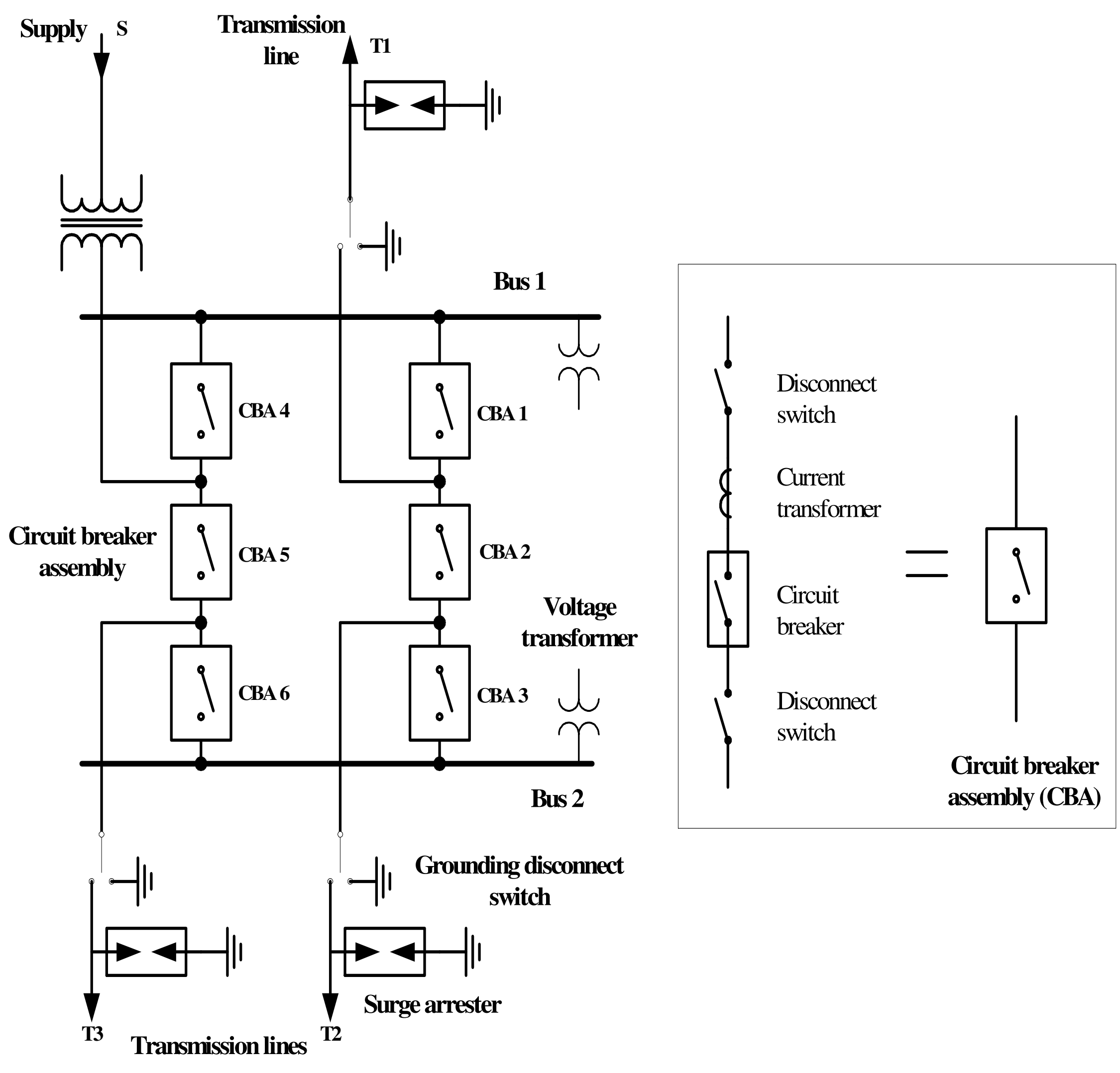


Figure 2.12 – Substation Circuit Diagram (An example view)

Chapter 3

General Fault calculation Procedures Substation including Its Methods

3.1 <u>Analyzing what the most common management methods may be in relation to the layout of the power supply transformers for a substation supplied by a single medium voltage line :</u>

There are various methods in relation to the layout of the power supply transformers for a Substation supplied by a single medium voltage line. These management methods are to determine the layout of the power supply transformers. In case of a LV short-circuit on the supply side of the LV main circuit-breaker, only the MV circuit-breaker of the user, installed to protect the transformer, and not the line protection device of the utility, trips.
The methods are discussed as follows:

<u>Method 1:</u>

<u>Substation with a single transformer:</u>

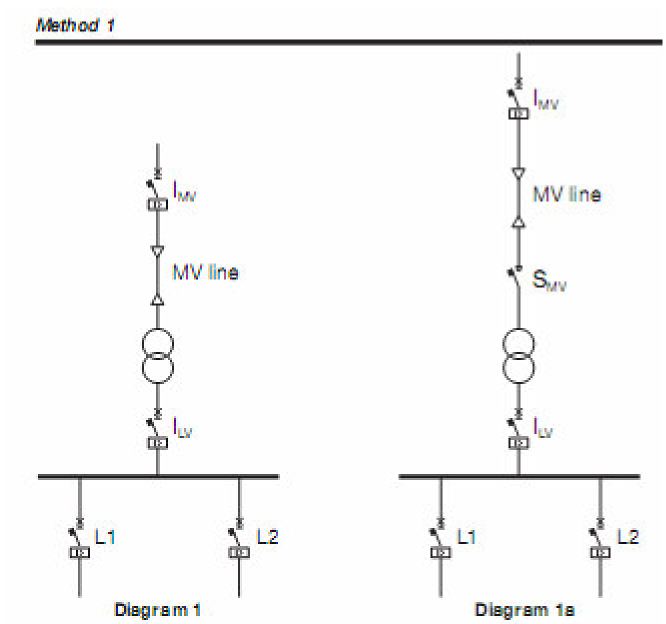


Figure 3.1 – The layout of the power supply transformers for a substation supplied by a single medium voltage line by Method 1.

When the plant foresees installation of an "I_{MV}" over current protection device where the line which supplies the substation originates, as shown in diagram 1, this device must ensure protection of both the MV line as well as the transformer. In the case where the protection device also carries out switching and isolation functions, an interlock must be provided which allows access to the transformer only when the power supply line of the substation has been isolated. Another management method is shown in diagram 1a, which foresees installation of the "SMV" switching and isolation device positioned immediately to the supply side of the transformer and separate from the protection device which remains installed at the beginning of the line.

Method 2:

Substation with two transformers with one as a spare for the other:

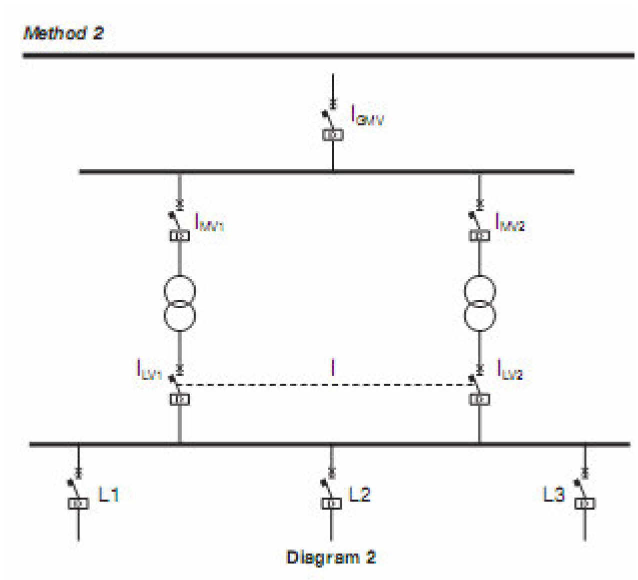


Figure 3.2 – The layout of the power supply transformers for a substation supplied by a single medium voltage line by Method 2.

When the plant foresees installation of a transformer considered as a spare, the circuit-breakers on the LV side must be connected with an "I" interlock whose function is to prevent the transformers from operating in parallel.

Apart from the switching and isolation device on the incoming MV line (I_{GMV}), it is advisable to provide a switching, isolation and protection device on the individual MV risers of the two transformers (I_{MV1} and I_{MV2}) as well. In this way, with opening of the device on the supply and load side of a transformer, it is possible to guarantee isolation and access the machine without putting the whole substation out of service.

Method 3 :

Substation with two transformers which operate in parallel on the same bus bar

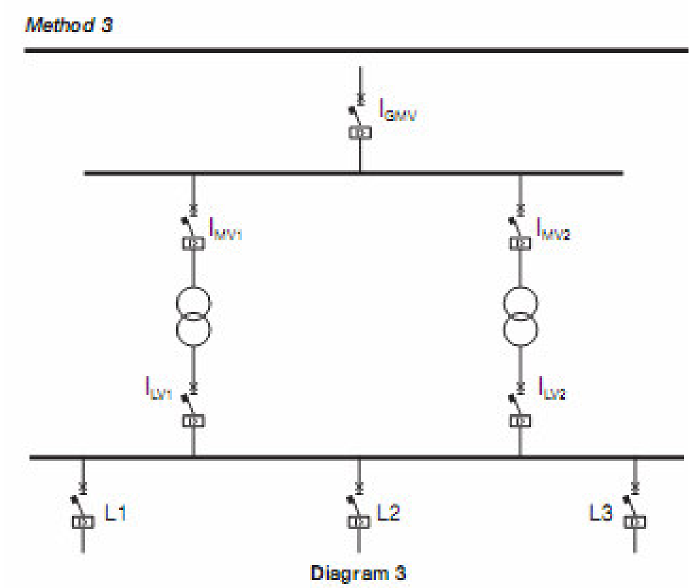


Figure 3.3 – The layout of the power supply transformers for a substation supplied by a single medium voltage line by Method 3.

When the plant foresees installation of two transformers operating in parallel at the same overall power required of the plant, it is possible to use two transformers with lower rated power. Compared with the management method described in the two previous cases, higher short-circuit currents could be generated for faults in the low voltage system due to reduction of the possible V_k% for lower power machines.
Operation in parallel of the transformers could cause greater problems in management of the network. Again in this case, however, outage of a machine might require a certain flexibility in load management, ensuring the power supply of those considered to be priority loads. When coordinating the protections, the fact that the over current on the LV side is divided between the two transformers must be taken into consideration.

Method 4:

Substation with two transformers which operate simultaneously on two separate half-busbars

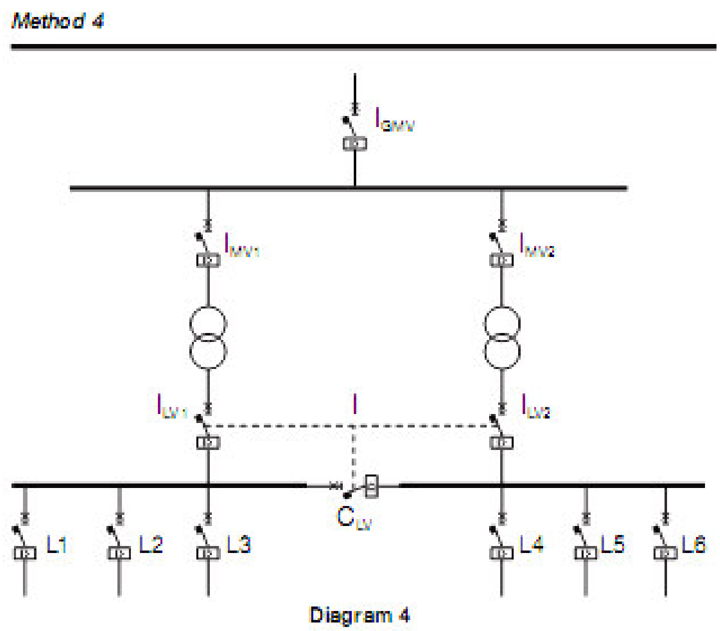


Figure 3.4 – The layout of the power supply transformers for a substation supplied by a single medium voltage line by Method 4.

Starting from the previous management method, by providing a "C_{LV}" bus-tie and an "I" interlock which prevents the bus-tie from being closed when both the incoming circuit-breakers from the transformer are closed, a substation managed as shown in diagram 4 is made, which foresees two transformers which individually supply the low voltage busbars, which are separate.
With the same power of the transformers installed, this management method allows a lower value of the short-circuit current on the busbar. In other words, each transformer establishes the short-circuit level for the busbar of its competence without having to consider the contribution of other machines. Again in this case, when a transformer is out of service, with any closure of the bus-tie you pass to a system with a single busbar supplied by the sound transformer alone, and a load management logic must be provided with disconnection of non-priority loads. Plant management according to diagram 4 is possible, for example by using the E_{max} series of air circuit-breakers with a wire interlock (mechanical interlock) between three circuit-breakers.

3.2 GENERAL PROCEDURES OF CALCULATING FAULTS OF A SUBSTATION :

In the presence of faults, this management method causes an increase in the short-circuit current value on the LV side, with a possible consequent increase in the size of the circuit-breakers outgoing from the busbar and heavier anchoring conditions for the busbars in comparison with operation with a single transformer. This is due to a smaller value of the $V_k\%$ which characterizes the transformers with less power. On the other hand, when suitably managed, the parallel method has the advantage of allowing power supply, at least to the users considered as primary users, through the possible bus-tie, even in the case of outage of one of the transformers.
The following example shows the increase in the short-circuit current value on the busbar in the case of transformers in parallel:

Example3.1

Supply network, short-circuit power…....................................S_{knet} = 750MVA
Plant secondary voltage…..V_{2n} = 400 V
Power of the single transformer…...S_{nTR} = 1600 KVA
Rated short-circuit voltage of the single transformer…...........$V_k\%$ = 6%
Power of the transformer provided for the parallel..................S_{nTR} = 800kVA
Short-circuit voltage of the transformer in parallel…................$V_k\%$ = 4%

From these data and from quick calculations, a short-circuit current value of 37 kA is obtained on the busbar with the single 1600kVA transformer. With two 800kVA transformers in parallel, the short-circuit current on the busbar shall be about 55kA. With reference to the electricity network outlined in Figure 3.5, the following considerations have the aim of illustrating the management philosophy for the protections:

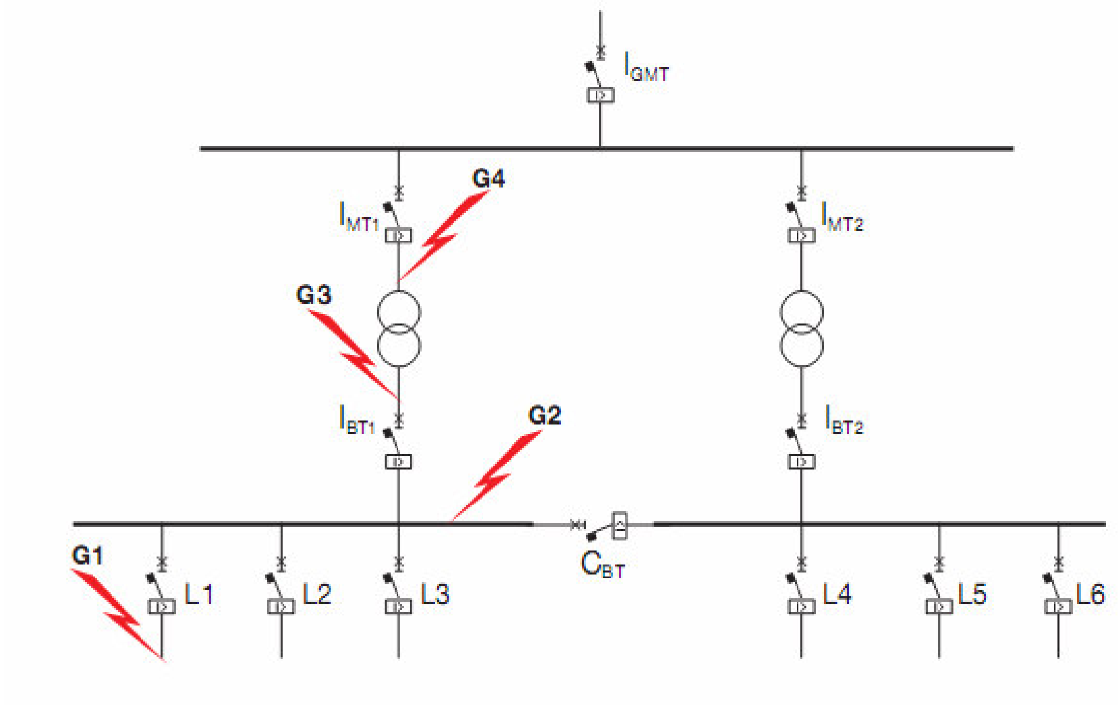


Figure 3.5 – Management philosophy for the protections

G1 Fault on one of the LV users

Regardless of the presence or absence of the bus-tie:

With appropriate selection of the protection devices and according to normal LV selectivity prescriptions, it is possible to discriminate the fault and ensure service continuity with opening just of the L1 circuit-breaker.

G2 Fault on the LV busbar

Without bus-tie:

The fault is extinguished by the two general LV side circuit-breakers (I_{LV1} and I_{LV2}) of the transformers, causing complete outage of the plant. The transformers remain no-load supplied. To prevent opening of the I_{MV}. Circuit-breakers, obtaining MV/LV selectivity is again important in this case.

With bus-tie:

The CLV bus-tie must open, with consequent separation of the busbars and complete elimination of the fault by means of the main I_{LV1} circuit-breaker opening. The action of the bus-tie allows power supply to be maintained to the half-busbar unaffected by the fault. The action of the LV devices (I_{LV1} – CLV – I_{LV2}), which are all affected by the fault, may be co-ordinated by using devices for which the directional zone selectivity is implemented, such as for example protection releases PR123 for the Emax series and PR333 for the Emax circuit-breaker type X1.

G3 Fault on the LV bus riser of the transformer

Without bus-tie:

The fault current affects the two transformers and it may be such as to cause opening of the two devices I_{MV} and I_{LV} of the transformers. The consequence would be to have all the plant disconnected. In this case it becomes important to study and implement a dedicated management logic (for example directional selectivity) which allows I_{LV1} and I_{MV1} opening in order to isolate only the transformer affected by the fault. Also a logic for the disconnection of non-priority loads should be foreseen, since the plant is functioning with one transformer only.

With bus-tie:

The management logic remains the same and it could possibly foresee also the bus-tie opening.

G4 Fault on the MV bus riser of the transformer

Without bus-tie:

The management logic must allow immediate opening of the I_{MV1} circuit-breaker affected by the full fault current (I_{MV2} shall see a lower current limited by the impedance of the two transformers) and, if the plant management foresees pulling, the opening of the I_{LV1} circuit-breaker with isolation of the fault point will follow with service continuity of the whole plant ensured by power supply through the other transformer. Also a logic for the disconnection of non-priority loads should be foreseen, since the plant is functioning with one transformer only.

With bus-tie:

The management logic remains the same, and the bus-tie would have only the function of separating the busbars by eliminating that of competence of the excluded transformer. After an analysis of the fault handling modalities, which under some circumstances result to be quite complex due to the double supply of the transformers in parallel, the minimum requirements to have two transformers operating in parallel are examined now:

a) the internal connections must belong to the same group (CEI group) and the transformers must have the same transformation ratio. By complying with these prescriptions, the two sets of voltage result to coincide and to be in phase opposition; consequently there are no vectorial differences between the secondary voltage of every single mesh and no circulation currents are generated. In the contrary case, circulation currents would be generated, which could damage the transformers also in no-load operation;

b) the short-circuit voltages ($V_k\%$) must have the same value. Thanks to this measure, the total load current is subdivided between the two transformers in proportion to their respective rated powers. If not, the two transformers would be differently loaded and the machine with the lower internal voltage drop would tend to be more loaded.

c) equal short-circuit power factor ($\cos Ø_m$). Thanks to this measure, the total load current is divided into two or more currents in phase and consequently with value reduced to the minimum. Since the $\cos\varphi_m$ value changes according to the power of the transformer, it is not advisable to connect in parallel a transformer with a power exceeding the double, or being lower than the half, of the other.

3.3 Calculation of short-circuit currents :

3.3.1 Data necessary for the calculation:

Some general indications regarding the typical parameters characterizing the main components of an installation are given hereunder. Knowledge of the following parameters is fundamental to carry out a thorough analysis of the installation.
Distribution networks:
In a MV network the rated voltage is the unique parameter usually known.
To calculate the short-circuit currents it is necessary to know the network short-circuit power, which can indicatively vary from 250MVA to 500MVA for systems up to 30kV.
When the voltage level rises, the short-circuit power can indicatively vary between 700MVA and 1500MVA. The voltage values of the MV distribution network and the relevant short-circuit power values accepted by the Standard IEC 60076-5 are reported in Table :

Distribution network voltage practice [kV]	Short-circuit apparent power Current European practice [MVA]	Short-circuit apparent power Current North-American [MVA]
7.2–12–17.5-24	500	500
36	1000	1500
52–72.5	3000	5000

Table 2 – Relevant short-circuit power values Standard IEC 60076-5

3.3.2 Synchronous generator:

The data usually known for an electrical machine are the rated voltage V_n and the rated apparent power S_n.
For synchronous generators, as for every electrical machine, to get a complete analysis it is necessary to evaluate also:

- the behavior under steady state conditions for an analysis of the problems of static stability

- the behavior under transitory conditions when the load suddenly varies for an analysis of the problems of dinamic stability, in particular when a three-phase short-circuit occurs. Therefore, it becomes necessary to know the values of the machine reactance, in particular:

- as regards the first type of problem, the determining parameter is represented by the synchronous reactance;

- as regards the second type of problem, the transitory reactance with the relevant time constants and the sub transitory reactance.

The behavior is due to the fact that the impedance of the generator, which is constituted practically by the reactance only, has no definite value, but it varies instant by instant, because the magnetic flux, which it depends on, does not reach immediately the steady state configuration. A different inductance value corresponds to any configuration of the flux, mainly because of the different path of the magnetic lines. Besides, there is not a single circuit and a single inductance, but more inductances (of the winding of the armature, of the winding of the field, of the damping circuits) which are mutually coupled. To simplify, the following parameters shall be taken into consideration:

Sub transient reactance, direct axis X''_d
Transient reactance, direct axis X'_d
Synchronous reactance, direct axis X_d

The evolution of these parameters during the time influences the course of the short-circuit current in the generator. Reactances are usually expressed in p.u. (per unit) and in percent, that is they are related to the nominal parameters of the machine. They can be determined by the following relationship:

$$X\% = \frac{\sqrt{3}.I_n.X}{V_n}.100$$

Where:

X is the real value in ohm of the considered reactance;
I_n is the rated current of the machine;
V_n is the rated voltage of the machine.

The following values can be indicated as order of quantity for the various reactances:

- sub transient reactance: the values vary from 10% to 20% in turbo-alternators (isotropic machines with smooth rotor) and from 15% to 30% in machines with salient pole rotor (anisotropic);

- transient reactance: it can vary from 15% to 30% in turbo-alternators (isotropic machines with smooth rotor) and from 30% to 40% in machines with salient pole rotor (anisotropic);
- synchronous reactance: the values vary from 120% to 200% in turbo-alternators (isotropic machines with smooth rotor) and from 80% to 150% in machines with salient pole rotor (anisotropic).

3.3.3 **Transformer :**

A MV/LV transformer with delta primary winding (Δ) and secondary winding with grounded star point ().The electrical parameters which are usually known and which characterize the machine are:

- rated apparent power S_n [kVA]
- primary rated voltage V_{1n} [V]
- secondary rated voltage V_{2n} [V]
- short-circuit voltage in percent $V_k\%$ (typical values are 4%and 6%)

With these data it is possible to determine the primary and secondary rated currents and the currents under short-circuit conditions.

3.3.4 **Calculation of the short-circuit current :**

With reference to the electrical network schematised in Figure 3.6, a short-circuit is assumed on the clamps of the load. The network can be studied and represented by using the parameters "resistances" and "reactances" of each electrical component. The resistance and reactance values must be all related to the same voltage value assumed as reference value for the calculation of the short-circuit current. The passage from the impedance values Z_1 , related to a higher voltage (V_1), to the values Z_2 , related to a lower voltage (V_2), occurs through the transformation ratio

$K = \frac{V_1}{V_2}$ in accordance with the following relationship: $Z_2 = \frac{Z_1}{K^2}$

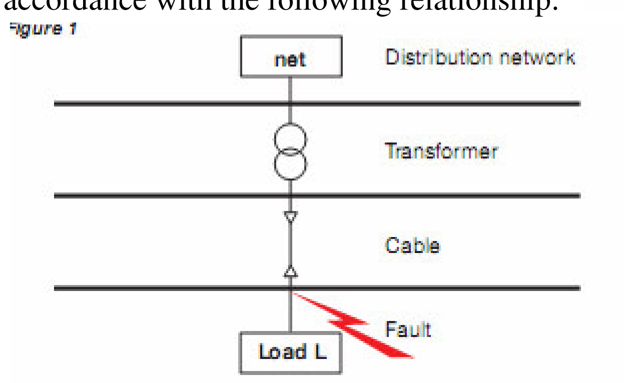


Figure 3.6 – Short-circuit on the clamps of the load

The structure of the electrical network taken into consideration can be represented Through elements in series; thus an equivalent circuit is obtained as that shown in Figure 3.7, which allows to calculate the equivalent impedance seen from the fault point.

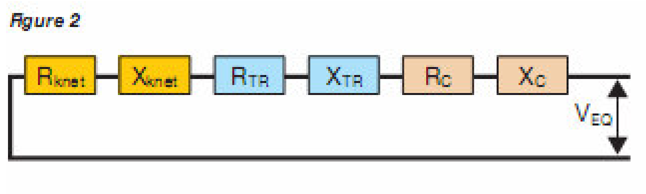


Figure 3.7 – The equivalent impedance seen from the fault point.

At the short-circuit point, an equivalent voltage source (V_{EQ}) is positioned, with value

$$V_{EQ} = \frac{c.V_n}{\sqrt{3}}$$

The factor "c" depends on the system voltage and takes into account the influence of the loads and of the variation in the network voltage. On the basis of these considerations, it is possible to determine the resistance and reactance values characterizing the elements which constitute the installation.

Supply network (net)

In the most cases, the installation results to be supplied by a medium voltage distribution network, whose supply voltage value V_{net} and initial short-circuit current I_{knet} can be easily found.

On the basis of these data and of a correction factor for the change of voltage caused by the short-circuit it is possible to calculate the short-circuit direct impedance of the network through the following formula:

$$Z_{Knet} = \frac{c.V_{net}}{\sqrt{3}.I_{knet}}$$

For the calculation of the parameters network resistance and network reactance, the following relationships can be used:

$$X_{knet} = 0.995 * Z_{knet}$$

$$R_{knet} = 0.1 * X_{knet}$$

If the short-circuit apparent power S_{knet} for the distribution network were known, it would be also possible to determine the impedance representing the network through the following relationship:

$$Z_{knet} = \frac{c^2 . V_{net}^2}{S_{knet}}$$

Transformer

The impedance of the machine can be calculated with the nominal parameters of the machine itself (rated voltage V_{2n} ; apparent power S_{nTR}; percentage voltage drop $V_k\%$) by using the following formula:

$$Z_{TR} = \frac{V_{2n}^2 . v_{k\%}}{100 . S_{nTR}}$$

The resistive component can be calculated with the value of the total losses P_{PTR} related to the rated current in accordance with the following relationship:

$$R_{TR} = \frac{P_{PTR}}{3 \cdot I_{2n}^2}$$

The reactive component can be determined by the classical relationship

$$X_{TR} = \sqrt{(Z_{TR}^2 - R_{TR}^2)}$$

Cables and overhead lines

The impedance value of these connection elements depends on different factors (constructional techniques, temperature, etc....) which influence the line resistance and the line reactance. These two parameters expressed per unit of length are given by the manufacturer of the cable.

The impedance is generally expressed by the following formula:

$$Z_C = L . (r_c + x_c)$$

The resistance values are generally given for a reference temperature of 20°C; for different operating temperatures θ with the following formula it is possible to calculate the relevant resistance value:

$$r_\Theta = [\ 1 + (\alpha - 20)] . r_{20}$$

Where: α is the temperature coefficient which depends on the type of material (for copper it is 3.95×10^{-3}).

Calculation of the short-circuit current

Determination of the short-circuit resistance and reactance values of the main elements of a circuit allow the short-circuit currents of the installation to be calculated.

With reference to Figure and applying the reduction modality for elements in series, the following values can be determined :

- the short-circuit total resistance $R_{Tk} = \Sigma R$
- the short-circuit total reactance $X_{Tk} = \Sigma X$

Once these two parameters are known, it is possible to determine the short-circuit total impedance value Z_{Tk}

$$Z_{TK} = \sqrt{(X_{TR}^2 + R_{TR}^2)}$$

Once determined the equivalent impedance seen from the fault point, it is possible to proceed with the calculation of the three-phase short-circuit current:

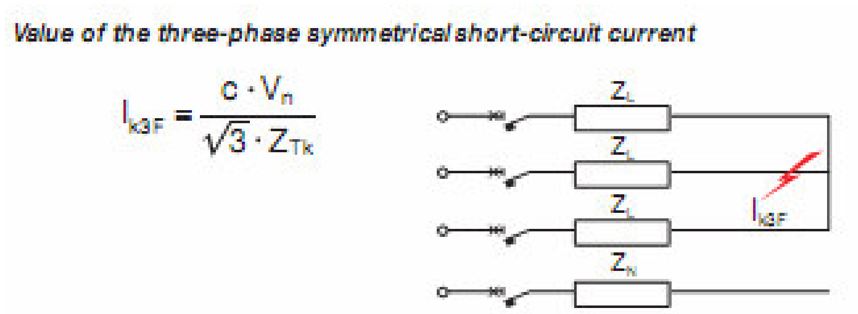


Figure 3.8 – Calculation of the three-phase short-circuit current

This is generally considered as the fault which generates the highest currents (except for particular conditions). When there are no rotary machines, or when their action has decreased, this value represents also the steady state short-circuit current and is taken as reference to determine the breaking capacity of the protection device.

<u>Example3.2:</u>

With reference to the schematized network, the electrical parameters of the different components are:

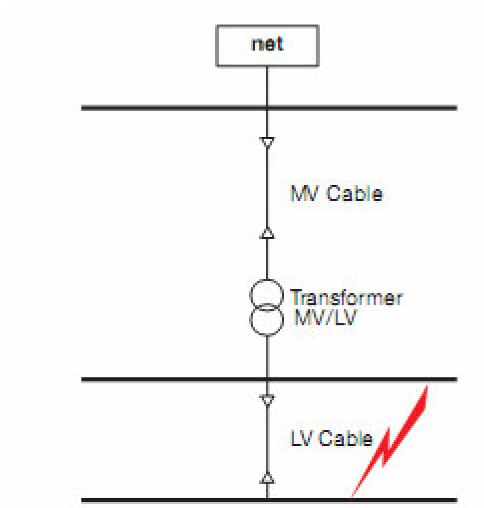


Figure 3.9 – Schematized network system with different electrical parameters.

Short-circuit power and current of the supply network
$S_{knet} = 500MVA$ $I_{knet} = 14.4kA$
Rated voltage of the supply network $V_{net} = 20kV$
MV cable:
Resistance $R_{CMV} = 360m\Omega$
Reactance $X_{CMV} = 335m\Omega$
Rated power of the transformer $S_{nTR} = 400kVA$
Secondary rated voltage of the transformer $V_{2n} = 400V$
Short-circuit test for the transformer: $V_k\% = 4\%$; $P_k\% = 3\%$
LV cable with length L = 5m:
Resistance $R_{CLV} = 0.388m\Omega$
Reactance $X_{CLV} = 0.395m\Omega$

Making reference to the previous relationship, the calculation of the total impedance of the different elements is carried out in order to determine the three-phase short-circuit current at the given point. Since the fault is on the LV side, all the parameters determined for the MV section of the network shall be related to the secondary rated voltage by applying the coefficient

$$K = 20000 / 400 = 50$$

Supply network

$$Z_{knet} = \frac{c\ .V_{net}}{\sqrt{3}.I_{knet}} = \frac{1.1.20000}{\sqrt{3}*14.4*10^3} = 0.88\Omega$$

$$Z_{knet\ 400V} = \frac{Z_{knet}}{K^2} = \frac{0.88}{50^2} = 0.00035\Omega$$

$$X_{knet\ 400V} = 0.995 * Z_{knet\ 400V} = 0.000348\ \Omega$$

$$R_{knet\ 400V} = 0.1 * X_{knet\ 400V} = 0.0000348\ \Omega$$

MV cable

$$R_{CMV\ 400V} = \frac{R_{CMT}}{K^2} = \frac{360*10^{-3}}{50^2} = 0.\ 000144\ \Omega$$

$$X_{CMV\ 400V} = \frac{X_{CMT}}{K^2} = \frac{335*10^{-3}}{50^2} = 0.\ 000134\ \Omega$$

Transformer

$$Z_{TR} = \frac{V_{2n}^2 . v_{k\%}}{100.S_{nTR}} = \frac{400^2 \cdot 4}{100 \cdot 400 \cdot 10^3} = 0.016\ \Omega$$

$$P_{PTR} = \frac{S_{nTR} . P_{k\%}}{100} = \frac{3 \cdot 400 \cdot 10^3}{100} = 12kW$$

$$I_{2n} = \frac{S_{nTR}}{\sqrt{3} \cdot V_{2n}} = \frac{400 \cdot 10^3}{\sqrt{3} \cdot 400} = 577\ A$$

$$R_{TR} = \frac{P_{PTR}}{3 \cdot I_{2n}^2} = \frac{12000}{3 \cdot 577^2} = 0.012\ \Omega$$

$$X_{TR} = \sqrt{(Z_{TR}^2 - R_{TR}^2)} = \sqrt{(0.016^2 - 0.012^2)}$$

$$= 0.0106\ \Omega$$

LV cable

$$R_{CLV} = 0.388\ m\Omega\ , \quad X_{CLV} = 0.395\ m\Omega$$

The total short-circuit resistance value is given by : $R_{TK} = \sum R$

$$R_{TK} = R_{Knet\ 400\ V} + R_{CMV\ 400\ V} + R_{TR} + R_{CLV}$$

$$R_{TK} = 0.0000348 + 0.000144 + 0.012 + 0.000388$$

$$= 0.01256\ \Omega$$

The total short-circuit resistance value is given by : $X_{TK} = \sum X$

$$X_{TK} = X_{Knet\ 400\ V} + X_{CMV\ 400\ V} + X_{TR} + X_{CLV}$$

$$X_{TK} = 0.000348 + 0.000134 + 0.0106 + 0.000395$$

$$= 0.01147\ \Omega$$

Value of the three-phase symmetrical short-circuit current :

Calculating the value of the total short-circuit impedance

$$Z_{TK} = \sqrt{(R_{TR}^2 + X_{TR}^2)} = \sqrt{(0.01256^2 + 0.01147^2)}$$

$$= 0.017\ \Omega$$

and assuming the factor $C^{(1)}$ = 1.1 the short-circuit current value is:

$$I_{k3F} = \frac{c \cdot V_{2n}}{\sqrt{3} \cdot Z_{TK}} = \frac{1 \cdot 1 \cdot 400}{\sqrt{3} \cdot 0.017} = 14943 \text{ A} = 14.95 \text{ kA}$$

3.4 Example of calculation of the short-circuit current:

The study of the short-circuit currents is one of the classic problems plant engineers have to face; knowledge of the values of such currents is fundamental for the proper dimensioning of lines and transformers, but above all of protection devices. If an accurate analysis which takes into account the electromagnetic and electromechanical transients is not the aim, the study of the short-circuit currents is quite easy from a conceptual point of view, since it is based on a few concepts, which however have to be understood in depth and correctly used. But this study may be more complex from a computational point of view, in particular when the network has remarkable dimensions or when meshed networks and asymmetric faults are dealt with. Here is an example of short-circuit current calculation in an electric network by using first an "exact method'' based on the theory of symmetrical components, and then an approximate method defined as "power method".

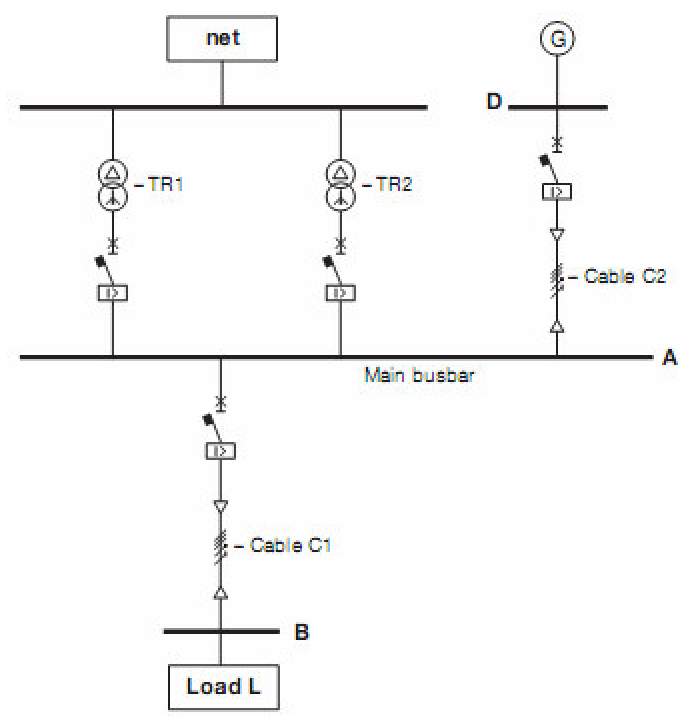


Figure 3.10 – Short-circuit current calculation in an electric network

Plant data

Here under the electrical data of the objects in the network are defined:

Supply network (net)

V_{1n} = 20 kV rated voltage

f = 50 Hz rated frequency

S_k = 750 MVA short-circuit power of the supply network

$Cos\phi_k$ = 0.2 power factor under short-circuit conditions

Transformers TR1-TR2

V_{1n} = 20 kV primary rated voltage

V_{2n} = 400 V secondary rated voltage

S_n = 1600 kVA rated power

V_k %= 6 % voltage drop in percent under short-circuit conditions

P_k%= 1 % rated losses in percent

Generator G

V_{2n} = 400 V rated voltage

S_n = 1250 kVA rated apparent power

$Cos\phi_n$ rated power factor

$X''_{d\%}$= 14 % sub-transient reactance in percent, direct axis

$X''_{q\%}$= 20 % sub-transient reactance in percent, quadrature axis

$X'_{d\%}$= 50 % synchronous transient reactance in percent

$X_{d\%}$= 500 % synchronous reactance in percent-age

$X_{2\%}$= 17 % negative-sequence short-circuit reactance in percent

$X_{0\%}$= 9 % zero-sequence reactance in percent

T''_d = 40 ms sub-transient time constant

T'_d = 600 ms transient time constant

T_a = 60 ms armature time constant (that is of the unidirectional component)

Cable C1

Length L= 50m

Formation: 3 x (2 x 185) + (2 x 95) + G185

R_{F1} = 2.477 mΩ phase resistance

X_{F1} = 1.850 mΩ phase reactance

R_{n1} = 4.825 mΩ neutral resistance

X_{n1} = 1.875 mΩ neutral reactance

R_{PE1} = 4.656 mΩ PE resistance

X_{PE1} = 1.850 mΩ PE reactance

Cable C2

Length L= 15 m

Formation: 3 x (2 x 500) + (2 x 300) + G500

R_{F2} = 0.2745 mΩ phase resistance

X_{F2} = 1.162 mΩ phase reactance

R_{n2} = 0.451 mΩ neutral resistance

X_{n2} = 1.177 mΩ neutral reactance

R_{PE2} = 0.517 mΩ PE resistance

X_{PE2} = 1.162 mΩ PE reactance

The installation typology represented by the single line diagram of Figure may be significant of a generic industrial plant, where a unique overall outgoing feeder has been considered for simplification. Only the passive load has been taken into account, by considering also as negligible the contribution of possible motors to the short-circuit current (complying with the condition:

$\Sigma I_{nM} \leq I_k /100$ prescribed by the Standard IEC 60909, where I_{nM} is the rated current of the various motors and I_k is the initial symmetrical short-circuit current on the busbar without motor contribution).

The values of the impedances to be used in the sequence networks for the calculation of the fault currents can be derived from the data above. The subscripts have the following meaning:

- d positive sequence component;
- i negative sequence component;
- o zero-sequence component.

Supply network

The parameters of positive and negative sequence of the network impedance related to 400 V are:

$$Z_{dnet} = Z_{inet} = \frac{V_{2n}^2}{S_k} = 2.133 \cdot 10^{-4}\ \Omega$$

$$R_{dnet} = R_{inet} = Z_{dnet} \cdot \cos\phi_k = 4.266 \cdot 10\text{-}5\ \Omega$$

$$X_{dnet} = X_{inet} = Zdnet \cdot \sin\phi k = 2.090 \cdot 10\text{-}4\ \Omega$$

The zero-sequence impedance of the supply is not considered, since the delta windings of the transformers block the zero-sequence component.

Transformers TR1-TR2

A classic type delta/star grounded transformer (Δ/Y), which allows to have a distribution system LV side of TN-S type, is taken into consideration. The impedances of the various sequences (o-d-i) take the same value:

$$Z_{dTR} = Z_{iTR} = Z_{oTR} = \frac{V_{k\%}}{100} = 0.006\ \Omega$$

$$R_{TR} = \frac{P_{k\%}}{100} \times \frac{V_{2n}^2}{S_n} = 0.001\ \Omega$$

$$X_{TR} = \sqrt{Z_{dTR}^2 - R_{dTR}^2} = 5.916 \cdot 10^{-3}\ \Omega$$

Generator G

In this example, only the subtransient reactance value determining the greatest short-circuit current value for the generator is considered. Real part of the expression of the impedances of sequence o-d-i:

$$R_G = \frac{X_d^{''}}{2 \cdot \Pi \cdot f \cdot T_a} = 9.507 \cdot 10^{-4}\ \Omega$$

Imaginary part of the expression of the positive sequence impedance :

$$X_d^{''} = \frac{X_d^{'}\%}{100} \times \frac{V_{2n}^2}{S_n} = 0.018\ \Omega$$

Imaginary part of the expression of the negative sequence impedance:

$$X_2 = \frac{X_2\%}{100} \times \frac{V_{2n}^2}{S_n} = 0.022\ \Omega$$

X_2 is a parameter of the machine among the data given by the manufacturer. As an alternative, the imaginary part of the negative sequence impedance could have been calculated as the average value between the subtransient positive sequence reactance and that in quadrature:

$$X_i = \frac{X_d^{'} + X_q^{'}}{2}$$

Imaginary part of the expression of the zero-sequence impedance :

$$X_0 = \frac{X_0\%}{100} \times \frac{V_{2n}^2}{S_n} = 0.0115\ \Omega$$

Therefore:

$Z_{dG} = R_G + i \cdot X''_d$ $Z_{iG} = R_G + i \cdot X_2$ $Z_{oG} = R_G + i .X_o$

Cables C1 - C2

$Z_{dC..} = Z_{iC..} = R_{F..} + i \cdot X_F$

$Z_{o\,(F\text{-}N)\,C..} = (R_{F..} + 3 \cdot R_{N..}) + i \cdot (X_{F..} + 3 \cdot X_{N..})$

zero-sequence impedance due to line-to-neutral fault

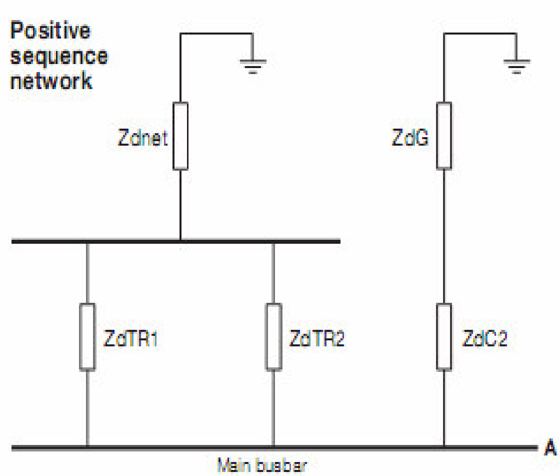
$Z_{o\,(F\text{-}PE)\,C..} = (R_{F..} + 3 \cdot R_{PE..}) + i \cdot (X_{F..} + 3 \cdot X_{PE..})$

zero-sequence impedance due to line-to-earth fault

Having defined all the sequence impedances of the different plant components, an analysis of the various fault situations can be carried out. Making reference to the network schematization of Figure, the three points A-B-D are highlighted where the fault is assumed and where the current values for the different fault typologies are calculated.

Still with reference to the network represented in Figure, the sequence networks with impedances in series or in parallel are drawn according to the way they are seen by an imaginary observer located at the fault point and looking at the supply source.

Fault in A Based on the above considerations, the following sequence networks can be drawn for a fault at point A.



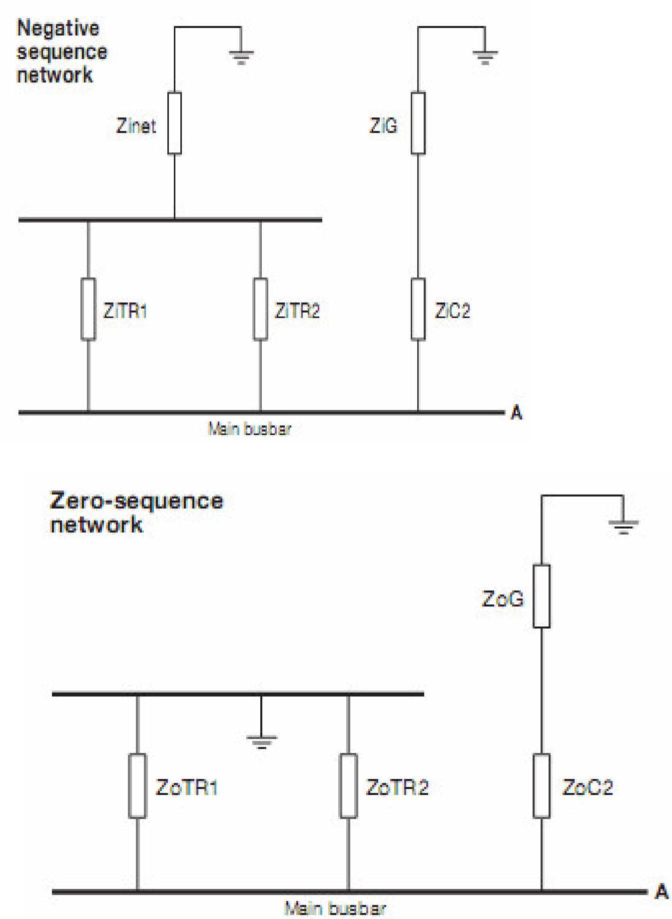


Figure 3.11 – Positive, Negative & Zero sequence network drawn at point A

Once identified the three sequence networks, the calculation of the short-circuit currents for the different fault typologies can be carried out:

Three-phase fault

Since the three-phase fault is a symmetrical fault, only the equivalent impedance of the positive sequence network shall be considered, complying also with what expressed by the formula for the calculation of currents. Therefore the equivalent impedance which is obtained by the reduction of the positive sequence network is:

$$Z_{dEq.A} = ((Z_{dTR1} \| Z_{dTR2}) + Z_{dnet}) \| (Z_{dG} + Z_{dC2}) = 4.237 \cdot 10^{-4} + i \cdot 0.0027 \ \Omega$$

["||" means "in parallel"] and the three-phase fault current value is expressed by the following formula:

$$I_{k3A} = \frac{V_{2n}}{\sqrt{3} Z_{dEqA}} = 83.9 \cdot 10^{-3} \angle -81.15° \text{ A}$$

By using the current divider rule, the contributions of the single electrical machines (generator and transformer) to the short-circuit current on the main busbar can be determined. In particular, the contributions are subdivided as follows :

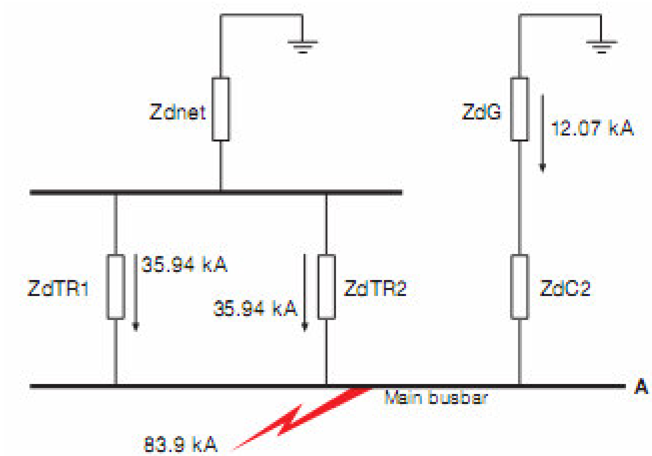


Figure 3.12 – Short Circuit according to current divider rule.

Two-phase fault

In this case the fault affects only two of the three phases; as a consequence it is necessary to evaluate the equivalent impedance not only of the positive sequence network but also that of the negative sequence network seen from the fault point A, as shown in the fault current formula.

The equivalent positive sequence impedance is:

$$Z_{dEq.A} = ((Z_{dTR1} \| Z_{dTR2}) + Z_{dnet}) \| (Z_{dG} + Z_{dC2}) = 4.237 \cdot 10^{-4} + i \cdot 0.0027\ \Omega$$

The equivalent negative sequence impedance is:

$$Z_{iEq.A} = ((Z_{iTR1} \| Z_{iTR2}) + Z_{inet}) \| (Z_{iG} + Z_{iC2}) = 4.367 \cdot 10^{-4} + i \cdot 0.0028\ \Omega$$

The two-phase fault current value is therefore equal to:

$$I_{k2A} = \frac{V_{2n}}{Z_{dEqA} + Z_{iEQA}} = 71.77 \cdot 10^{-3} \angle -81.12°\ A$$

<u>Single-phase fault</u>

As regards the single-phase fault a distinction must be made between:

- single-phase fault to earth, then return through the protection conductor, being a distribution system of TN-S type
- line-to-neutral fault, then return through the neutral conductor.

As expressed in the formulas for the calculation of the fault current, it is necessary to take into consideration the contribution of the three sequence circuits. To this purpose, it should be noted how the zero-sequence network is topologically different from the other sequence networks, since it is strongly influenced by the typology of the transformer windings. Besides, the values of the zero-sequence impedances of the cables depend on the type of single-phase fault (F-N or F-PE).
The equivalent positive sequence impedance is:

$$Z_{dEq.A} = ((Z_{dTR1} \| Z_{dTR2}) + Z_{dnet}) \| (Z_{dG} + Z_{dC2}) = 4.237 \cdot 10^{-4} + i \cdot 0.0027\ \Omega$$

The equivalent negative sequence impedance is:

$$Z_{iEq.A} = ((Z_{iTR1} \| Z_{iTR2}) + Z_{inet}) \| (Z_{iG} + Z_{iC2}) = 4.367 \cdot 10^{-4} + i \cdot 0.0028\ \Omega$$

The equivalent zero-sequence impedance line-to-neutral is:

$$Z_{o(F\text{-}N)Eq.A} = ((Z_{oTR1} \| Z_{oTR2}) \| (Z_{oG} + Z_{o(F\text{-}N)C2}) = 4.189 \cdot 10^{-4} + i \cdot 0.0025\ \Omega$$

The equivalent zero-sequence impedance line-to-earth is:

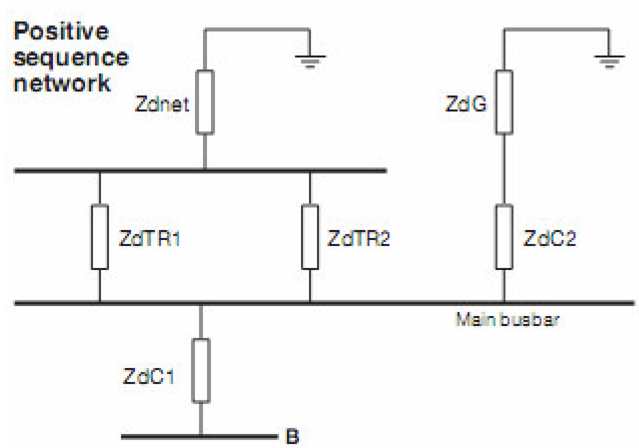
$$Z_{o(F\text{-}PE)Eq.A} = ((Z_{oTR1} \| Z_{oTR2}) \| (Z_{oG} + Z_{o(F\text{-}N)C2}) = 4.237 \cdot 10^{-4} + i \cdot 0.0025\ \Omega$$

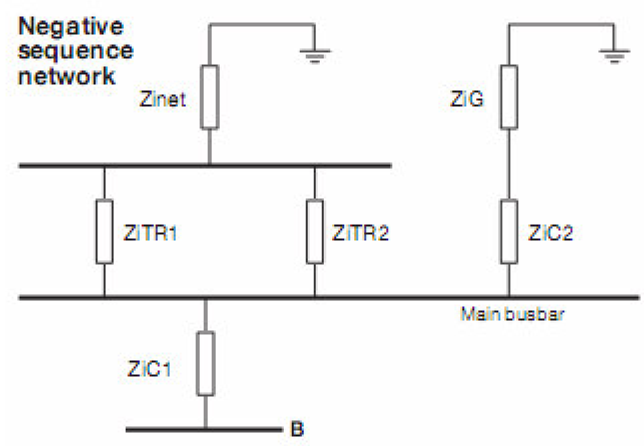
The value of the fault current line-to-neutral instead is equal to:

$$I_{k1(F\text{-}N)A} = \frac{\sqrt{3} \cdot V_{2n}}{Z_{dEq.A} + Z_{iEq.A} + Z_{O(F\text{-}PE)Eq.A}} = 85.43\ . \cdot 10^{-4} \angle -80.89°\ A$$

3.4.1 **Fault in B**

Complying with what described for the fault at point A, the three sequence networks are drawn now taking into consideration the impedances as seen from point B. As it results evident in this new case, also the cable C1 is to be considered in the sequence circuits.





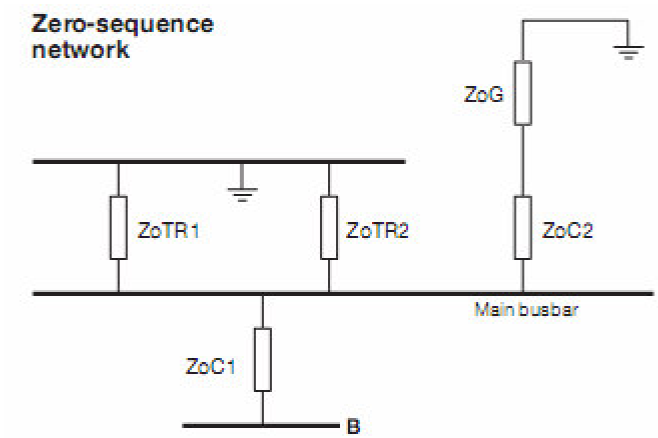


Figure 3.13 - Positive, Negative & Zero sequence network drawn at point B

Through a process and considerations analogous to the above case, the equivalent impedances are obtained and calculation of the short-circuit currents for the different fault typologies can be carried out.

<u>Three-phase fault</u>

The equivalent positive sequence impedance deriving from the reduction of the relevant sequence network is:

$$Z_{dEq.B} = ((Z_{dTR1} \| Z_{dTR2}) + Z_{dnet}) \| (Z_{dG} + Z_{dC2}) + Z_{dC1} = 0.003 + i \cdot 0.0046\ \Omega$$

Then the three-phase fault current value is equal to:

$$I_{k3B} = \frac{V_{2n}}{\sqrt{3} \cdot Z_{dEq.B}}$$

The contributions are subdivided as follows

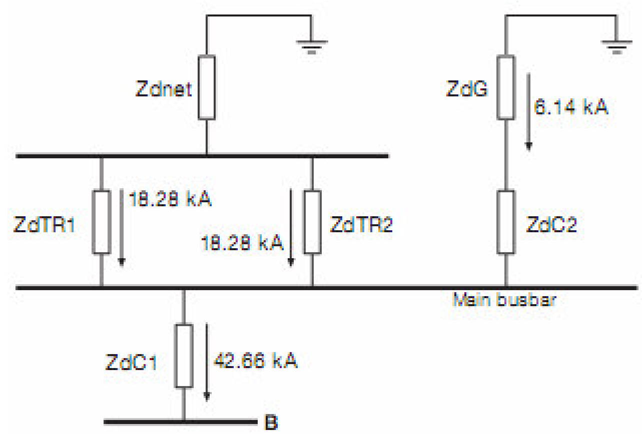


Figure 3.14 - The equivalent positive sequence impedance deriving from the reduction

Two-phase fault

The equivalent positive sequence impedance is:

$$Z_{dEq.B} = ((Z_{dTR1} \| Z_{dTR2}) + Z_{dnet}) \| (Z_{dG} + Z_{dC2}) + Z_{dC1} = 0.003 + i \cdot 0.0046\ \Omega$$

The equivalent negative sequence impedance is:

$$Z_{iEq.B} = ((Z_{iTR1} \| Z_{iTR2}) + Z_{inet}) \| (Z_{iG} + Z_{iC2}) + Z_{iC1} = 0.003 + i \cdot 0.0046\ \Omega$$

Then the two-phase fault current value is equal to:

$$I_{k3B} = \frac{V_{2n}}{Z_{dEq.B} \cdot Z_{iEq.B}} = 36.73 \ .\ 10^3\ \angle - 57.72°\ A$$

Single-phase fault
The equivalent positive sequence impedance is :

$$Z_{dEq.B} = ((Z_{dTR1} \| Z_{dTR2}) + Z_{dnet}) \| (Z_{dG} + Z_{dC2}) + Z_{dC1} = 0.003 + i \cdot 0.0046\ \Omega$$

The equivalent negative sequence impedance is:

$$Z_{iEq.B} = ((Z_{iTR1} \| Z_{iTR2}) + Z_{inet}) \| (Z_{iG} + Z_{iC2}) + Z_{iC1} = 0.003 + i \cdot 0.0046\ \Omega$$

The equivalent zero-sequence impedance line-to-neutral is:

$$Z_{o(F-N)Eq.B} = ((Z_{oTR1} \| Z_{oTR2}) \| (Z_{oG} + Z_{o(F-N)C2}) + Z_{O(F-PE)C1}$$

$$= 0.017 + i * 0.010\ \Omega$$

The equivalent zero-sequence impedance line-to-earth is:

$$Z_{o(F\text{-}PE)Eq.B} = ((Z_{oTR2} \| Z_{oTR2}) \; \| \; (Z_{oG} + Z_{o(F\text{-}PE)C2}) + Z_{o(F\text{-}PE)C1}$$

$$= 0.017 + \; i \cdot 0.010 \; \Omega$$

The value of the fault current line-to-neutral instead is equal to:

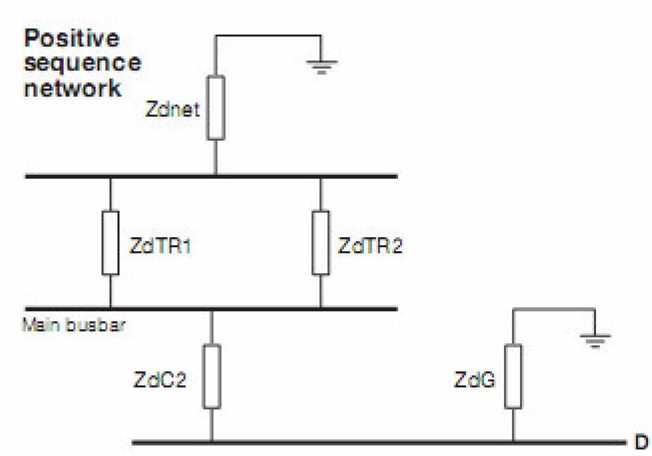
$$I_{k1(F\text{-}N)B} = \frac{\sqrt{3} \cdot V_{2n}}{Z_{dEq.B} + Z_{iEq.B} + Z_{O(F\text{-}N)Eq.B}} = 23.02 \cdot 10^3 \angle -39.60° \text{ A}$$

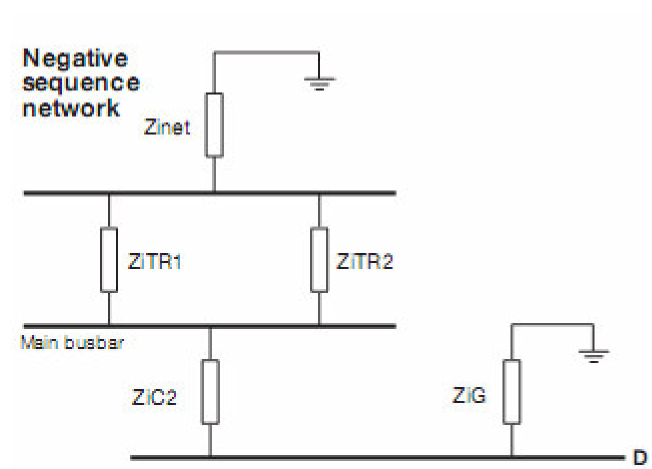
whereas the fault current value line-to-earth is equal to:

$$I_{k1(F\text{-}PE)B} = \frac{\sqrt{3} \cdot V_{2n}}{Z_{dEq.B} + Z_{iEq.B} + Z_{O(F\text{-}PE)Eq.B}} = 23.35 \cdot 10^3 \angle -40.09° \text{ A}$$

3.4.2 **Fault in D**

Assuming a fault in D, we take into consideration the case when the fault occurs immediately on the load side of the transformer. In accordance with what described in the cases above, the three sequence networks are drawn considering the impedances as seen from point D.





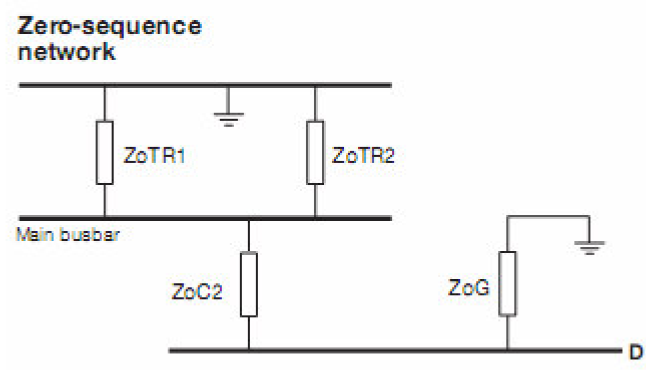


Figure 3.15 - Positive, Negative & Zero sequence network drawn at point D

Through a process and considerations analogous to the above ones, the equivalent impedances are obtained and calculation of the short-circuit currents for the different fault typologies can be carried out.

Three-phase fault

The equivalent positive sequence impedance is:

$$Z_{dEq.B} = ((Z_{dTR1} \| Z_{dTR2}) + Z_{dnet} + + Z_{dc2}) \| (Z_{dG}) = 5.653 \cdot 10^{-4} + i \cdot 0.0046\ \Omega$$

Then the three-phase fault current value is:

$$I_{k3B} = \frac{V_{2n}}{\sqrt{3}\ Z_{dEq.D}} = 65.19\ .\ 10^{3} \angle -80.82°\ A$$

The contributions are subdivided as follows:

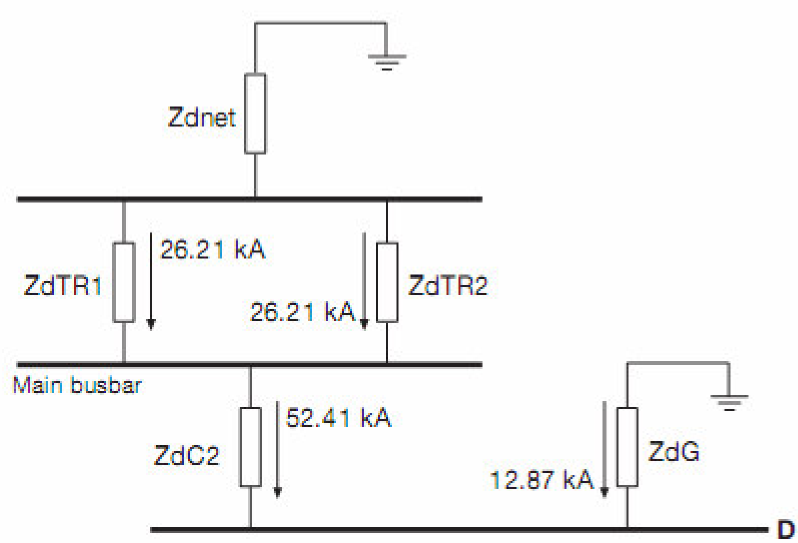


Figure 3.16 - The equivalent positive sequence impedance & fault current

Two-phase fault

The equivalent positive sequence impedance is:

$$Z_{dEq.D} = ((Z_{dTR1} \| Z_{dTR2}) + Z_{dnet} + + Z_{dc2}) \| (Z_{dG}) = 5.653 \cdot 10^{-4} + i \cdot 0.0035\ \Omega$$

The equivalent negative sequence impedance is:

$$Z_{iEq.D} = ((Z_{iTR1} \| Z_{iTR2}) + Z_{inet} + + Z_{ic2}) \| (Z_{dG}) = 5.94 \cdot 10^{-4} + i \cdot 0.0036\ \Omega$$

The two-phase fault current value is therefore equal to:

$$I_{k2D} = \frac{V_{2n}}{Z_{dEq.D} \cdot Z_{iEq.D}} = 55.46 \cdot 10^{3} \angle -80.75° \text{ A}$$

Single-phase fault

The equivalent positive sequence impedance is:

$$Z_{dEq.D} = ((Z_{dTR1} \| Z_{dTR2}) + Z_{dnet} + + Z_{dc2}) \| (Z_{dG}) = 5.653 \cdot 10^{-4} + i \cdot 0.0035\ \Omega$$

The equivalent negative sequence impedance is:

$$Z_{iEq.D} = ((Z_{iTR1} \| Z_{iTR2}) + Z_{inet} + Z_{ic2}) \| (Z_{iG}) = 5.94 \cdot 10^{-4} + i \cdot 0.0036\ \Omega$$

The equivalent zero-sequence impedance line-to-neutral is:

$$Z_{o(F\text{-}N)Eq.D} = ((Z_{OTR1} \| Z_{OTR2}) + Z_{O(F\text{-}N)c2}) \| (Z_{OG}) = 9.127 \cdot 10^{-4} + i \cdot 0.0046\ \Omega$$

The equivalent zero-sequence impedance line-to-earth is:

$$Z_{o(F\text{-}PE)Eq.D} = ((Z_{OTR1} \| Z_{OTR2}) + Z_{O(F\text{-}PE)c2}) \| (Z_{OG}) = 9.85 \cdot 10^{-4} + i \cdot 0.0046\ \Omega$$

The fault current value line-to-neutral is therefore:

$$I_{k1(F\text{-}N)B} = \frac{\sqrt{3} \cdot V_{2n}}{Z_{dEq.D} + Z_{iEq.D} + Z_{O(F\text{-}N)Eq.D}} = 58.03 \cdot 10^{3} \angle -80.01° \text{ A}$$

whereas, the fault current value line-to-earth is equal to:

$$I_{k1(F\text{-}PE)B} = \frac{\sqrt{3} \cdot V_{2n}}{Z_{dEq.D} + Z_{iEq.D} + Z_{O(F\text{-}PE)Eq.D}} = 57.99 \cdot 10^{3} \angle -79.66° \text{ A}$$

3.4.3 **Power method (another method)** :

This method allows a quick but approximate evaluation of the three-phase short-circuit current in a network. It is necessary to calculate the power short-circuits of the various elements constituting the network (transformers – generators – cables), before determining the total short-circuit power at the point where the fault current has to be evaluated.
Power fluxes due to elements operating in parallel can be reduced by applying the formula of the resistances in series, whereas power fluxes due to elements working in series can be reduced by applying the formula of the resistances in parallel. Here is an example of calculation applied to the network previously examined. It can be observed how, for the same typology of fault (three-phase short-circuit at points A – B – D), this "approximate" method gives results quite similar to those obtained by applying the method of the symmetrical components. Making reference to the plant data previously reported, it is possible now to proceed with the calculation of the short-circuit powers of the different elements of the installation:

Supply network

$S_{knet} = 750MVA$ is a plant datum

Transformer TR1-TR2

$$S_{kTR1} = \frac{S_{nTR1}}{V_k\%} \cdot 100 \qquad S_{kTR1} = 26.67MVA$$

$$S_{kTR2} = \frac{S_{nTR2}}{V_k\%} \cdot 100 \qquad S_{kTR2} = 26.67MVA$$

Generator G

$$S_{kG} = \frac{S_{nG}}{X''_d\%} \cdot 100 \qquad S_{kG} = 8.93\ MVA$$

Cables C1-C2

$$S_{kC1} = \frac{V_{2n}^2}{Z_{FC1}} \qquad S_{kC1} = 51.75MVA$$

$$S_{kC2} = \frac{V_{2n}^2}{Z_{FC2}} \qquad S_{kC2} = 51.75MVA$$

where: $Z_{FC1} = \sqrt{(R_{F1}^2 + X_{F1}^2)}$ $\qquad Z_{FC1} = 0.0031\Omega$

$$Z_{FC2} = \sqrt{(R_{F2}^2 + X_{F2}^2)} \qquad Z_{FC2} = 0.0012\Omega$$

Taking into consideration the fault in A, the network schematizing the contribution of the short-circuit powers is the following:

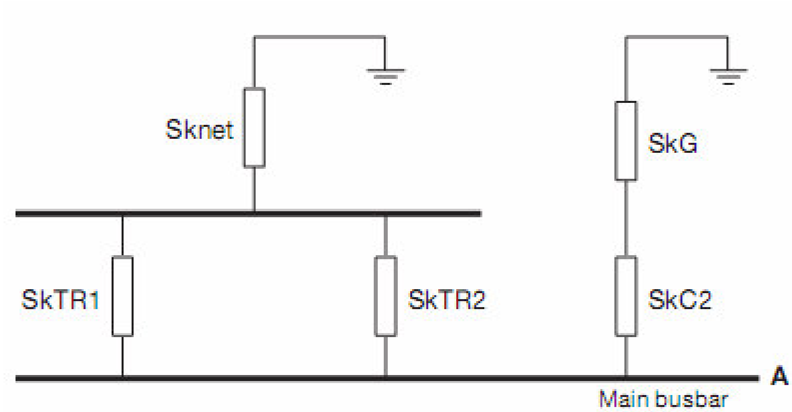


Figure 3.17 - Network schematizing the contribution of the short-circuit powers in fault A

By the reduction of the elements in series – in parallel, the following expression for the total power is obtained:

$S_{kTOT(A)} = ((S_{kTR1} + S_{kTR2}) // S_{kR}) + (S_{kG} // S_{kC2}) = 58.16MVA$

$$I_{k3A} = \frac{S_{kTOT(A)}}{\sqrt{3} \cdot V_{2n}} \quad \text{from which it results} \quad I_{k3A} = 83.95kA$$

Taking into consideration the fault in B, the network schematizing the contribution of the short-circuit powers is the following:

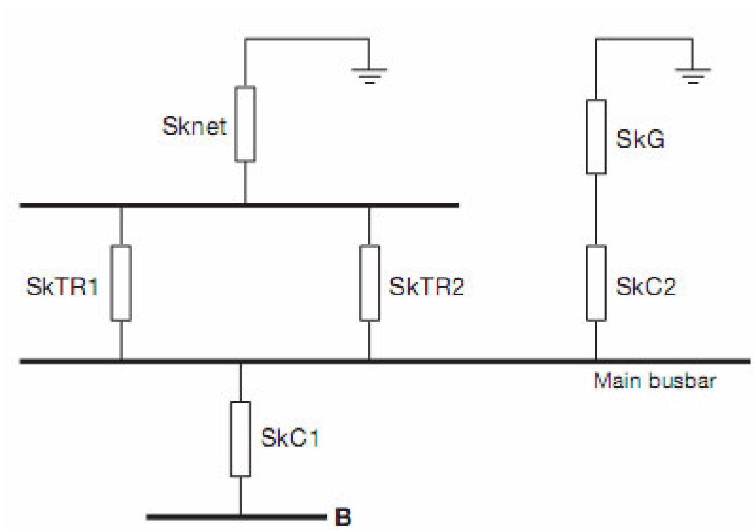


Figure 3.18 - Network schematizing the contribution of the short-circuit powers in fault B

By the reduction of the elements in series – in parallel, the following expression for the total power is obtained:

$$S_{kTOT(B)} = [((S_{kTR1} + S_{kTR2}) \,//\, S_{kR}) + (S_{kG} \,//\, S_{kC2})] \,//\, S_{kC1} = 27.38MVA$$

$$I_{k3B} = \frac{S_{kTOT(B)}}{\sqrt{3} \cdot V_{2n}} \qquad \text{from which it results } I_{k3B} = 39.52kA$$

Taking into consideration the fault in D, the network schematizing the contribution of the short-circuit powers is:

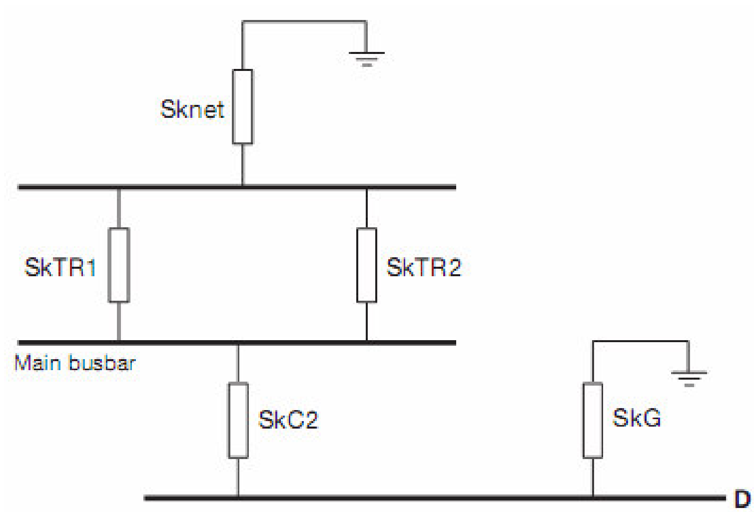


Figure 3.19 - Network schematizing the contribution of the short-circuit powers in fault D

By the reduction of the elements in series – in parallel, the following expression for the total power is obtained:

$$S_{kTOT(D)} = \{[(S_{kTR1} + S_{kTR2}) \,//\, S_{kR}] \,//\, S_{kC2}\} + S_{kG} = 45.23MVA$$

$$I_{k3D} = \frac{S_{kTOT(D)}}{\sqrt{3} \cdot V_{2n}} \qquad \text{from which it results } I_{k3D} = 65.28kA$$

3.5 <u>Considerations about the results obtained :</u>

From the above example, it is evident that the use of the power method offers the advantage of simplicity and speed, but it could give results less precise compared with the method of the symmetrical components.
The most evident difference regards the three-phase fault calculated at point B, where the presence of the cable C2, characterized by particular values for "L"

and "R", introduces a different ratio between the imaginary and the real parts of the expressions as regards to the other elements, thus highlighting the approximate character of the power method.

However, the effect of the approximation is not such as to invalidate this method, in particular if it is used to carry out preliminary calculations, as often happens.

3.6 CASE STUDY :

In Figure 3.11 a MV study case distribution network is shown, fed from a 50 MVA HV/MV transformer. Four DG stations with a total power of about 17 MW are connected to the substation MV busbars by dedicated lines (three wind farms, each having six identical wind turbines, and one small hydroelectric plant consisting of three identical turbines).

Fault level calculation results are presented for a three-phase fault at the MV busbars of the substation. The following observations hold:

- The total fault level is 301 MVA (239 MVA due to the upstream grid and 62 MVA due to the DG stations).
- Wind farm 2 contributes about four times more current than wind farm 1, due to the different technology of the WTs.
- The reactor R at the output of wind farm 3 effectively reduces its contribution (without the reactor, the sc current of the wind farm would increase by more than 50%). With the reactor in place, wind farm 3 contributes less than wind farm 2, although its output power is higher.

Most important is the fact that the design fault level of such a distribution network would be around 250 MVA (HV/MV transformer with u_k~20% @50 MVA). Hence, the connection of even a moderate amount of DG (17 MW in this case, which is realistic) drives the fault level to unacceptably high values.

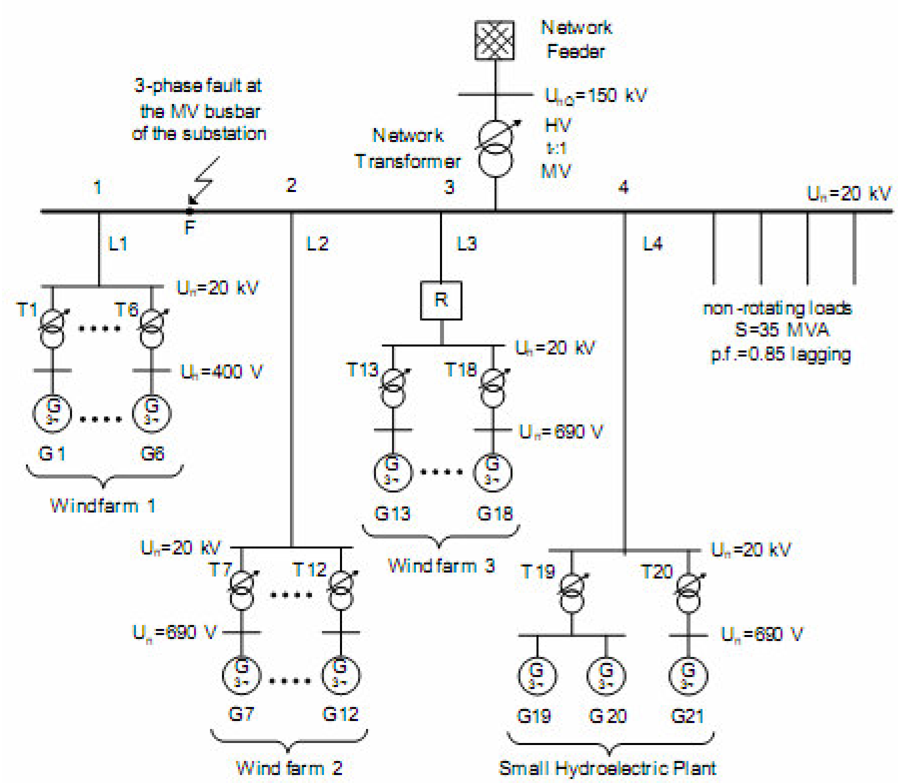


Figure 3.11 – Case study MV distribution network.

Chapter 4

PROTECTION SYSTEMS FOR DIFFERENT TYPES OF FAULT OF SUBSTATION

4.1 Protection and Substation Automation

There are a number of applications for which multiple setting groups can upgrade the scheme performance, for example:

- For use as a voltage-dependent control of overcurrent-time relay pickup values to overcome alternator fault current decrement to below normal load current when the automatic voltage regulator (AVR) is not in automatic operation
- For maintaining short operation times with lower fault currents, e.g., automatic change of settings if one supply transformer is taken out of service
- For "switch-onto-fault" protection to provide shorter time settings when energizing a circuit after maintenance so that normal settings can be restored automatically after a time delay.
- For auto-reclosure programs, that is, instantaneous operation for first trip and delayed operation after unsuccessful reclosure.
- For cold load pickup problems where high starting currents may cause relay operation.
- For "ring open" or "ring closed" operation.

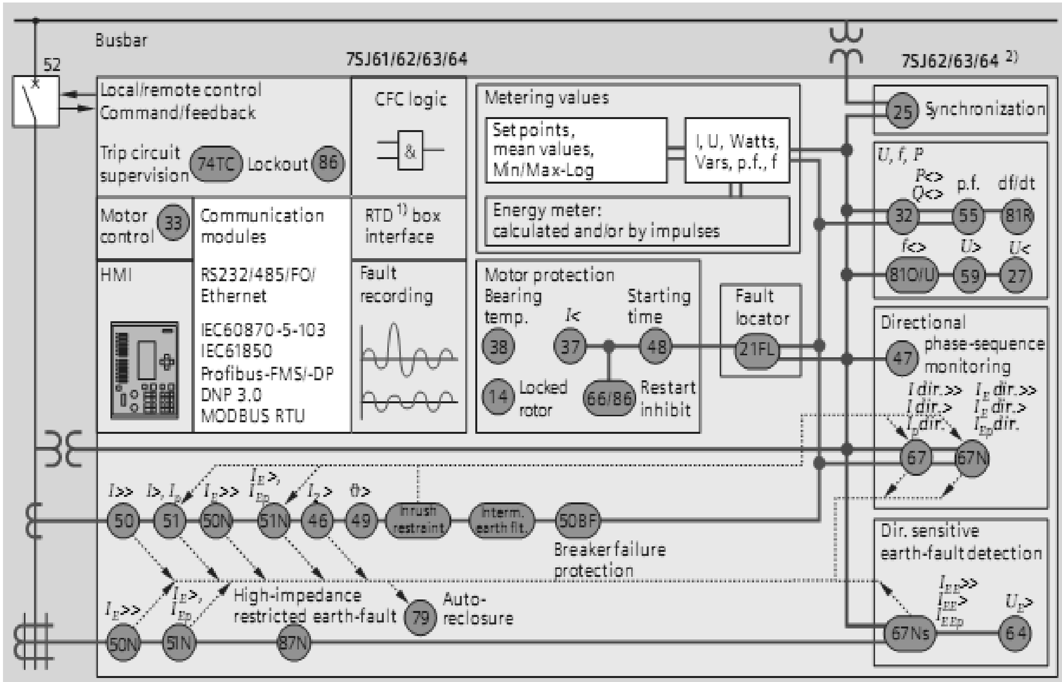
4.2 Implemented functions:

SIPROTEC relays are available with a variety of protective functions. The high processing power of modern numerical units allows further integration of non-protective add-on functions. In transmission-type substations, separation into independent hardware units is still preferred, whereas a trend toward higher function integration can be observed on the distribution level.
Relays with protection functions only and relays with combined protection and control functions are being offered. SIPROTEC 4 relays offer combined protection and control functions. SIPROTEC 4 relays support the "one relay one feeder" principle and thus contribute to a considerable reduction in space and wiring requirements. With the well-proven SIPROTEC 4 family, Siemens supports both stand-alone and combined solutions on the basis of a single hardware and software platform. The user can decide within wide limits on the configuration of the control and protection, and the reliability of the protection functions (fig. 4.1).

The following solutions are available within one relay family:

- Separate control and protection relays.
- Feeder protection and remote control of the line circuit-breaker via the serial communication link.
- Combined relays for protection, monitoring and control.

Mixed use of the different relay types is possible on account of the uniform operation and communication procedures.



1) RTD = Resistance temperature Detector 2) VT connection for 7SJ62/63/64 only

Figure 4.1 – SIPROTEC 4 relays 7SJ61/62/63, 64 implemented functions

To fulfill vital protection redundancy requirements, only those functions that are interdependent and directly associated with each other are integrated into the same unit. For backup protection, one or more additional units should be provided. All relays can stand fully alone. Thus, the traditional protection principle of separate main and backup protection as well as the external connection to the switchyard remains unchanged. "One feeder, one relay" concept Analog protection schemes have been engineered and assembled from individual relays. Inter wiring between these relays and scheme testing has been carried out manually in the workshop. Data sharing now allows for the integration of several protection and protection-related tasks into one single numerical relay. Only a few external devices may be required for completion of the total scheme. This has significantly lowered the costs of engineering, assembly, panel wiring, testing and commissioning. Scheme failure probability has also been lowered. Engineering has moved from schematic diagrams toward a parameter definition procedure. The powerful user-definable logic of
SIPROTEC 4 allows flexible customized design for protection, control and measurement.

Measuring included

For many applications, the accuracy of the protection current transformer is sufficient for operational measuring. The additional measuring current transformer was required to protect measuring instruments under short-circuit conditions. Due to the low thermal withstand capability of the measuring instruments, they could not be connected to the protection current transformer. Consequently, additional measuring core current transformers and measuring instruments are now only necessary where high accuracy is required, e.g., for revenue metering.

Corrective rather than preventive maintenance

Numerical relays monitor their own hardware and software. Exhaustive self-monitoring and failure diagnostic routines are not restricted to the protection relay itself but are methodically carried through from current transformer circuits to tripping relay coils.
Equipment failures and faults in the current transformer circuits are immediately reported and the protection relay is blocked.
Thus, service personnel are now able to correct the failure upon occurrence, resulting in a significantly upgraded availability of the protection system.

4.3 Typical Protection Schemes:

Cables and overhead lines

4.3.1 Radial systems:

1) Auto-reclosure (ANSI 79) only with overhead lines.
2) Negative sequence overcurrent protection 46 as sensitive backup protection against asymmetrical faults.

General notes:
The relay at the far end (D) is set with the shortest operating time. Relays further upstream have to be time-graded against the next downstream relay in steps of about 0.3s.

Inverse time or definite time can be selected according to the following criteria:

– Definite time:
Source impedance is large compared to the line impedance, that is, there is small current variation between near and far end faults.

– Inverse time:
Longer lines, where the fault current is much less at the far end of the line than at the local end.

– Strong or extreme inverse-time:
Lines where the line impedance is large compared to the source impedance (high difference for close-in and remote faults), or lines where coordination with fuses or reclosers is necessary. Steeper characteristics also provide higher stability on service restoration (cold load pickup and transformer inrush currents)

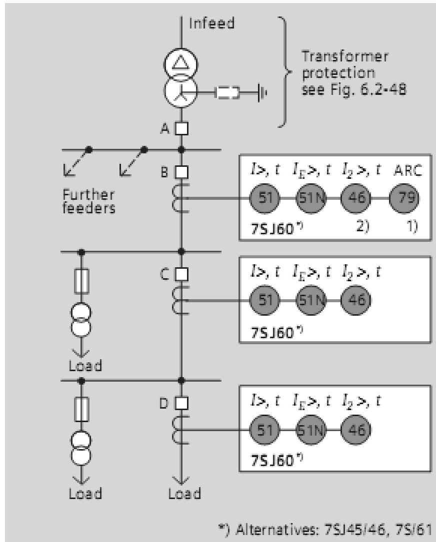


Figure 4.2 – Radial systems

4.3.2 <u>Ring-main circuit:</u>

General notes:

- Operating time of overcurrent relays to be coordinated with downstream fuses of load transformers (preferably with strong inverse-time characteristic with about 0.2 s grading-time delay)
- Thermal overload protection for the cables (option)
- Negative sequence overcurrent protection (46) as sensitive protection against asymmetrical faults (option)

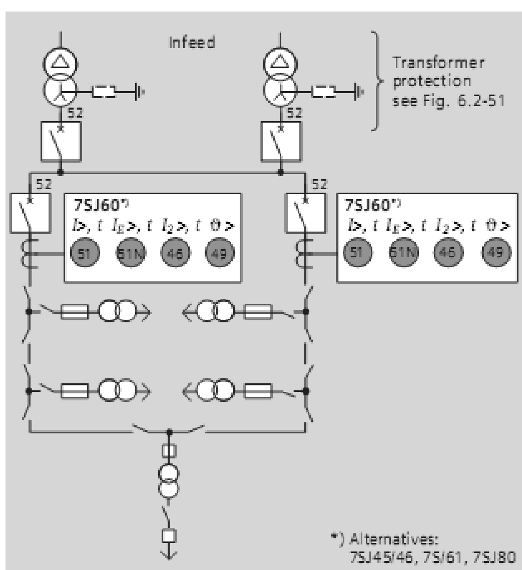


Figure 4.3 – Ring-main circuit

4.3.3 Switch-onto-fault protection:

If switched onto a fault, instantaneous tripping can be effected. If the internal control function is used (local, via binary input or via serial interface), the manual closing function is available without any additional wiring. If the control switch is connected to a circuit-breaker bypassing the internal control function, manual detection using a binary input is implemented.

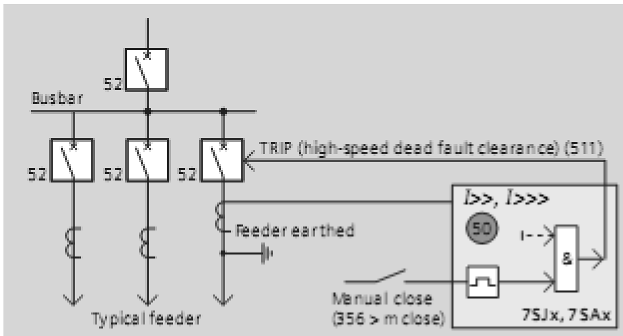


Figure 4.4 – Switch-onto-fault protection

4.3.4 Directional comparison protection (cross-coupling):

Cross-coupling is used for selective protection of sections fed from two sources with instantaneous tripping, that is, without the disadvantage of time coordination. The directional comparison protection is suitable if the distances between the protection stations are not significant and pilot wires are available for signal transmission. In addition to the directional comparison protection, the directional coordinated time-over current protection is used for complete selective backup protection. If operated in a closed-circuit connection, an interruption of the transmission line is detected.

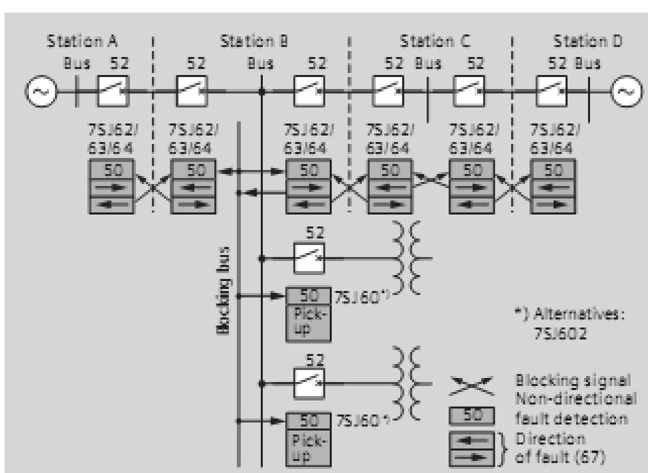


Figure 4.5 – Directional comparison protection

4.3.5 **Distribution feeder with reclosers:**

General notes:

- The feeder relay operating characteristics, delay times and auto-reclosure cycles must be carefully coordinated with downstream reclosers, sectionalizers and fuses. The 50/50N instantaneous zone is normally set to reach out to the first main feeder sectionalizing point. It has to ensure fast clearing of close-in faults and prevent blowing of fuses in this area ("fuse saving"). Fast auto-reclosure is initiated in this case. Further time-delayed tripping and reclosure steps (normally two or three) have to be graded against the recloser.

- The overcurrent relay should automatically switch over to less sensitive characteristics after long breaker interruption times in order to enable overriding of subsequent cold load pickup and transformer inrush currents.

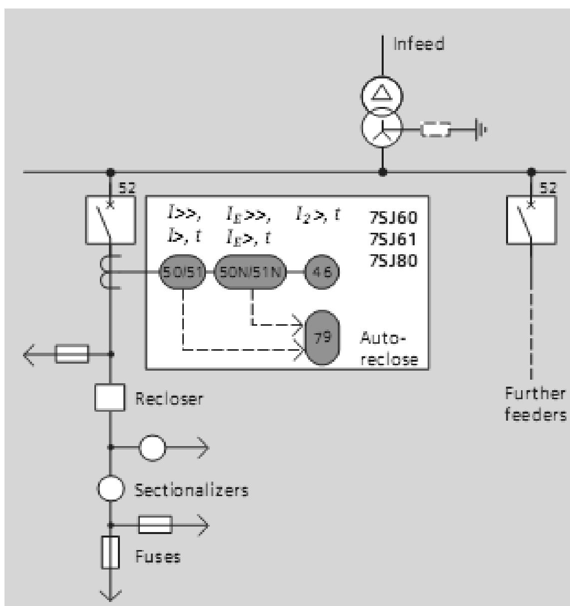


Figure 4.6 – Distribution feeder with reclosers

4.3.6 **Three-pole multi shot auto-reclosure (AR, ANSI 79) :**

Auto-reclosure (AR) enables 3-phase auto-reclosing of a feeder that has previously been disconnected by overcurrent protection.The SIPROTEC 7SJ61 allows up to nine reclosing shots. The first four dead times can be set individually. Reclosing can be blocked or initiated by a binary input or internally. After the first trip in a reclosing sequence, the high-set instantaneous elements (I>>>, I>>, I_E>>) can be blocked. This is used for fuse-saving applications and other similar transient schemes using simple overcurrent relays instead of fuses. The low-set defi nite-time (I>, I_E>) and the inverse-time (I_p, I_{Ep}) overcurrent elements remain operative during the entire sequence.

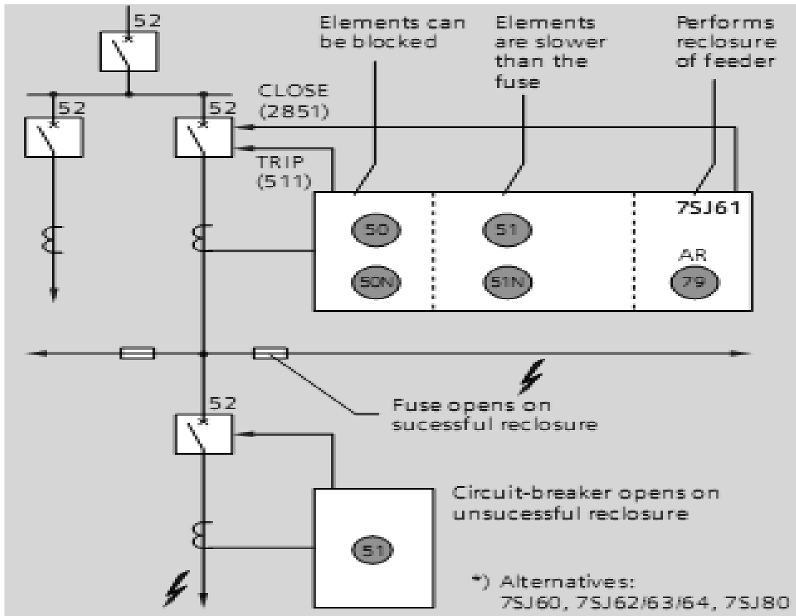


Figure 4.7 – 3-pole multishot auto-reclosure (AR, ANSI 79)

4.3.7 <u>Parallel feeder circuit:</u>

General notes:

- The preferred application of this circuit is in the reliable supply of important consumers without significant infeed from the load side.
- The 67/67N directional overcurrent protection trips instantaneously for faults on the protected line. This saves one time-grading interval for the overcurrent relays at the infeed.
- The 51/51N overcurrent relay functions must be time-graded against the relays located upstream.

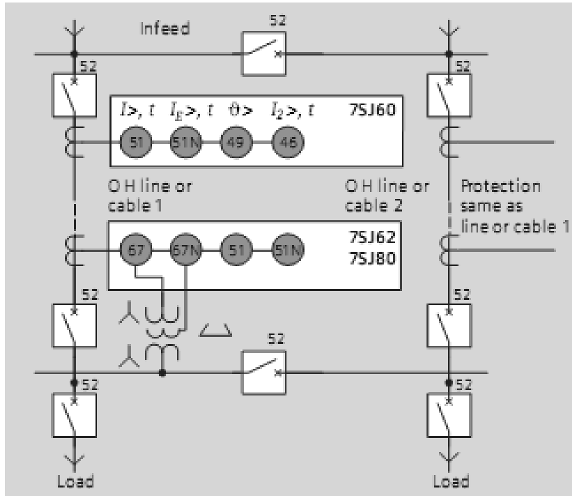


Figure 4.8 – Parallel feeder circuit

4.3.8 <u>Reverse-power monitoring at double infeed</u>

If a busbar is fed from two parallel in feeds and a fault occurs on one of them, only the faulty infeed should be tripped selectively in order to enable supply to the busbar to continue from the remaining supply. Unidirectional devices that can detect a short-circuit current or energy flow from the busbar toward the incoming feeder should be used. Directional time-overcurrent protection is usually set via the load current. However, it cannot clear weak-current faults. The reverse-power protection can be set much lower than the rated power, thus also detecting the reverse-power flow of weak-current faults with fault currents significantly below the load current.

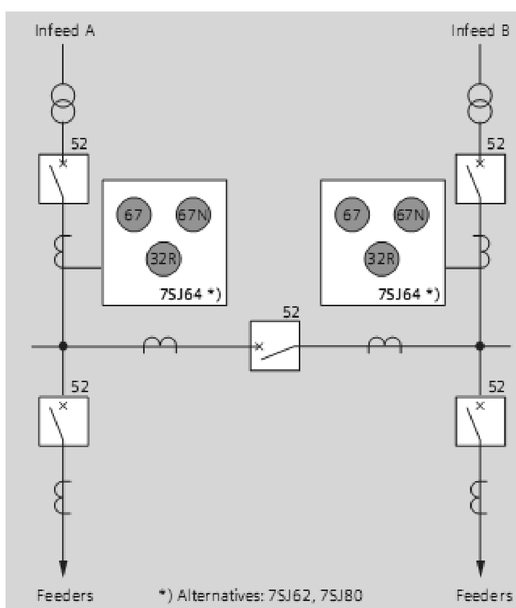


Figure 4.9 – Reverse-power monitoring at double infeed

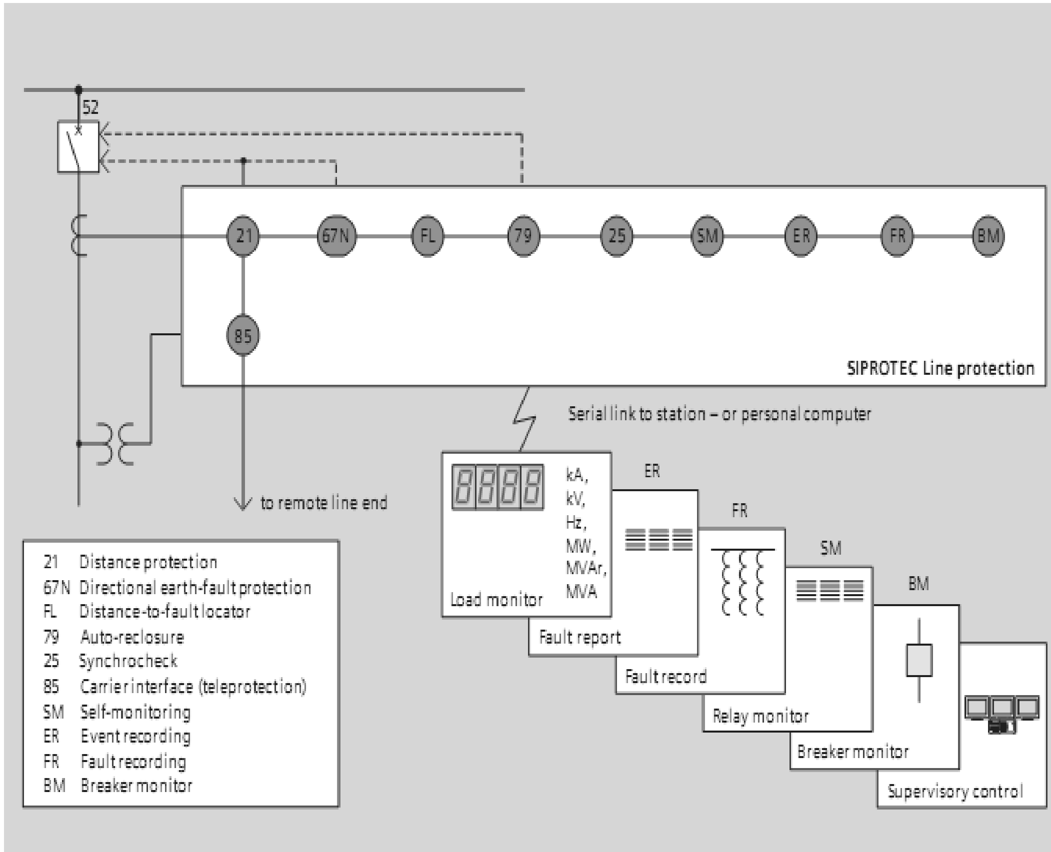


Figure 4.10 – Different Types of Protection of a Substation Scheme

Example 4.1: Stability verification of the numerical busbar protection relay 7SS52

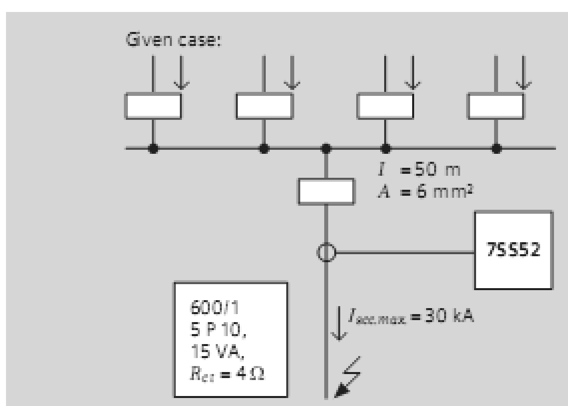


Figure 4.11 – Stability verification of the numerical busbar protection relay 7SS52

$$\frac{I_{scc\,max}}{I_{pn}} = \frac{30{,}000A}{600A} = 50$$

According to $K_{td} = 1/2$

$K'_{ssc} \geq ½ \times 50 = 25$

$$R_b = \frac{15VA}{1A^2} = 15\Omega$$

$R_{relay} = 0.1\ \Omega$

$$R_{lead} = \frac{2 \cdot 0.0175.50}{6} = 0.3\Omega$$

$R'_b = R_{lead} + R_{relay} = 0.3\ \Omega + 0.1\ \Omega = 0.4\ \Omega$

$$K'_{ssc} = \frac{R_{ct} + R_b}{R_{ct} + R'_b} \times K_{ssc} = \frac{4+15}{4+0.4} \times 10 = 43.2$$

Result:

The effective K'_{ssc} is 43.2, the required K'_{ssc} is 25. Therefore the stability criterion is fulfilled. Relay burden The CT burdens of the numerical relays of Siemens are below 0.1 VA and can therefore be neglected for a practical estimation. Exceptions are the busbar protection 7SS60 and the pilot-wire relays 7SD600. Intermediate CTs are normally no longer necessary, because the ratio adaptation for busbar and transformer protection is numerically performed in the relay. Analog static relays in general have burdens below about 1 VA. Mechanical relays, however, have a much higher burden, up to the order of 10 VA. This has to be considered when older relays are connected to the same CT circuit. In any case, the relevant relay manuals should always be consulted for the actual burden values. Burden of the connection leads; the resistance of the current loop from the CT to the relay has to be considered:

$$R_{lead} = \frac{2 \cdot \rho I}{A}$$

I = single conductor length from the CT to the relay in m

Specific resistance:

$\rho = 0.0175\ \ \Omega \cdot mm^2/m$ (copper wires) at 20 °C
A = Conductor cross-section in mm2

Chapter 5

Discussion & Conclusion

5.1 Discussion :

Fault Calculations also result to at least three very significant outputs which will become the bases of the following:

1) First: Proper selection of protective equipment ratings as circuit breakers or fuses that suit to system requirements;
2) Second: Realistic arming up of protective relays to trigger operation of circuit breakers once faults do occur;

3) Thirdly: Proper coordination of operation of these protective devices to effect selective interruptions of the only required breakers to trip faulted circuits without the hassle of rendering the other portions of the system powerless.

This paper has derived a set of equations providing a more accurate calculation of the fault current distribution and related voltages in conductors and the accompanied parallel wire interconnecting neighboring substations. These equations are based on the assumption of a uniformly distributed conductance between earthing wire and earth.

Furthermore, the procedure for determining resulting nominal screening factor of multi-conductor connection between two power substations has been presented. The earthing wire connection is always in favor of both the substation safety and cable thermal withstanding. It also provides better screening for nearby auxiliary cables against inductive interference.

5.2 Conclusion :

The fault current occurs in the Substation due to abnormal behavior under conditions of symmetrical short circuit are caused in the system accidentally through insulation failure of equipment or flashover of lines initiated by a lighting stroke or through accidental faulty operation. As a result, the substation must be protected against flow of heavy short circuit currents (which can cause permanent damage to major equipment) by disconnecting the faulty part of the system by means of circuit breakers operated by protective relaying.

Under operations of system impedances in each phase are identical and the three-phase voltages and currents though out the system are completely balanced, i.e. they have equal magnitudes in each phase and are progressively displaced in time phase by 120^0 (phase a leads /lags phase b by 120^0 phase b leads /lags phase c by 120^0).

While over-current protective devices (OCPD's) are provided for overload protection for system components such as switchgears, busses, wires & cables, motor controllers, etc; it is also necessary as discussed earlier to place protection for more damaging events such as faults. To obtain a reliable operation and to assure that system components are protected from damage during abnormal events, it is necessary to first calculate the fault duties at various points in the electrical system while still on the drawing boards and adequate protective devices must subsequently be in place to anticipate these faults.

For all possible conditions, it is the responsibility of the system designer to design electric power systems with adequate control of short circuits as one major consideration. It is also the plant engineer's responsibility to see to it that the protective relaying devices are armed to pre-determined settings either by him-self or by consultants. As can be recalled, uncontrolled short circuits can cause service outages with accompanying production downtime and associated inconvenience, interruption of essential facilities, extensive equipment damage, personnel injury or fatality and a possible full-blown fire.

It is therefore important to de-mystify the stigma of faults and its counter-measures. Again, the system designer is responsible for the selection of the right equipment; and would generally have the task of calculating system short circuits.

APPENDIX

Power System Analysis: Faults

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, and physical damage or human error. These faults may either be three phases in nature involving al 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 helps 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.

1 Equivalent Circuits - Single phase and Equivalent Single Phase Circuits

In a balanced three phase circuit, since the information relating to one single phase gives the information relating to the other two phases as well, it is sufficient to do calculations in a single phase circuit.

There are two common forms used. These are (i) to take any one single phase of the three phase circuit and (ii) to take an equivalent single phase circuit to represent the full three phase circuit.

1.1 Single Phase Circuit

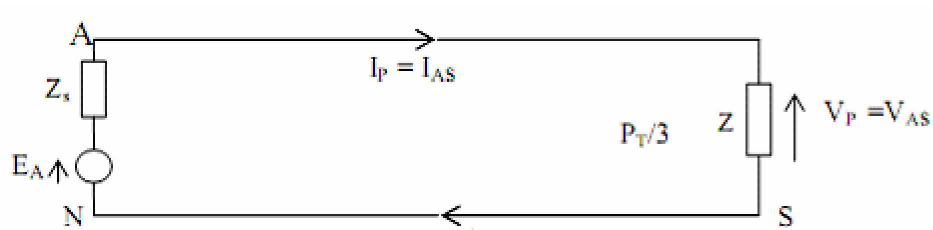


Figure 1 - Single Phase Circuit

Figure 1 shows one single phase "**AN**" of the three phase circuit "*ABC* N". Since the system is balanced, there is no current in the neutral, and there is no potential drop across the neutral wire. Thus the star point "**S**" of the system would be at the same potential as the neutral point "**N**". Also, the line current is the same as the phase current, the line voltage is √3 times the phase voltage, and the total power is 3 times the power in a single phase.

$$I = I_P = I_L, V = V_P = V_L / \sqrt{3}, S = S_P = S_T / 3$$

Working with the single phase circuit would yield single phase quantities, which can then be converted to three phase quantities using the above conversions.

1.2 Equivalent Single Phase Circuit

Of the parameters in the single phase circuit shown in figure 1, the Line Voltage and the Total Power (rather than the Phase Voltage and one-third the Power) are the most important quantities. It would be useful to have these quantities obtained directly from the circuit rather than having conversion factors of √3 and 3 respectively. This is achieved in the Equivalent Single Phase circuit, shown in figure 2, by multiplying the voltage by a factor of √3 to give Line Voltage directly.

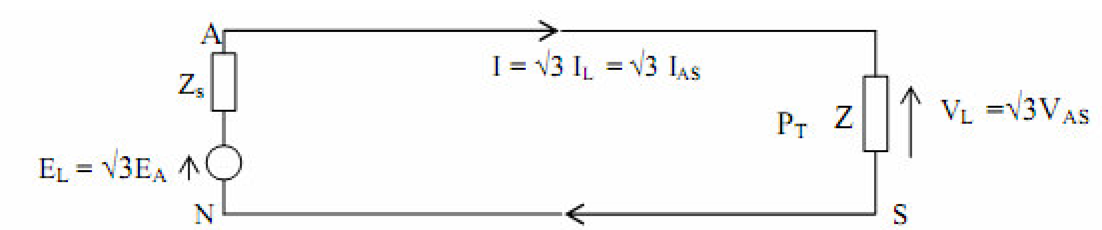


Figure 2 - Equivalent Single Phase Circuit

The Impedance remains as the per-phase impedance. However, the Line Current gets artificially amplified by a factor of √3. This also increases the power by a factor of $(\sqrt{3})^2$, which is the required correction to get the total power. Thus, working with the Equivalent single phase circuit would yield the required three phase quantities directly, other than the current which would be $\sqrt{3}\ I_L$.

1.3 Revision of Per Unit Quantities

Per unit quantities, like percentage quantities, are actually fractional quantities of a reference quantity. These have a lot of importance as per unit quantities of parameters tend to have similar values even when the system voltage and rating change drastically. The per unit system permits multiplication and division in addition to addition and subtraction without the requirement of a correction factor (when percentage quantities are multiplied or divided additional factors of 0.01 or100 must be brought in, which are not in the original equations, to restore the percentage values). Per-unit values are written with "pu" after the value. For power, voltage, current and impedance, the per unit quantity may be obtained by dividing by the respective base of that quantity.

$$S_{pu} = \frac{S}{S_{base}} \qquad V_{pu} = \frac{V}{V_{base}} \qquad I_{pu} = \frac{I}{I_{base}} \qquad Z_{pu} = \frac{Z}{Z_{base}}$$

Expressions such as Ohm's Law can be applied for per unit quantities as well. Since Voltage, Current, Impedance and Power are related, only two Base or reference quantities can be independently defined. The Base quantities for the other two can be derived there from. Since Power and Voltage are the most often specified, they are usually chosen to define the independent base quantities.

1.4.1 Calculation for Single Phase Systems

If VA_{base} and V_{base} are the selected base quantities of power (complex, active or reactive) and voltage respectively, then

Base current $\qquad I_{base} = \frac{V_{base} \times I_{base}}{V_{base}} = \frac{VA_{base}}{V_{base}}$

Base Impedance $\qquad Z_{base} = \frac{V_{base}}{I_{base}} = \frac{V_{base}^2}{I_{base} \times V_{base}} = \frac{V_{base}^2}{VA_{base}}$

In these expressions, all the quantities are single phase quantities.

1.4.2 Calculations for Three Phase Systems

In three phase systems the line voltage and the total power are usually used rather than the single phase quantities. It is thus usual to express base quantities in terms of these. If $VA_{3\varphi base}$ and V_{LLbase} are the base three-phase power and line-to-line voltage respectively,

Base Current $\qquad I_{base} = \frac{VA_{base}}{V_{base}} = \frac{3VA_{base}}{3V_{base}} = \frac{VA_{3\Phi base}}{\sqrt{3}V_{LLbase}}$

Base Impedance $\qquad Z_{base} = \frac{V_{base}^2}{VA_{base}} = \frac{(\sqrt{3})^2 V_{base}^2}{3VA_{base}} = \frac{V_{LLbase}^2}{VA_{3\Phi base}}$

and in terms of $MVA_{3\varphi base}$ and kV_{LLbase}

Base current $$I_{base} = \frac{MVA_{3\Phi base}}{\sqrt{3} kV_{LLbase}} \quad \text{in kA}$$

Base Impedance $$Z_{base} = \frac{kV^2_{LLbase}}{MVA_{3\Phi base}} \quad \text{in } \Omega$$

It is to be noted that while the base impedance for the three phase can be obtained directly from the $VA_{3\varphi base}$ and V_{LLbase} (or $MVA_{3\varphi base}$ and kV_{LLbase}) without the need of any additional factors, the calculation of base current needs an additional factor of √3. However this is not usually a problem as the value of current is rarely required as a final answer in power systems calculations, and intermediate calculations can be done with a variable $\sqrt{3}\, I_{base}$.

Thus in three phase, the calculations of per unit quantities becomes

$$S_{pu} = \frac{S_{actual}(MVA)}{MVA_{3\Phi base}},$$

$$V_{pu} = \frac{V_{actual}(kV)}{kV_{LLbase}},$$

$$I_{pu} = I_{actual}(kA) \times \frac{\sqrt{3} kV_{LLbase}}{MVA_{3\Phi base}}$$

and $$Z_{pu} = Z_{actual}(\Omega) \times \frac{MVA_{3\Phi base}}{kV^2_{LLbase}}$$

P and Q have the same base as S, so that

$$P_{pu} = \frac{P_{actual}(MW)}{MVA_{3\Phi base}} \ ,$$

$$Q_{pu} = \frac{Q_{actual}(M\,var)}{MVA_{3\Phi base}}$$

Similarly, R and X have the same base as Z, so that

$$R_{pu} = R_{actual}(\Omega) \times \frac{MVA_{3\Phi base}}{kV^2_{LLbase}} \ ,$$

$$X_{pu} = X_{actual}(\Omega) \times \frac{MVA_{3\Phi base}}{kV_{LLbase}^2}$$

The power factor remains unchanged in per unit.

1.5 Conversions from one Base to another

It is usual to give data in per unit to its own rating [ex: The manufacturer of a certain piece of equipment, such as a transformer, would not know the exact rating of the power system in which the equipment is to be used. However, he would know the rating of his equipment]. As different components can have different ratings, and different from the system rating, it is necessary to convert all quantities to a common base to do arithmetic or algebraic operations. Additions, subtractions, multiplications and divisions will give meaningful results only if they are to the same base. This can be done for three phase systems as follows.

$$S_{puNew} = S_{puGiven} \times \frac{MVA_{3\Phi basegiven}}{MVA_{3\Phi baseNew}}, \quad V_{puNew} = V_{puGiven} \times \frac{kV_{LLbasegiven}}{kV_{LLbaseNew}}$$

$$\text{and} \quad Z_{pu} = Z_{puGiven} \times \frac{MVA_{3\Phi baseNew}}{MVA_{3\Phi baseGiven}} \times \frac{kV_{LLbaseGiven}^2}{kV_{LLbaseNew}^2}$$

1.6 Per Unit Quantities across Transformers

When a transformer is present in a power system, although the power rating on either side of a transformer remains the same, the voltage rating changes, and so does the base voltage across a transformer. [This is like saying that full or 100% (or 1 pu) voltage on the primary of a 220kV/33 kV transformer corresponds to 220 kV while on the secondary it corresponds to 33 kV.] Since the power rating remains unchanged, the impedance and current ratings also change accordingly.

While a common $MVA_{3\varphi base}$ can and must be selected for a power system to do analysis, a common V_{LLbase} must be chosen corresponding to a particular location (or side of transformer) and changes in proportion to the nominal voltage ratio whenever a transformer is encountered. Thus the current base changes inversely as the ratio. Hence the impedance base changes as the square of the ratio. For a transformer with turns ratio $N_P:N_S$, base quantities change as follows.

Quantity	Primary Base	Secondary Base
Power (S, P and Q)	S_{base}	S_{base}
Voltage (V)	V_{1base}	$V_{1base} . N_S/N_P = V_{2base}$
Current (I)	$S_{base}/\sqrt{3}V_{1base}$	$S_{base}/\sqrt{3}V_{1base} . N_P/N_S = S_{base}/\sqrt{3}V_{2base}$
Impedance (Z, R and X)	V_{1base}^2/S_{base}	$V_{1base}^2/S_{base} . (N_S/N_P)^2 = V_{2base}^2/S_{base}$

1.7 Symmetrical Three Phase Fault Analysis

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

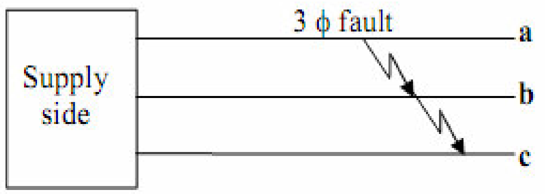


Figure 3a : Balanced 3-Ø fault

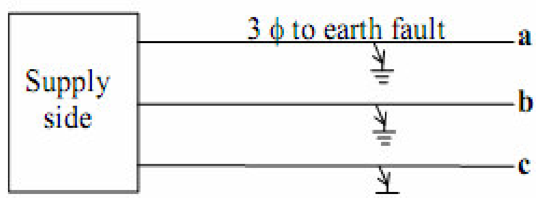


Figure 3b : Balanced 3-Ø fault to earth fault

This is in general a balanced condition, and we need to only know the positive-sequence network to analyze faults. Further, the single line diagram can be used, as all three phases carry equal currents displaced by 120^o.
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.

1.8 Fault Level Calculations

In a power system, the maximum the fault current (or fault MVA) that can flow into a zero impedance fault is necessary to be known for switch gear solution. This can either be the balanced three phase value or the value at an asymmetrical condition. The Fault Level defines the value for the symmetrical condition. The fault level is usually expressed in MVA (or corresponding per-unit value), with the maximum fault current value being converted using the nominal voltage rating.

$$MVA_{base} = \sqrt{3} \times \text{Nominal Voltage(kV)} \, . \, I_{base}\,(kA)$$

$$MVA_{fault} = \sqrt{3} \times \text{Nominal Voltage(kV)} \, . \, I_{sc}\,(kA)$$

Where,

MVA_{Fault} – Fault Level at a given point in MVA

I_{base} – Rated or base line current

I_{sc} – Short circuit line current flowing in to a fault

The per unit value of the Fault Level may thus be written as

$$\text{Fault Level} = \frac{\sqrt{3}.\text{Nominal Voltage}.I_{sc}}{\sqrt{3}\,.\,\text{Nominal Voltage}\,.\,I_{base}}$$

$$= \frac{\sqrt{3}I_{sc}}{\sqrt{3}I_{base}} = I_{sc,pu} = \frac{V_{Nominal,pu}}{Z_{pu}}$$

The per unit voltage for nominal value is unity, so that

$$\text{Fault Level (pu)} = \frac{1}{Z_{pu}},$$

$$\text{Fault MVA} = \text{Fault Level (pu)} * MVA_{base} = \frac{MVA_{base}}{Z_{pu}}$$

The Short circuit capacity (SCC) of a busbar is the fault level of the busbar. The strength of a busbar (or the ability to maintain its voltage) is directly proportional to its SCC. An infinitely strong bus (or Infinite bus bar) has an infinite SCC, with a zero equivalent impedance and will maintain its voltage under all conditions.

Magnitude of short circuit current is time dependant due to synchronous generators. It is initially at its largest value and decreasing to steady value. These higher fault levels tax Circuit Breakers adversely so that current limiting reactors are sometimes used. The Short circuit MVA is a better indicator of the stress on CBs than the short circuit current as CB has to withstand recovery voltage across breaker following arc interruption. The currents flowing during a fault is determined by the internal emfs of machines in the network, by the impedances of the machines, and by the impedances between the machines and the fault. Figure 4 shows a part of a power system, where the rest of the system at two points of coupling have been represented by their Thevenin's equivalent circuit (or by a voltage source of 1 pu together its fault level which corresponds to the per unit value of the effective Thevenin's impedance).

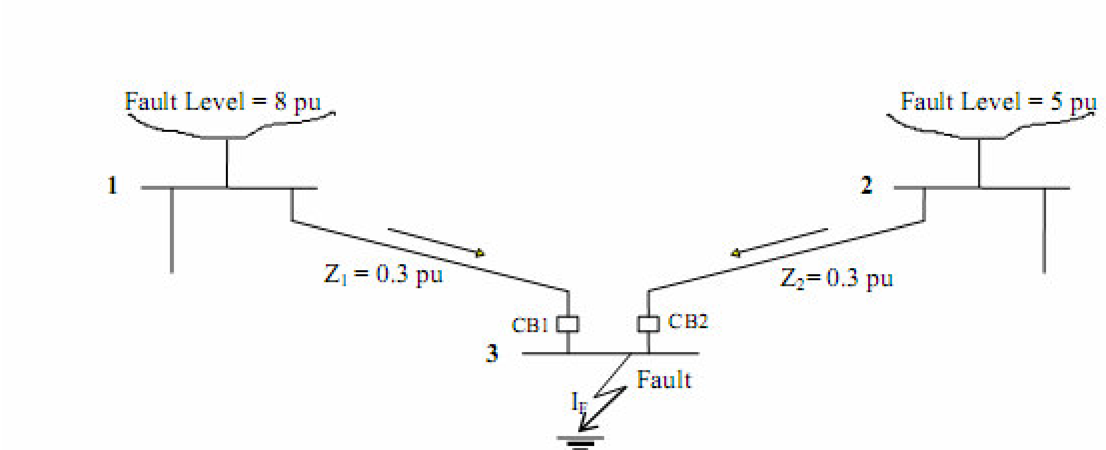


Figure 4: Circuit for Fault Level Calculation

With CB1 and CB2 open, short circuit capacities are

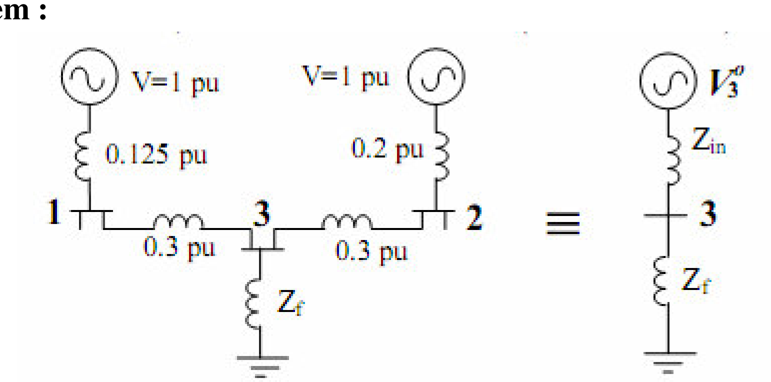
SCC at bus 1 = 8 p.u. gives $Z_{g1} = 1/8 = 0.125$ pu

SCC at bus 2 = 5 p.u. gives $Z_{g2} = 1/5 = 0.20$ pu

Each of the lines are given to have a per unit impedance of 0.3 pu.

$Z_1 = Z_2 = 0.3$ p.u.

With CB1 and CB2 closed, the SCCs (or Fault Levels) of the busbars in the system :



System Equivalent Circuit Thevenin's Equivalent at 3

Figure 5 : Determination of Short circuit capacities

This circuit can be reduced and analysed as in figure 6.

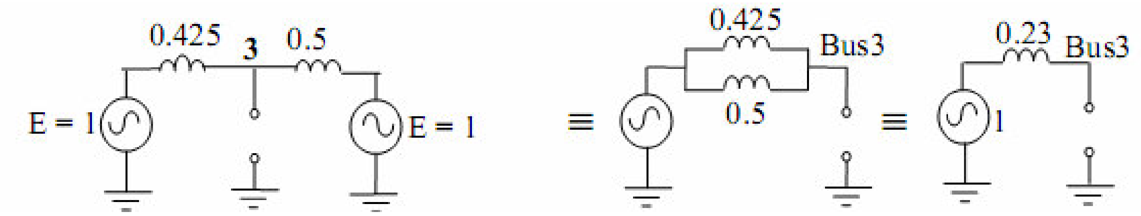


Figure 6: Determination of Short circuit capacity at Bus 3

Thus, the equivalent input impedance is given by to give Z_{in} as 0.23 pu at bus 3, So that the short circuit capacity at busbar 3 is given as

$$|SCC3| = 1/0.23 = 4.35 \text{ p.u}$$

The network may also be reduced keeping the identity of Bus 1 as in figure 7.

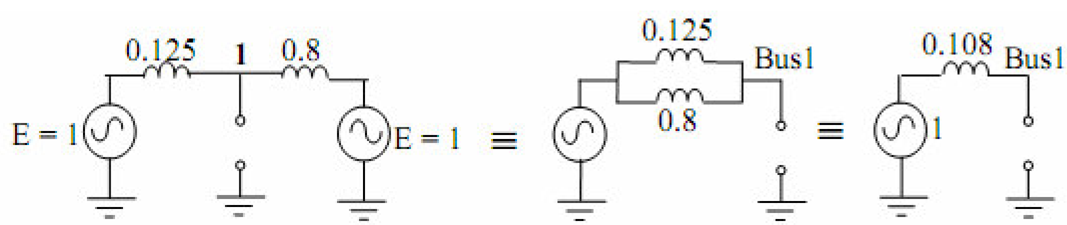


Figure 7: Determination of Short circuit capacity at Bus 1

Thus, the equivalent input impedance is given by to give Z_{in} as 0.108 pu at bus 1, so that the short circuit capacity at busbar 1 is given as

$$|SCC1| = 1/0.108 = 9.25 \text{ p.u}$$

This is a 16% increase on the short circuit capacity of bus 1 with the circuit breakers open. The network may also be reduced keeping the identity of Bus 2. This would yield a value of Z_{in} as 0.157 pu, giving the short circuit capacity at busbar 2 as

$$|SCC2| = 1/0.157 = 6.37 \text{ p.u}$$

This is a 28% increase on the short circuit capacity of bus 2 with the circuit breakers open.

1.9 Fault Currents in synchronous machines

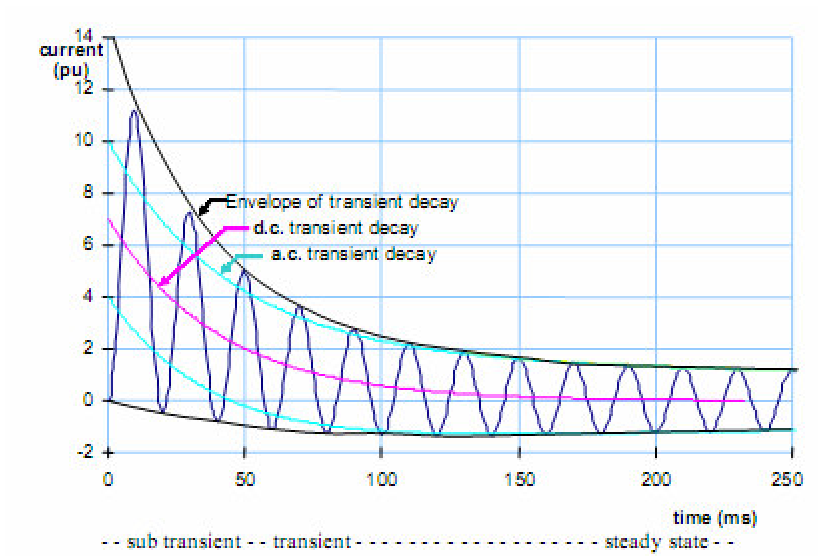


Figure 8 – Transient decay of current in synchronous generator

As mentioned earlier, the currents flowing in the power system network during a fault is dependant on the machines connected to the system. Due to the effect of armature current on the flux that generates the voltage, the currents flowing in a synchronous machine differs immediately after the occurrence of the fault, a few cycles later, and under sustained or steady-state conditions. Further there is an exponentially decaying d.c. component caused by the instantaneous value at the instant of fault occurring. These are shown in figure 9.

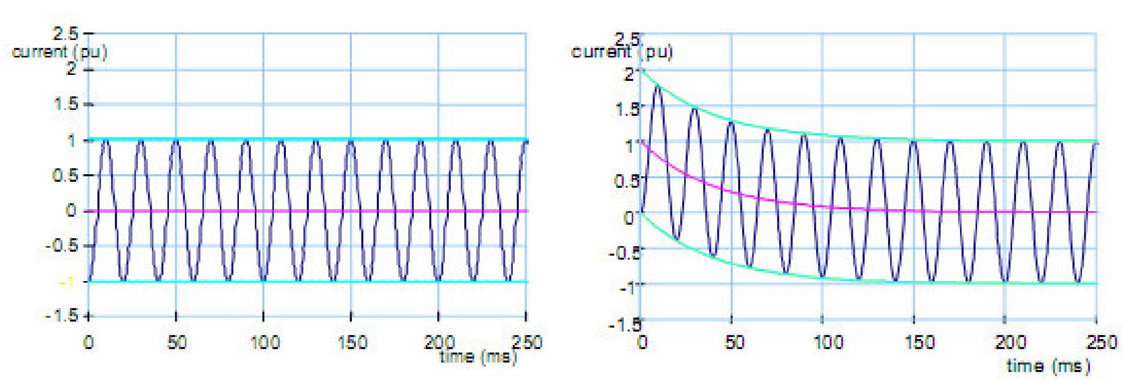
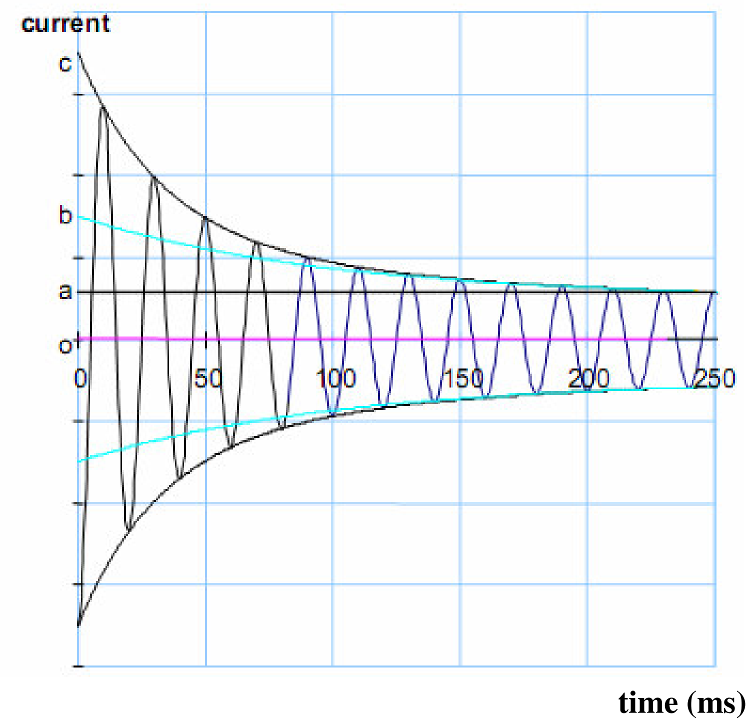


Figure 9a & b – Steady state and Transient current

Figure 9a and 9b show the steady state current waveform, and the transient waveform of a simple R-L circuit, to show the decay in the d.c. component. In addition to this, in the synchronous machine, the magnitude of the a.c. current peak also changes with time as shown in figure 9c, with the unidirection component of the transient waveform removed.



oa - peak value of steady state short-circuit current

ob - peak value of transient short-circuit current

oc - peak value of sub-transient short-circuit current

Figure 9c–Synchronous machine transient

Due to the initial low back emf at the instant of fault resulting in high current, the effective impedance is very low. Even when the d.c. transient component is not present, the initial current can be several times the steady state value. Thus three regions are identified for determining the reactance. These are the sub-transient reactance x_d" for the first 10 to 20 ms of fault, the transient reactance x_d' for up to about 500 ms, and the steady state reactance x_d (synchronous reactance). The sub-transient must usually be used in fault analysis.

The r.m.s. values of current are given by

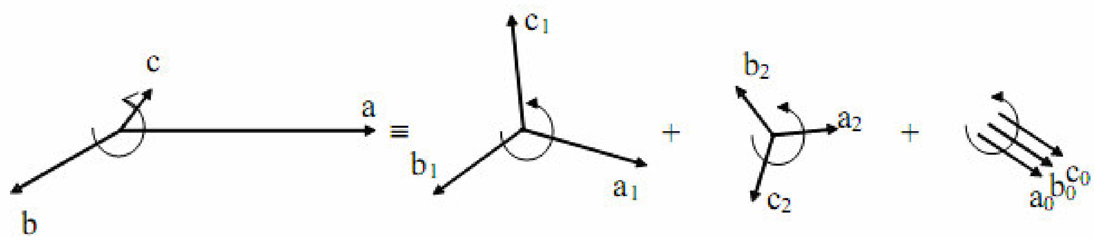
$$|I| = \frac{oa}{\sqrt{2}} = \frac{|E|}{X_d}$$

$$|I'| = \frac{ob}{\sqrt{2}} = \frac{|E|}{X'_d}$$

$$|I''| = \frac{oc}{\sqrt{2}} = \frac{|E|}{X''_d}$$

1.10 Revision of Symmetrical Component Analysis

Unbalanced three phase systems can be split into three balanced components, namely Positive Sequence (balanced and having the same phase sequence as the unbalanced supply), Negative Sequence (balanced and having the opposite phase sequence to the unbalanced supply) and Zero Sequence (balanced but having the same phase and hence no phase sequence). These are known as the Symmetrical Components or the Sequence Components and are shown in figure 10.



Unbalanced system	Positive Sequence	Negative Sequence	Zero Sequence
3 unknown magnitudes	1 unknown magnitude	1 unknown magnitude	1 unknown magnitude
3 unknown angles	1 unknown angle	1 unknown angle	1 unknown angle

Figure 1 Symmetrical Components of unbalanced 3 phase

The phase components are the addition of the symmetrical components and can be written as follows. $a = a_1 + a_2 + a_0$

$$b = b_1 + b_2 + b_0$$

$$c = c_1 + c_2 + c_0$$

The unknown unbalanced system has three unknown magnitudes and three unknown angles with respect to the reference direction. Similarly, the combination of the 3 sequence components will also have three unknown magnitudes and three unknown angles with respect to the reference direction.
Thus the original unbalanced system effectively has 3 complex unknown quantities a, b and c (magnitude and phase angle of each is independent), and that each of the balanced components have only one independent complex unknown each, as the others can be written by symmetry. Thus the three sets of symmetrical components also have effectively 3 complex unknown quantities. These are usually selected as the components of the first phase a (i.e. a_0, a_1 and a_2) . One of the other phases could have been selected as well, but all 3 components should be selected for the same phase.

Thus it should be possible to convert from either sequence components to phase components or vice versa.

1.11 Definition of the operator α

When the balanced components are considered, we see that the most frequently occurring angle is 120^o.
In complex number theory, we defined j as the complex operator which is equal to √-1 and a magnitude of unity, and more importantly, when operated on any complex number rotates it anti-clockwise by an angle of 90^o.

i.e. $j = \sqrt{-1} = 1 \angle 90^o$

In like manner, we define a new complex operator α which has a magnitude of unity and when operated on any complex number rotates it anti-clockwise by an angle of 120^o .

i.e. $\alpha = 1 \angle 120^0 = - 0.500 + j\, 0.866$

Some Properties of α

$$\alpha = 1\angle 2\pi/3 \text{ or } 1\angle 120^o$$

$$\alpha^2 = 1\angle 4\pi/3 \text{ or } 1\angle 240^o \text{ or } 1\angle -120^o$$

$$\alpha^3 = 1\angle 2\pi \text{ or } 1\angle 360^0 \text{ or } 1$$

i.e. $\alpha^3 - 1 = (\alpha - 1) (\alpha 2 + \alpha + 1) = 0$

Since α is complex, it cannot be equal to 1, so that α - 1 cannot be zero.

$$\alpha^2 + \alpha + 1 = 0$$

This also has the physical meaning that the three sides of an equilateral triangles must close as in figure 11.

Also $\alpha^{-1} = \alpha^2$ and $\alpha - 2 = \alpha$

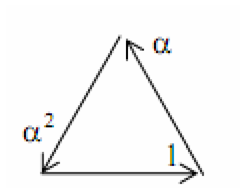


Figure11 Phasor Addition

1.12 Analysis of decomposition of phasors

Let us again examine the sequence components of the unbalanced quantity, with each of the components written in terms of phase a components, and the operator α, as in figure 2.12.

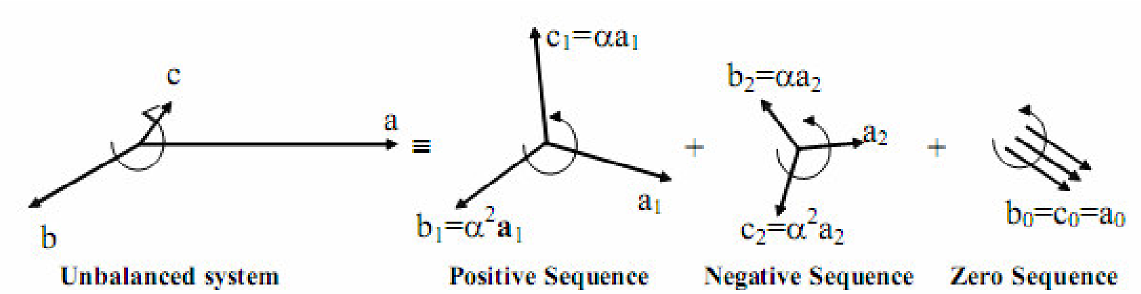


Figure 12 – Expressing components in terms of phase **a**

We can express all the sequence components in terms of the quantities for A phase using the properties of rotation of 0^o, 120^o or 240^o.
Thus

$$a = a_0 + a_1 + a_2$$
$$b = a_0 + \alpha 2\, a_1 + \alpha\, a_2$$
$$c = a_0 + \alpha\, a_1 + \alpha 2\, a_2$$

This can be written in matrix form.

$$\begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \end{bmatrix}$$
$$\underline{Ph} \qquad [\Lambda] \qquad \underline{Sy}$$

This gives the basic symmetrical component matrix equation, which shows the relationship between the phase component vector Ph and the symmetrical component vector Sy using the symmetrical component matrix [A]. Both the phase component vector Ph and the symmetrical component vector Sy can be either voltages or currents, but in a particular equation, they must of course all be of the same type. Since the matrix is a [3×3] matrix, it is possible to invert it and express Sy in terms of Ph.

1.13 Decomposition of phasors into symmetrical components

Now let us invert the symmetrical component matrix [A].

$$[\Lambda]^{-1} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix}^{-1} = \frac{1}{\Delta}\begin{bmatrix} \alpha^4-\alpha^2 & -(\alpha^2-\alpha) & \alpha-\alpha^2 \\ -(\alpha^2-\alpha) & \alpha^2-1 & 1-\alpha \\ \alpha-\alpha^2 & 1-\alpha & \alpha^2-1 \end{bmatrix}$$

$$= \frac{1}{\Delta}\begin{bmatrix} \alpha-\alpha^2 & \alpha-\alpha^2 & \alpha-\alpha^2 \\ \alpha-\alpha^2 & \alpha^2-1 & 1-\alpha \\ \alpha-\alpha^2 & 1-\alpha & \alpha^2-1 \end{bmatrix} = \frac{1}{\Delta}\begin{bmatrix} \alpha(1-\alpha) & \alpha(1-\alpha) & \alpha(1-\alpha) \\ \alpha(1-\alpha) & -(1-\alpha)(\alpha+1) & 1-\alpha \\ \alpha(1-\alpha) & 1-\alpha & -(1-\alpha)(\alpha+1) \end{bmatrix}$$

and the discriminent $\Delta = 3(\alpha - \alpha^2) = 3\alpha\,(1-\alpha)$

Substituting, the matrix equation simplifies to give

$$[\Lambda]^{-1} = \frac{1}{3\alpha}\begin{bmatrix} \alpha & \alpha & \alpha \\ \alpha & -(\alpha+1) & 1 \\ \alpha & 1 & -(\alpha+1) \end{bmatrix}$$

Since $\alpha^{-1} = \alpha^2$, $\alpha^{-2} = \alpha$ and $1 + \alpha + \alpha^2 = 0$, the matrix equation further simplifies to

$$[\Lambda]^{-1} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix}$$

It is seen that α is the complex conjugate of α^2, and α^2 is the complex conjugate of α.

Thus the above matrix $[\Delta]^{-1}$ is one-third of the complex conjugate of [Δ].

i.e. $[A]^{-1} = \frac{1}{3}\,[A]^*$

This can now be written in the expanded form as

$$\begin{bmatrix} A_0 \\ A_1 \\ A_2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix}\begin{bmatrix} A \\ B \\ C \end{bmatrix}$$

$$\underline{Sy} \qquad [\Lambda] \qquad \underline{Ph}$$

1.14 Sequence Impedances

Consider how the impedance appears in sequence components.
To do this we must first look at the impedance matrix in phase components.

$$Vp = [Zp].Ip$$

Substituting for Vp and Ip in terms of the symmetrical components we have

$$[A]\ Vs = [Zp].\ [A]\ Is$$

pre-multiplying equation by $[A]^{-1}$ we have

$$Vs = [A]^{-1}.[Zp].\ [A]\ Is$$

This gives the relationship between the symmetrical component voltage Vs and the symmetrical component current Is, and hence defines the symmetrical component impedance matrix or Sequence Impedance matrix.

Thus $\quad [Zs] = [A]^{-1}.[Zp].\ [A] = \frac{1}{3}\ [A]^{*}.[Zp].\ [A]$

In a similar manner, we could express the phase component impedance matrix in terms of the symmetrical component impedance matrix as follows.

$$[Zp] = [A].[Zs].\ [A]^{-1} = \frac{1}{3}\ [A].[Zs].\ [A]^{*}$$

The form of the sequence impedance matrix for practical problems gives one of the main reasons for use of symmetrical components in practical power system analysis. If we consider the simple arrangement of a 3 phase transmission line (figure 13), we would have the equivalent circuit as

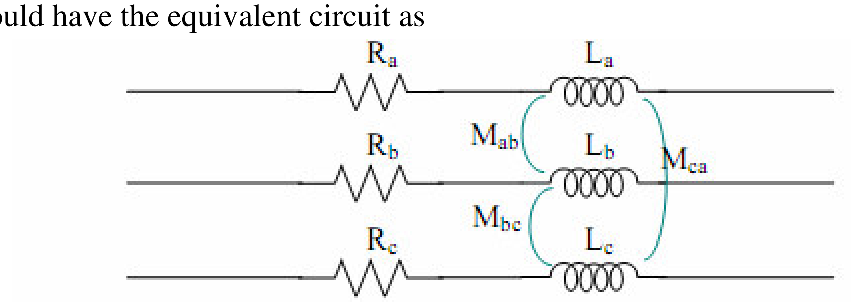


Figure 13 – 3 phase transmission line

If we think of an actual line such as from Victoria to Kotmale, we would realise that all 3 phase wires would have approximately the same length (other than due to differences in sagging) and hence we can assume the self impedance components to be equal for each phase.

i.e. $R_a = R_b = Rc$ and $L_a = L_b = L_c$

When a current passes in one phase conductor, there would be induced voltages in the other two phase conductors. In practice all three phase conductors behave similarly, so that we could consider the mutual coupling between phases also to be equal.

i.e. $M_{ab} = M_{bc} = M_{ca}$

In such a practical situation as above, the phase component impedance matrix would be fully symmetrical, and we could express them using a self impedance term z_s and a mutual impedance term z_m.

Thus we may write the phase component impedance matrix as

$$[Z_p] = \begin{bmatrix} z_s & z_m & z_m \\ z_m & z_s & z_m \\ z_m & z_m & z_s \end{bmatrix}$$

We may now write the symmetrical component impedance matrix as

$$[Z_s] = \tfrac{1}{3}[\Lambda]^*.[Z_p].[\Lambda] = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix}\begin{bmatrix} z_s & z_m & z_m \\ z_m & z_s & z_m \\ z_m & z_m & z_s \end{bmatrix}\begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix}$$

$$= \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix}\begin{bmatrix} z_s + 2z_m & z_s + (\alpha+\alpha^2)z_m & z_s + (\alpha+\alpha^2)z_m \\ z_s + 2z_m & \alpha^2 z_s + (1+\alpha)z_m & \alpha z_s + (1+\alpha^2)z_m \\ z_s + 2z_m & \alpha z_s + (1+\alpha^2)z_m & \alpha^2 z_s + (1+\alpha)z_m \end{bmatrix}$$

This can be simplified using the property $1+\alpha+\alpha^2 = 0$ as follows

$$[Z_s]=\frac{1}{3}\begin{bmatrix}1 & 1 & 1\\ 1 & \alpha & \alpha^2\\ 1 & \alpha^2 & \alpha\end{bmatrix}\begin{bmatrix}z_s+2z_m & z_s-z_m & z_s-z_m\\ z_s+2z_m & \alpha^2(z_s-z_m) & \alpha(z_s-z_m)\\ z_s+2z_m & \alpha(z_s-z_m) & \alpha^2(z_s-z_m)\end{bmatrix}$$

$$=\frac{1}{3}\begin{bmatrix}3(z_s+2z_m) & 0 & 0\\ 0 & (1+\alpha^3+\alpha^3)(z_s-z_m) & 0\\ 0 & 0 & (1+\alpha^3+\alpha^3)(z_s-z_m)\end{bmatrix}$$

i.e. $$[Z_s]=\begin{bmatrix}(z_s+2z_m) & 0 & 0\\ 0 & (z_s-z_m) & 0\\ 0 & 0 & (z_s-z_m)\end{bmatrix} = \begin{bmatrix}Z_0 & 0 & 0\\ 0 & Z_1 & 0\\ 0 & 0 & Z_2\end{bmatrix}$$

We see an important result here. While the phase component impedance matrix was a full matrix, although it had completely symmetry, the sequence component impedance matrix is diagonal. The advantage of a diagonal matrix is that it allows decoupling for ease of analysis.

1.15 Power associated with Sequence Components

With phase components, power in a single phase is expressed as

$$P_{phase} = V\ I \cos\varphi$$

Thus in three phase, we may either write $P = \sqrt{3}\ V_L\ I_L \cos\varphi = 3\ V_p\ I_p \cos\varphi$ for a balanced three phase system. However, with an unbalanced system this is not possible and we would have to write the power as the addition of the powers in the three phases.

Thus Apparent Complex Power $S = V_a I_a^* + Vb\ Ib^* + Vc\ Ic^*$

The active power P is obtained as the Real part of the complex variable S.

This equation may be re-written in matrix form as follows.

$$S = \begin{bmatrix}V_a & V_b & V_c\end{bmatrix}\begin{bmatrix}I_a^*\\ I_b^*\\ I_c^*\end{bmatrix} = \underline{V}_p^T.\underline{I}_p^*$$

Let us now convert it to symmetrical components, as follows.

$$S = \underline{V}_p^T.\underline{I}_p^* = [[\Lambda]\underline{V}_s]^T.[[\Lambda]\underline{I}_s]^*$$

which may be expanded as follows.

$$S = \underline{V}_s^T[\Lambda]^T.[\Lambda]^*.\underline{I}_s^* = \underline{V}_s^T[\Lambda].3[\Lambda]^{-1}.\underline{I}_s^* = 3\,V_s^T.\,I_s^*$$

i.e. $S = 3\,(V_{a0}\,I_{a0}^* + V_{a1}\,I_{a1}^* + V_{a2}\,I_{a2}^*)$

This result can also be expected, as there are 3 phases in each of the sequence components taking the same power.

Thus $P = 3\,(V_{ao}\,I_{ao}\cos\varphi_o + V_{a1}\,I_{a1}\cos\varphi_1 + V_{a2}\,I_{a2}\cos\varphi_2)$

1.16.1 Assumptions Commonly Made in Three Phase Fault Studies

The following assumptions are usually made in fault analysis in three phase transmission lines.

- All sources are balanced and equal in magnitude & phase
- Sources represented by the Thevenin's voltage prior to fault at the fault point
- Large systems may be represented by an infinite bus-bars
- Transformers are on nominal tap position
- Resistances are negligible compared to reactances
- Transmission lines are assumed fully transposed and all 3 phases have same Z
- Loads currents are negligible compared to fault currents
- Line charging currents can be completely neglected

1.16.2 Basic Voltage – Current Network equations in Sequence Components

The generated voltages in the transmission system are assumed balanced prior to the fault, so that they consist only of the positive sequence component Vf (pre-fault voltage). This is in fact the Thevenin's equivalent at the point of the fault prior to the occurrence of the fault.

$$V_{a0} = 0 - Z_0 I_{a0}$$

$$V_{a1} = E_f - Z_1 I_{a1}$$

$$V_{a2} = 0 - Z_2 I_{a2}$$

This may be written in matrix form as

$$\begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix} = \begin{bmatrix} 0 \\ E_f \\ 0 \end{bmatrix} - \begin{bmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix} \begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix}$$

These may be expressed in Network form as shown in figure 14.

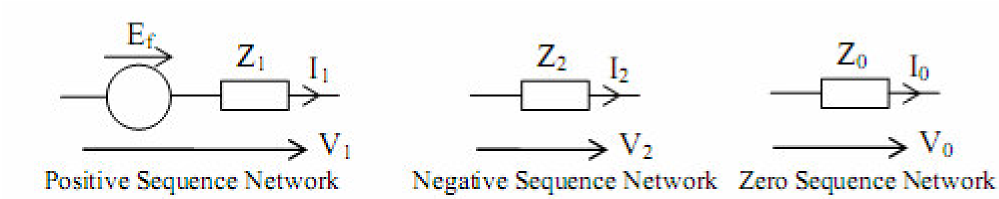


Figure 14 – Elementary Sequence Networks

1.18 Analysis of Asymmetrical Faults

The common types of asymmetrical faults occurring in a Power System are single line to ground faults and line to line faults, with and without fault impedance. These will be analysed in the following sections.

1.19 Single Line to Ground faults (L – G faults)

The single line to ground fault can occur in any of the three phases. However, it is sufficient to analyse only one of the cases. Looking at the symmetry of the symmetrical component matrix, it is seen that the simplest to analyse would be the phase a.

Consider an L-G fault with zero fault impedance as shown in figure 15.

Since the fault impedance is 0, at the fault
Va = 0, Ib = 0, Ic = 0
since load currents are neglected. These can be converted to equivalent conditions in symmetrical components as follows.

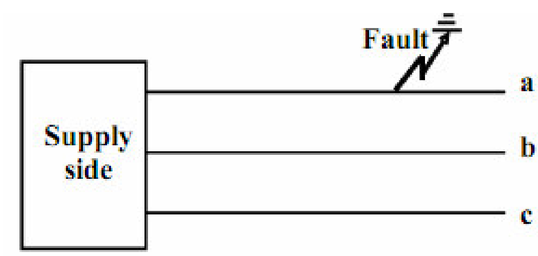


Figure 15 – L-G fault on phase a

$V_a = V_{a0} + V_{a1} + V_{a2} = 0$

and,

$$\begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix}\begin{bmatrix} I_a \\ I_b = 0 \\ I_c = 0 \end{bmatrix}$$, giving $I_{a0} = I_{a1} = I_{a2} = I_a/3$

Mathematical analysis using the network equation in symmetrical components would yield the desired result for the fault current $I_f = I_a$.

$$\begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix} = \begin{bmatrix} 0 \\ E_f \\ 0 \end{bmatrix} - \begin{bmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix} \begin{bmatrix} I_{a0} = I_a/3 \\ I_{a1} = I_a/3 \\ I_{a2} = I_a/3 \end{bmatrix}$$

Thus $V_{a0} + V_{a1} + V_{a2} = 0 = -Z_0.I_a/3 + E_f - Z_1.I_a/3 - Z_2.I_a/3$

Simplification, with If = Ia, gives

Simplification, with If = Ia, gives

$$I_f = \frac{3E_f}{Z_1 + Z_2 + Z_0}$$

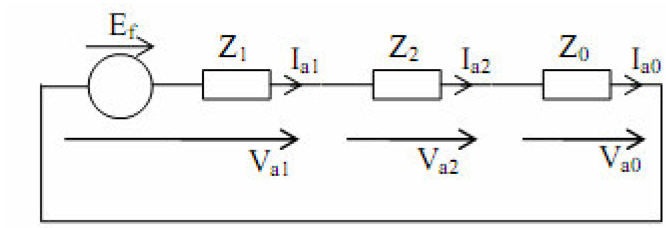


Figure 16 – Connection of Sequence series

Also, considering the equations $V_{a0} + V_{a1} + V_{a2} = 0$, and $I_{a0} = I_{a1} = I_{a2}$ indicates that the three networks (zero, positive and negative) must be connected in (same current, voltages add up) and short-circuited, giving the circuit shown in figure 16.

Networks for L-G fault with Zf = 0

Mathematical analysis may be done by substituting these conditions to the relevant symmetrical component matrix equation. However, the network solution after converting the boundary conditions is more convenient and will be considered here.

$I_a = 0$ and $I_b = -I_c$ when substituted into the matrix equation gives

$$\begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \begin{bmatrix} I_a = 0 \\ I_b \\ I_c = -I_b \end{bmatrix}$$

which on simplification gives $I_{a0} = 0$, and $I_{a1} = -I_{a2}$ or $I_{a1} + I_{a2} = 0$

and $V_b = V_c$ on substitution gives

which on simplification gives $V_{a1} = V_{a2}$. The boundary conditions $I_{a0} = 0$, $I_{a1} + I_{a2} = 0$, and $V_{a1} = V_{a2}$ indicate a solution where the two networks positive and negative are in parallel and the zero sequence on open circuit, as given in figure 17.

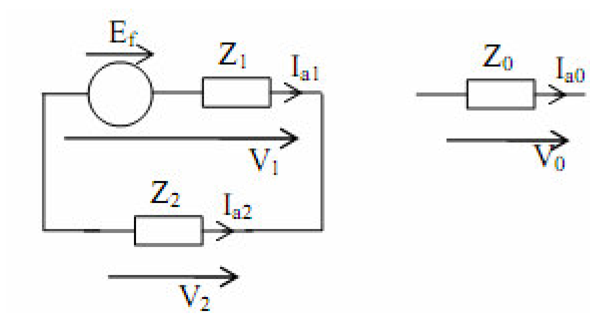


Figure 17 – Connection of Sequence Networks for L-L fault

(b) L-L-G fault with earth and no Z_f

At the fault, $I_a = 0$, $V_b = V_c = 0$
gives $I_{a0} + I_{a1} + I_{a2} = Ia = 0$
and the condition
$V_{a0} = V_{a1} = V_{a2}$ (can be shown)
These conditions taken together,
can be seen to correspond to all three
sequence networks connected in parallel.

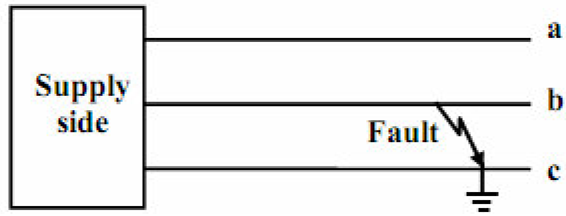


Figure 18 – L-L fault on phases b-c

(c) L-L-G fault with earth and Z_f

If Z_f appears in the earth path, it could be included as $3Z_f$, giving $(Z_0 + 3Z_f)$ in the zero sequence path.

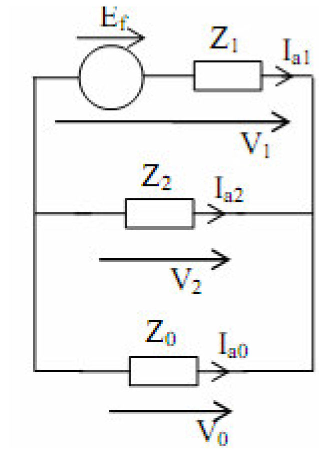


Figure 19 – Connection for L-L-G fault

(d) L-L fault with Z_f and no earth

If Z_f appears in the fault path, between phases b and c, it could be included as ½ Z_f in each of b and c. Inclusion of ½ Z_f in a havin zero current would not affect it, so that in effect, ½ Z_f can be added to each of the three phases and hence to each of the 3 sequence networks as $(Z_1+½\ Z_f)$, $(Z_2+½\ Z_f)$ and $(Z_0+½\ Z_f)$. The normal circuit analysis would have yielded the positive and negative sequence networks in parallel with a connecting impedance of Z_f, which is effectively the same.

1.20 Sequence impedances of network components

The main network components of interest are the transmission lines, transformers, and synchronous machines.

(a) The conductors of a transmission line, being passive and stationary, do not have an inherent direction. Thus they always have the same positive sequence impedance and negative sequence impedance. However, as the zero sequence path also involves the earth wire and or the earth return path, the zero sequence impedance is higher in value.
(b) The transformer too, being passive and stationary, do not have an inherent direction. Thus it always has the same positive sequence impedance, negative sequence impedance and even the zero sequence impedance. However, the zero sequence path across the windings of a transformer depends on the winding connections and even grounding impedance.

(c) The generator (or a synchronous machine), on the other hand, has a inherent direction of rotation, and the sequence considered may either have the same direction (no relative motion) or the opposite direction (relative motion at twice the speed). Thus the rotational emf developed for the positive sequence and the negative sequence would also be different. Thus the generator has different values of positive sequence, negative sequence and zero sequence impedance.

1.21 Single-line diagrams for network components

(a) Generator

The generator may, in general, be represented by the star-connected equivalent with possibly a neutral to earth reactance as shown in figure 20, together with the three phase diagrams for the positive sequence, negative sequence and zero sequence equivalent circuits. The neutral path is not shown in the positive and negative sequence circuits as the neutral current is always zero for these balanced sequences. Also, by design, the generator generates a balanced voltage supply and hence only the positive sequence will be present in the supply.

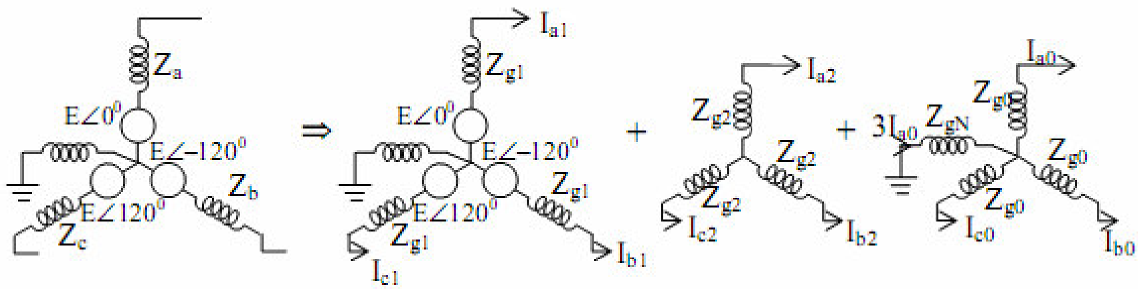


Figure 20 – Sequence component networks of generator

Since the 3 component networks are balanced networks, they may be represented by single-line diagrams in fault calculations.

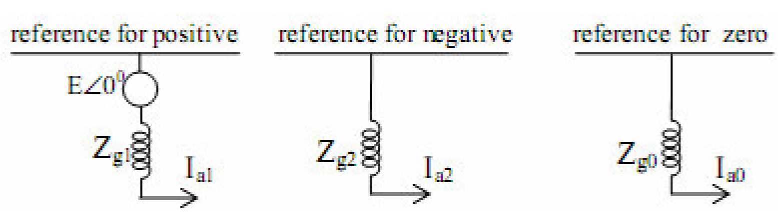


Figure 21 –single-line networks for sequences of generator

(b) Transmission lines and cables

The transmission line (or cable) may be represented by a single reactance in the single-line diagram. Typically, the ratio of the zero sequence impedance to the positive sequence impedance would be of the order of 2 for a single circuit transmission line with earth wire, about 3.5 for a single circuit with no earth wire or for a double circuit line. For a single core cable, the ratio of the zero sequence impedance to the positive sequence impedance would be around 1 to 1.25. Transmission lines are assumed to be symmetrical in all three phases. However, this assumption would not be valid for long un-transposed lines (say beyond 500 km) as the mutual coupling between the phases would be unequal, and symmetrical components then cannot be used.

(c) Single windings

Consider each of the simple types of windings for the zero sequence path. These diagrams are shown, along with the zero sequence single line diagram in figure 22.

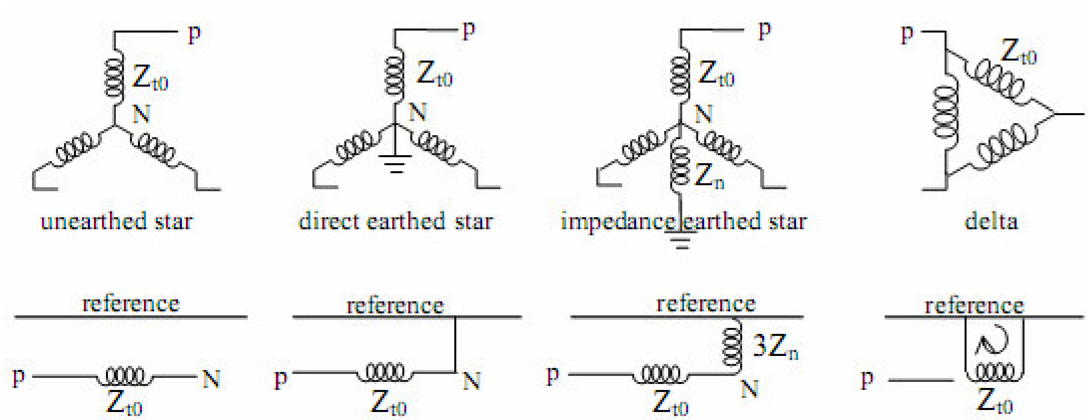


Figure 22 –single-line networks for sequences of generator

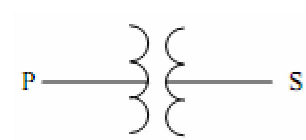
The unearthed star connection does not provide a path for the zero sequence current to pass across, and hence in the single line diagram, there is no connection to the reference. With an earthed star connection, the winding permits a zero sequence current to flow, and hence is shown with a direct connection to the reference. The earthed star with impedance, is similar except that 3 times the neutral impedance appears in the zero sequence path. The delta connection on the other hand does not permit any zero sequence current in the line conductors but permits a circulating current. This effect is shown by a closed path to the reference.

(d) Transformers

The equivalent circuit of the transformer would be a single reactance in the case of positive sequence and negative sequence for a two-winding transformer, but highly dependant on the winding connection for the zero sequence. The transformer would be a combination of single windings. The magnetising impedance is taken as open circuit for fault studies.

Two-winding transformers

Two winding (primary and secondary), three phase transformers may be categorised into (i) star-star, (ii) earthed star – star, (iii) earthed star – earthed star, (iv) delta – star, (v) delta – earthed star, (vi) delta – delta. There are also zig-



zag windings in transformers which has not been dealt with in the following sections The figure 23 shows the zero-sequence diagrams of the transformers are drawn.

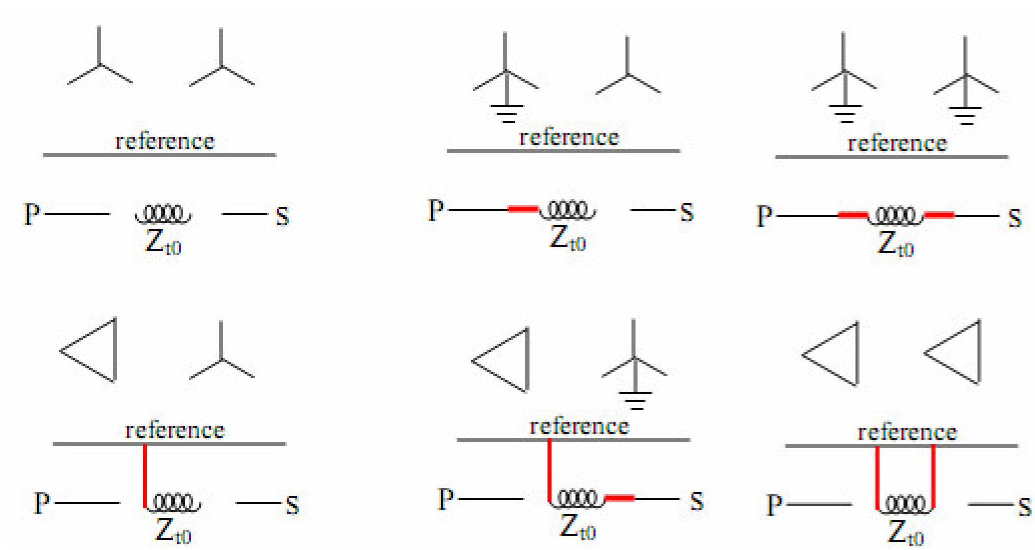
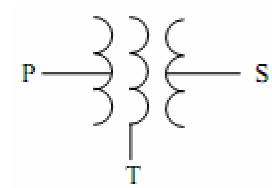


Figure 23 – single-line networks for sequences of two-winding transformers

Considering the transformer as a whole, it can be seen that the single-line diagrams indicate the correct flow of the zero-sequence current from primary to secondary.

Three-winding transformers

Three phase, three winding have an additional tertiary winding, and may be represented by a single line diagram corresponding to the ampere-turn balance, or power balance.



$N_P I_P + N_S I_S + N_T I_T = 0$ or $V_P I_P + V_S I_S + V_T I_T = 0$

which in per unit quantities would yield the common equation $I_{P,pu} + I_{S,pu} + I_{T,pu} = 0$

This may be represented by three reactances

connected in T, giving the general single line diagram for fault studies for the 3 winding transformer, as shown in figure 24.

The positive sequence and negative sequence

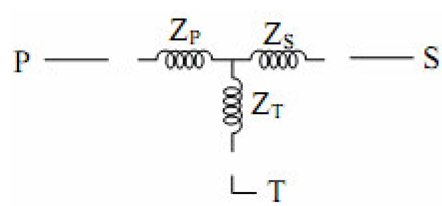


Figure 24 - three-winding transformer

diagrams would have a direct connection to the T connection of reactances from P, S and T.

The zero sequence network would again be built up from the single winding arrangements described and would yield the single line diagrams given in the following section, and other combinations.

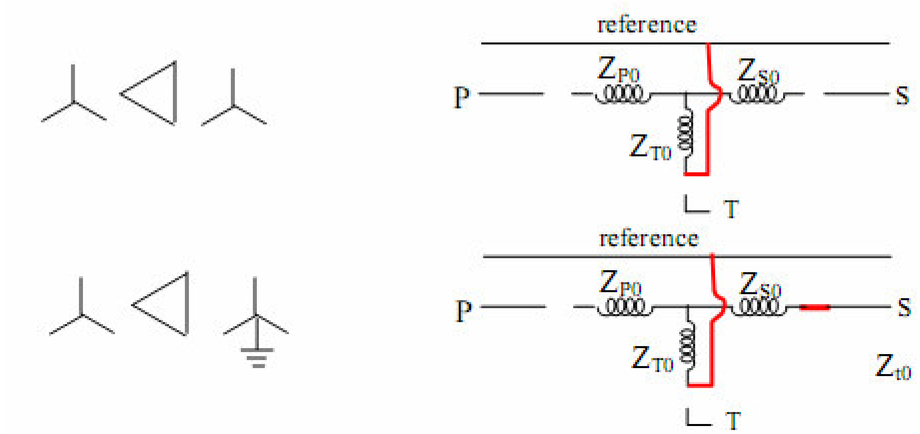


Figure 25a – single-line networks for sequences of three-winding transformers

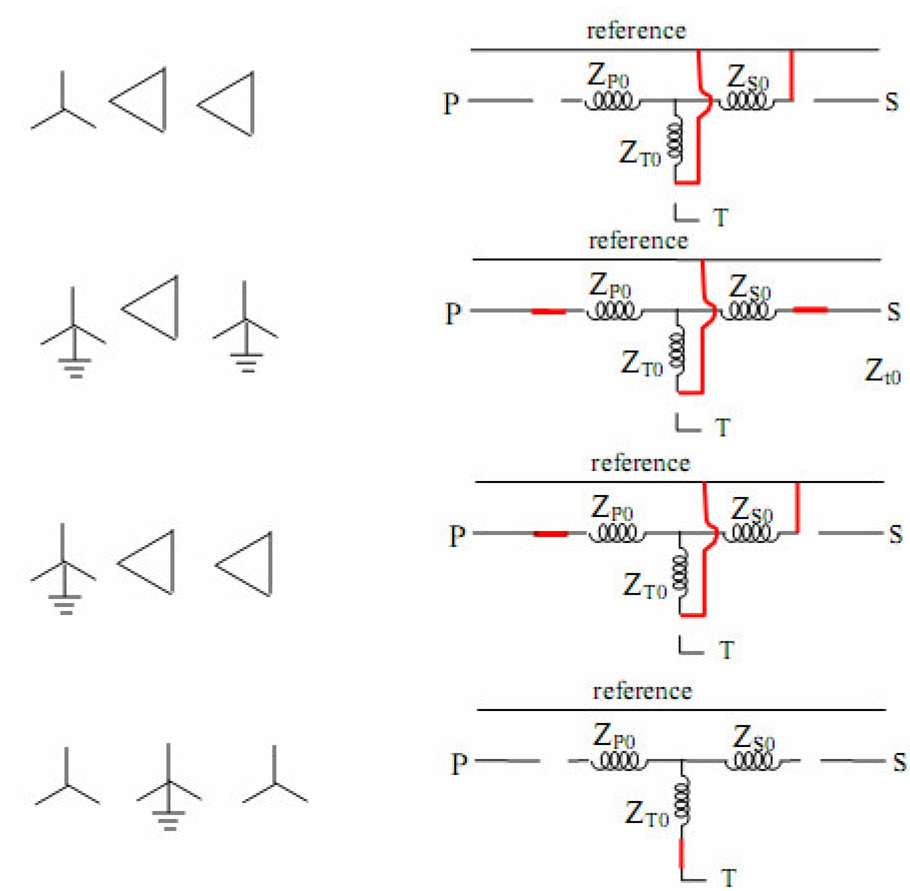


Figure 25b – single-line networks for sequences of three-winding transformers

A particular point to keep in mind is that what is generally available from measurements for a 3 winding transformer would be the impedances across a pairs of windings. (ie. Z_{PS}, Z_{PT}, and Z_{ST}), with the third winding on open circuit. Thus we could relate the values to the effective primary, secondary and tertiary impedances (Z_P, Z_S and Z_T) as follows, with reference to figure 25.

$$Z_{PS} = Z_P + Z_S, \quad Z_{PT} = Z_P + Z_T, \quad Z_{ST} = Z_S + Z_T,$$

The values of Z_P, Z_S and Z_T can then be determined as

$$Z_P = \tfrac{1}{2}(Z_{PS} + Z_{PT} - Z_{ST}), \quad Z_S = \tfrac{1}{2}(Z_{PS} + Z_{ST} - Z_{PT}), \quad Z_T = \tfrac{1}{2}(Z_{PT} + Z_{ST} - Z_{PS})$$

As in the case of the 2 winding transformer, $3Z_n$ is included wherever earthing of a neutral point is done through an impedance Z_n.

In Summary

An unearthed star winding does not permit any zero sequence current to flow so that it could be represented in the single line diagram by a 'break' between the line terminal and the winding. If the star point is solidly earthed, it could be represented by a solid connection across the break and for an earth connection through an impedance, by 3 times the earthing impedance across the break.

In the case of a delta winding, no current would flow from the line, but a current is possible in the winding depending on the secondary winding connections. This could be represented by a break in connection with the line but with the winding impedance being connected to the reference.

2.22 Broken conductor faults

In broken conductor (or open conductor) faults, the load currents cannot be neglected, as these are the only currents that are flowing in the network. The load currents prior to the fault are assumed to be balanced.

2.23 Single conductor open on phase "a"

In the case of open conductor faults, the voltages are measured across the break, such as a-a′. For the single conductor broken on phase "a" condition, shown in figure 26. , the boundary conditions are $I_a = 0$, $V_b = V_c = 0$

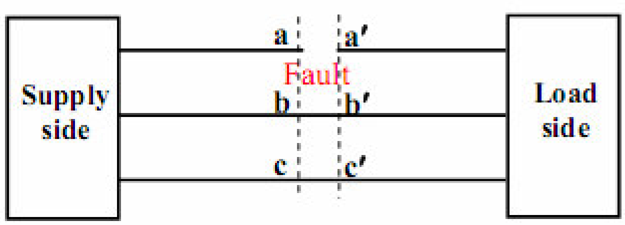


Figure 26 – Open conductor fault on phase a

This condition is mathematically identical to the condition in the L-L-G fault in the earlier section, except that the voltages are measured in a different manner. The connection of sequence networks will also be the same except that the points considered for connection are different.

2.24 Two conductors open on phases "b" and "c"

For the two conductors broken on phases "b" and "c" condition, the boundary conditions are $V_a = 0$, $I_b = I_c = 0$

This condition is mathematically identical to the condition in the L-G fault in the earlier section.

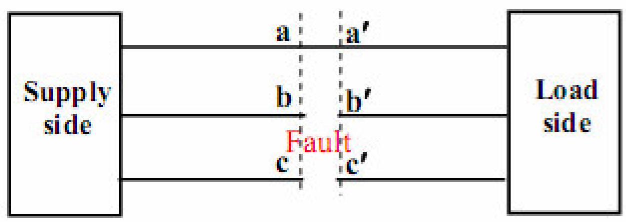


Figure 27 – Open conductor fault on phases b & c

The connection of sequence networks will also be the same except that the points considered for connection are different.

2.25 Simultaneous faults

Sometimes, more than one type of fault may occur simultaneously. These may all be short circuit faults, such as a single-line-to-ground fault on one phase, and a line-to-line fault between the other two phases. They may also be short-circuit faults coupled with open conductor faults.

Solution methods are similar, if the equations are considered, however they may not have an equivalent circuit to ease analysis. Sometimes, the constraints required cannot be directly translated to connections, but may also need ideal transformers to account for the different conditions.

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