SHORT CIRCUIT ANALYSIS AND CIRCUIT BREAKER INTERRUPTING CAPABILITY VALIDATIONS FOR INDUSTRIAL POWER PLANTS

by

VIJAYANAND APPANAICKENPATTI RAMACHANDRAN

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ABSTRACT

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VIJAYANAND APPANAICKNEPATTI RAMACHANDRAN, M.S.

The University of Texas at Arlington, 2011

Supervising Professor: Wei-Jen Lee

The purpose of this study is to determine the short circuit current as well as evaluate the interrupting capability of the circuit breaker with higher accuracy for industrial power plants. Power plant protection and coordination involves prevention of injury to personnel, minimizing damage to the system components, and limiting the extent and duration of service interruption whenever equipment failure, human error, or adverse natural events occur on any portion of the system. The cause for any of these circumstances is very unpredictable, but through sound system design we can reduce the levels of impact.

Power plant protection is one of the most essential features during the planning, design, and operation of power plant as it ensures the safety of the personnel, reliability of electrical supply and has a profound influence on the economics of system. It is therefore essential that system protection is examined in each stage to ensure a proper protection plan that is capable of being coordinated and is flexible enough to grow with the system.

The isolation of short circuits requires the application of protective equipment that will both sense the presence of abnormal current and remove the affected portion of the system.

Fuses, Circuit Breakers and Relays are the main types of protective equipment that sense and remove the affected system during faults. One of the most important tasks of the system designer is to determine the interrupting capability of the protective equipment such that it is compatible with the available ratings of the circuit breaker and fuses.

This study validates circuit breaker interrupting capability for industrial power plants through the short circuit analysis. As the interrupting capability allows determining the exact rating of the protective equipment, the more precise the method to determine these values allows the system design to be safer and efficient. The existing techniques of short circuit analysis would be discussed in detail and the validation procedure will be explained with the help of IEEE13 bus Industrial Distribution system.

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CHAPTER 1

INTRODUCTION

1.1 Industrial Power Plants

Industrial power generation has been a widespread practice since the beginning of the electric era. Early in the 20th century approximately 50 percent of electricity generated in the United States was by industrial power plants. As major changes were occurring in the power generating industry, such as economies of scale in generation, decreased rates, and greatly improved reliability, electricity was inexpensive and demand soared. For these reasons, most industrial plants shifted away from generating their own power and opted to purchase electricity from their local utilities.

As the utility industry matured it resulted in the development of a complex interstate electricity marketplace that allowed utilities to become national in scope. By 1950, the electric utility industry was supplying majority of electricity demand with the exception for a few industries that generated small amounts for their own use. In the 1970's, inflation, oil-price increases, energy crises, environmental concerns, and the rising costs of nuclear power raised electricity rates. As a result industrial plants invested to generate their own power; the independent power production included several advantages:

- Higher energy conversion efficiency resulting in lower energy cost
- Hedge the utility rate increases
- Environmental benefits to increase the reliability and economic considerations.

A non-utility power generating facility seeking to establish an interconnected operation with an electric utility faced few major obstacles:

- Utilities were not willing to purchase power from non-utility producers
- Some utilities charged high rates for back-up services to non-utility power producers

- Once connected to the utility the power plants had the risk of being subject to extensive state and federal regulations.

These factors were addressed in the Public Utility Regulatory Policies Act (PURPA) [8] [9] [18] law passed in the year 1978, to encourage the use of alternative source of energy. PURPA defined a set of criteria and standards for Industrial Power Plants that could be operated interconnected with an electric utility. The utilities required to

- Buy power from qualifying Industrial Power Plants facilities at a rate related to the utility's avoided cost of power generation.
- Provide backup power to the Industrial Power Plants at nondiscriminatory rates.
- Exempt qualifying cogeneration from state and federal regulations which govern public utilities.

The independent power production was made possible as a result of government actions and research done by manufactures which enabled the production of cost effective and highly efficient co-generating plants.

1.2 Design of Industrial Power System

The continuity of production in an industrial process plant is only as reliable as its electric power distribution system. No standard electric distribution system is adaptable to all industrial plants, because two plants rarely have the same requirements. The specific requirements must be analyzed qualitatively for each plant and the system designed to meet its electrical requirements. Equal and adequate considerations must be given to both present and future operating and load conditions.

Power system analysis is one of the basic activities that would be required to be performed during the design of the industrial power system. One of the important aspects in the design is planning the protective equipment for the power system. The short circuit analysis of power distribution system is just as basic and important as other fundamental power system studies such as power flow studies to analyze the power requirements of the plant and plan for back-up system, transient stability analysis to determine the effect of the system during disturbances, harmonic analysis to ensure the quality of the power supply, and etc. The short circuit current allows the design engineer to apply and coordinate protection schemes with proper selections and settings of relays, circuit breakers, fuses, and motor starters.

When planning an electrical system that will be isolated from the utility, the amount of generating capacity is a rather straightforward decision made by the electrical engineer. Generally, sufficient generation is provided to meet the load requirement, both in the normal situation and under various operation conditions such as large motor starting, load peaking, planned or unplanned generator outages. When an industrial plant is tied to a utility from which it purchases a portion of its power needs, with inplant generation supplying the rest, the situation is more complex and the issue of system protection becomes very critical.

1.3 Short Circuit Analysis

Even the best designed electric system occasionally experience short circuits resulting in abnormally high currents. Overcurrent protective devices, such as circuit breakers and fuses, should isolate faults at a given location safely with minimal circuit and equipment damage and minimum disruption of the plant’s operation. Other parts of the system, such as cables, busways, and disconnecting switches, shall be able to withstand the mechanical and thermal stresses resulting from maximum flow of short-circuit current through them. The magnitudes of the short-circuit currents are usually estimated by calculation, and equipment is selected using the calculation results.

The current flow during short circuit is not directly related to the size of the load on the system. However, additions to the system that increases its capacity to handle a growing load, such as large incoming transformers from a utility with smaller impedance, while not affecting the normal load at some existing locations in the system, may drastically increase the short-circuit currents at these locations. Whether an existing system is expanded or a new system is installed, potential short-circuit currents level should be examined for proper application of protective devices. Calculated maximum short circuit currents are nearly always required. In some cases, the minimum sustained values are also needed to check the sensitivity requirements of the current-responsive protective devices.

There are various methods used to calculate the fault currents. The size and complexity of many modern industrial systems may make longhand fault calculations impractically time consuming. Computers are generally used for major fault studies. In this thesis, a method to validate the circuit breaker interrupting capability by calculating the maximum fault current for designing the circuit breaker with greater accuracy is presented. The method is explained with the help of standard IEEE 13 bus industrial distribution system.

CHAPTER 2

INDUSTRIAL POWER SYSTEM

2.1 Overview

The electric design of the industrial plant should satisfy the fundamental objective of providing safe, energy-efficient and attractive environment for manufacturing, research, development and handling of industrial products.. As computer technology has advanced, so has the complexity of industrial and commercial power systems. These power systems have grown in recent decades with capacities far exceeding that of a small electric utility system. Today's intensely competitive business environment forces plant or building management personnel to be very aware of the total owning cost of the power distribution system.

In an industrial environment, electric power is used for a wide number of applications. The following is a brief list of the most common uses for electric power

- Illumination – Whether for providing light for an office environment or a manufacturing shop floor, illumination is one of the most important applications of electric power.
- Environmental systems – Electric heating, ventilation, and air-conditioning are a large application for electric power.
- Industrial processes – Industrial processes account for a large percentage of the global use of electric power. Typical process applications are pumping, chemical process, semiconductor preparation process, furnaces, rolling mills, refrigeration, material handling, water treatment process, and etc.
- Computers and Data Centers – With the advent of large computer network, the need also arisen for reliable power for these.

- Health Care – Reliable power has always been a requirement of the health care industry, but added to this is the need for power quality due to the nature of the equipment used.
- Safety Systems – Systems such as fire alarm and smoke detection systems, security systems, sprinkler systems, and fire pumps are vital to any commercial or industrial facility.
- Communication Systems – Systems such as telephone and intrusion detection and monitoring are critically important.

Because the characteristics of each load, process etc., served are unique, so too will each design be unique to match the requirements imposed.

2.2 Power Plant Design

The industrial power system planning and design must include the following considerations at the initial and planning or design stage.

2.2.1 Safety of Life

The system planning and design shall include the following to ensure the safety of personnel and preservation of plant property:

- Equipment and installation shall conform to relevant codes and standards.
- Provide adequate working space and safe clearances around the electrical equipment, dead-front equipment for low- and medium-voltage systems, insulated bus and connections for metal-enclosed equipment, and adequate system and equipment grounding.
- Design the system to permit maintenance of equipment and circuits in a de-energized state without plant shutdown.
- Provide fully rated and protected equipment to withstand maximum short-circuit and load currents.

- Provide personnel protective equipment (PPE) such as insulated gloves, fire-retardant or fireproof clothing, and warning signs.
- Provide operations and maintenance instructions, such as built-in wiring and interlocking diagrams.
- Install emergency lighting for the safety and safe exit of personnel during power outage.

Electrical equipment minimum quality standards are prescribed in the standards and guides of the Institute of Electrical and Electronics Engineers (IEEE), the National Electrical Manufacturer's Association (NEMA), Underwriters Laboratories (UL), and the International Electrotechnical Commission (IEC). UL maintains a continuing service in testing and certifying the products of electrical manufacturers, principally those to be used for industrial and commercial applications.

2.2.2 Reliability of Utility Power Supply

Utility power systems, including transmission and distribution lines, are subject to disturbances such as lightning strokes and faults that cause voltage sags, it is necessary to proper design a power system to ensure that the quantity, quality, and reliability of the utility power supply meets the plant power requirements to reduce the possibility for tripping the control devices and plant shutdown [21].

2.2.3 Reliability of Plant Distribution System

Plant power distribution system reliability must be considered during the planning and conceptual design stage [21]. The key steps to increase the reliability of the plant power system are:

- Select modern, standard, and reliable equipment. Apply good installation and preventive/predictive maintenance practice.

- Use a minimum of two circuits or feeds, each from a different bus, to major and critical load centers. Do not run both circuits in the same cable tray or duct bank.
- Do not use bare conductor overhead lines within the plant boundary. Run the distribution feeders above ground wherever possible; the failure rate of a directly buried cable is considerably higher.
- System neutral grounding reduces transient overvoltage on single line-to ground faults, thus minimizing insulation failures.
- A coordinated short-circuit and overcurrent protection isolates the faulted circuit, protects the equipment, confines the power outage to the protected zone, makes it easier to locate the fault, and prevents fires.

2.2.4 Simplicity of Operation and Maintenance

The majority of faults in utility distribution networks are caused by environmental reasons, such as a tree branch falling on the bare conductor overhead line, lighting strikes, etc. For this reason, the distribution networks are interconnected to facilitate alternative power supply routes. However, the majority of the faults in industrial systems are caused by insulation failure and sometimes by inadvertent or accidental contacts. The design of an industrial power distribution system shall be simple, utilizing radial feeds. This approach simplifies the interlocking and the maintenance, thus increasing safety.

2.2.5 Voltage Drop and Flicker

The performance of the utilization equipment (motors, lighting, etc.) is guaranteed when the voltage and frequency applied to its terminals is within the limits specified in the standards. Because the variation in power frequency is negligible during steady state conditions, the voltage spread from no load to full load, transient voltage dips during switching operations (such as starting a large motor), and voltage flicker caused by cyclic loads such as reciprocating compressors need to be checked [16].

- Steady-State Voltage Drop: The steady-state voltage drop is caused by the variation in utility power supply and by voltage drop in the transformer and feeders connected to the utilization equipment. The spread from the utility power supply is generally remedied by utilizing main step-down transformers with load tap changers.
- Voltage Flicker: The voltage changes of a transient nature, such as turning loads on and off, which last only a short duration, are generally referred to as voltage flicker. The rapid voltage fluctuations affect the light output from incandescent lamps.
- Voltage Drop Due to Motor Starting: Synchronous and squirrel-cage induction motors started on full voltage may draw four to eight times their rated full-load current. This excessive current may cause higher voltage drop and long acceleration time.
- Voltage Drop/Rise Due to Switching: Switching on or off a large block of load causes voltage change.

2.2.6 Cost

The cost of an electric power system is small compared with the total cost. Safety, reliability, voltage regulation, maintenance, and provision for future expansion shall be given priority.

2.3 Plant Distribution System

A typical process plant distribution system in a single (one)-line diagram form is shown in figure 2.1. This is composed of a main substation, primary distribution, secondary distribution, and in-plant generation [15] [16]. Electric utility companies supply power at high voltages (HV) via transmission lines or sometimes insulated power cable. HV power is stepped down to medium voltage for primary distribution to different plant facilities or load centers. Each industry has implemented some specific and unique features in its plant electrical systems that have evolved with time and are based on experience.

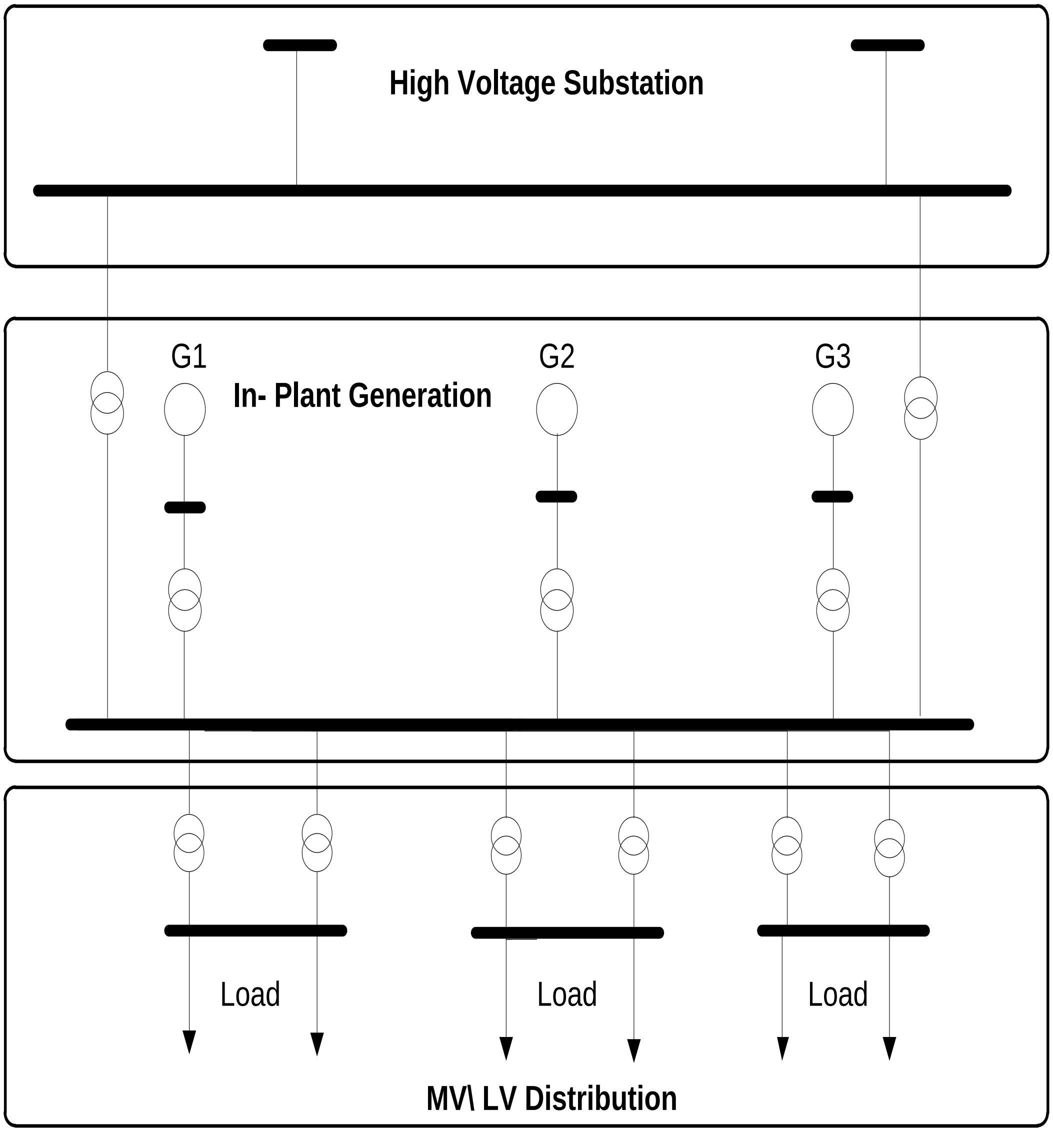


Figure 2.1 Typical Industrial Plant Distribution System Represented In a Single Line Form

2.3.1 High Voltage Substation

High-voltage power from the utility is stepped down in the high voltage substation for the primary distribution system. It consists of various electrical and non-electrical items such as gantry for terminating incoming and outgoing transmission lines, support structures, equipment foundation, perimeter fence, control building, grounding, underground oil containment, power transformers, circuit breakers, disconnect switches, instrument transformer s, reactors, capacitors, power and control cable, protection and control, communications, lightning, heating etc.

2.3.2 Primary Distribution System

This includes distribution from the plant main substation or generating station to the primary load centers or switchgear located in different plant facilities. A radial system with two feeders to each area is used for greater reliability. Typical voltage level for primary distribution system are 4.16 kV for small and medium sized plants, 13.8 kV for medium and large plants and 34.5 kV or 69kV for large plants where individual facilities are remote from each other.

2.3.3 Secondary Distribution System

This includes distribution from the primary load centers to secondary load centers, unit substations, low-voltage switchgear, and utilization equipment such as motor control centers, motors, heating, and lighting. For greater reliability, a secondary selective arrangement is recommended for the load centers.

2.3.4 In-plant Generation

In-plant generation is used when one of the following conditions is present:

- Steam is available at a suitable pressure and temperature. (It is economical to build a power plant using electric generators driven by steam turbines.)
- Power is not available from a utility company.
- Purchased power from the utility company is unreliable or the cost is very high.

2.3.5 Emergency Power Supply

Emergency power is required where an outage of normal source will be detrimental to process and equipment. This may include motors, valves, emergency lighting, controls, etc. Electric generators driven by diesel engines are used.

2.3.6 Power Supply for Monitoring and Control Systems

Power supply for monitoring and control systems shall be reliable, unaffected by voltage dip or sag and transients, and shall meet the requirements of load characteristics including voltage, frequency, and harmonics.

2.3.7 DC Power Supply for Protection and Control

In the US, power supply at 125 V DC is used for HV circuit breaker, medium-voltage switchgear, protection, control, monitoring, communications, emergency lighting, and emergency backup loads such as DC lube oil pump, etc. DC power supply consists of station battery, battery charger, and DC distribution.

CHAPTER 3

SHORT CIRCUIT ANALYSIS

Power system studies form the basic and necessary steps in planning a new power system or expanding an existing system. Load flow study, Transient analysis, Motor starting study, Harmonic analysis, and Short circuit analysis are the different types of analysis an engineer conducts during the planning stage of a power system.

3.1 Overview

The interaction of the various equipment used for generating, transmitting and distributing electric power to various through the electric power system makes it fairly complex system. The very complexity of these systems suggests that failures are unavoidable, no matter how carefully these systems have been designed. Within the context of short-circuit analysis, system failures manifest themselves as insulation breakdowns that may lead to one of the following phenomena [17].

- Undesirable current flow patterns
- Appearance of currents of excessive magnitudes that could lead to equipment damage and downtime
- Excessive overvoltage, of the transient and/or sustained nature, that compromise the integrity and reliability of various insulated parts
- Voltage depressions in the vicinity of the fault that could adversely affect the operation of rotating equipment
- Creation of system conditions that could prove hazardous to personnel

Additionally when a short circuit occurs the conductors experience strong electromagnetic forces of attraction and repulsion. [14]. As these forces are proportional to the square of the current, the rotating machinery, transmission, and switching equipment experience severe mechanical stresses and strains. These stress and strain on the equipment can cause deformation in rotational machines, transformer windings, and equipment bus bars, as result of which they might fail at a future time.

Apart from the mechanical forces generated by the current, they generate heat which is also proportional to the square of the magnitude of the current, I^2R. The main impact of the large amount of heat generated by the current is on the insulation of the equipment, the heat may damage the insulation of rotating machinery and apparatus that is connected in the faulted system, including cables, transformers, switched and circuit breakers. The permanent destruction of the insulation may be followed by actual fusion of the conducting circuit, with resultant additional arcing. The heat generated, apart from affecting the insulation materials it also exerts harmful effects upon the contact members of interrupting devices.

Because short circuits cannot always be prevented, we can only attempt to mitigate and to a certain extent contain their potentially damaging effects. One should, at first, aim to design the system so that the likelihood of the occurrence of the short circuit becomes small. If a short circuit occurs, however, mitigating its effects consists of managing the magnitude of the undesirable fault currents, and isolating the smallest possible portion of the system around the area of the mishap in order to retain service to the rest of the system. A significant part of system protection is devoted to detecting short-circuit conditions in a reliable fashion. The main reasons for performing short-circuit studies are the following [17]:

- Verification of the adequacy of existing interrupting equipment. These studies will form the basis for the selection of the interrupting equipment for system planning purposes.
- Determination of the system protective device settings, which is done primarily by quantities characterizing the system under fault conditions.
- Determination of the effects of the fault currents on various system components such as cables, lines, busways, transformers, and reactors during the time the fault persists. Thermal and mechanical stresses from the resulting fault currents should always be

compared with the corresponding short-term, usually first-cycle, withstand capabilities of the system equipment.

- Assessment of the effect that different kinds of short circuits of varying severity may have on the overall system voltage profile. These studies will identify areas in the system for which faults can result in unacceptably widespread voltage depressions.
- Conceptualization, design and refinement of system layout, neutral grounding, and substation grounding.

Short-circuit studies are performed on new and existing power system. For a new power system short-circuit studies are performed at the planning stage in order to help finalize the system layout, determine the voltage levels and size cables, transformers, and conductors. For existing power systems, fault studies are necessary in the cases of added generation, installation of extra rotating loads, system layout modifications, rearrangement of protection equipment, verification of the adequacy of existing breakers, relocation of already acquired switchgear in order to avoid unnecessary capital expenditures, etc.as well as during “Post-mortem” analysis short-circuit studies are performed in order to duplicate the reasons and system conditions that led to the system’s failure.

3.2 Sources of the Short-Circuit Faults Currents

Fundamental frequency currents that flow during a short circuit come from rotating electric machinery [16]. Charged power capacitors can also produce extremely high transient short-circuit discharge currents, but they are of natural frequency much higher than power frequency and usually of such short duration that the calculated power frequency short-circuit duty current is not significantly increased by adding the capacitor discharge. The fault current from each rotating machinery source is limited by the impedance of the machine and the impedance between the machine and the short circuit location. Fault currents generally are not dependent upon the pre-fault loading of the machine. The impedance of a rotating machine is not a simple value but is complex and varies with time.

3.2.1 Synchronous Machines

A running synchronous machine that has a bolted three-phase short circuit suddenly connected across its terminals will contribute currents to the short circuit. A typical fault current plot (without dc decay) is shown in figure 3.1. The plot shows a high initial decay (Sub-transient) followed by a slower rate of decay (Transient) and finally a steady-state value.

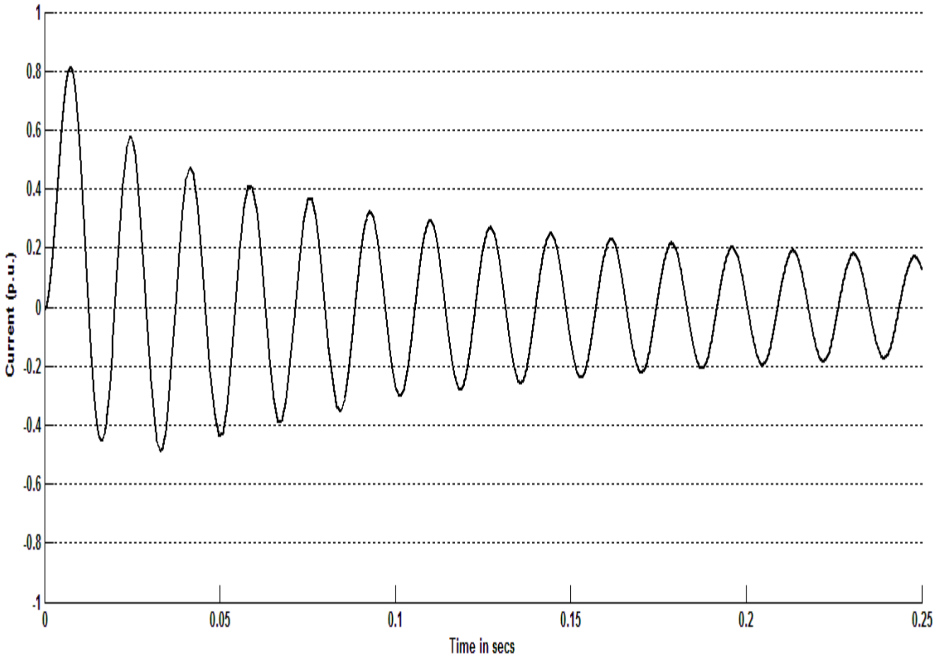


Figure 3.1 Typical Fault Current Plot for Synchronous Machine

The short-circuit current decreases exponentially in time from an initially high value to a lower steady-state level. This happens because the flux across the air gap of the synchronous machine is much larger at the instant the short-circuit occurs than it is a few cycles later. As the air-gap flux reduces because of limited field current capability, the stator current decreases. The internal voltage generated by the air-gap flux determines the magnitude of the short-circuit current. This changing air-gap flux accounts for the gradual decrease in the short-circuit current.

Synchronous machines have a number of reactance and time constants that can be used when modeling the machine. For short-circuit studies, these normally are reduced to the following:

- Direct-axis saturated subtransient reactance ($X^{''}_{dv}$) is the apparent reactance of the stator winding at the instant short-circuit occurs with the machine at rated voltage, no load.
- Direct-axis saturated transient reactance ($X^{'}_{dv}$) is the apparent reactance of the stator winding several cycles after initiation of the fault with the machine at rated voltage, no load.
- Direct-axis synchronous reactance X_d is the ratio of the fundamental-frequency component of reactive armature voltage (V_d) to the fundamental-frequency direct-axis positive-sequence component of armature current (I_{1d}) under sustained balanced conditions with rated field current applied.
- Negative sequence reactance is the apparent reactance determined by placing a line-to-line fault on the terminal of the generator at rated voltage. The negative sequence reactance is calculated from the direct-axis reactances by symmetrical components analysis.
- Zero sequence reactance is the apparent reactance determined by placing a line-to-ground fault on the terminal of the generator so that rated current flows. The zero sequence reactance is calculated using the direct-axis and negative sequence reactance and symmetrical components analysis.
- Three-phase short-circuit armature time constant is the time required for the ac short-circuit current to decay to 36.8% of its initial value. This time constant is a combination of the subtransient and transient time constants.

- Subtransient and Transient time constants are the times required for the respective components of subtransient and transient currents to decay to 36.8% of their initial value.

3.2.1.1 Synchronous Generators

If a short circuit is applied to the terminals of a synchronous generator, the short-circuit current starts out at a high value and decays to a steady-state value sometime after the inception of the short circuit. Since a synchronous generator continues to be driven by its prime mover and to have its field externally excited, the steady-state value of short-circuit current will persist unless interrupted by some switching means. An equivalent circuit consisting of a constant driving voltage in series with impedance that varies with time (figure 3.2) is used to represent this characteristic. The varying impedance consists primarily of reactance.

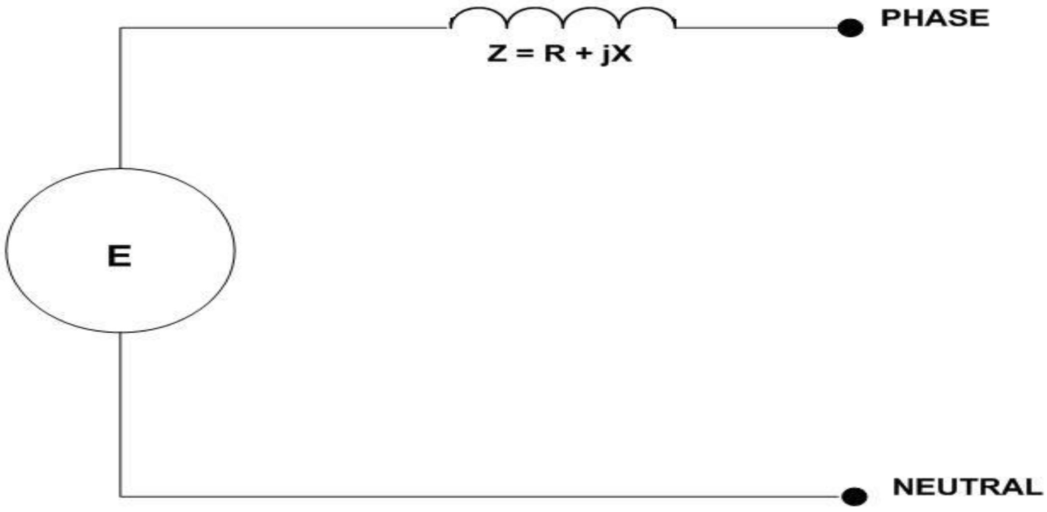


Figure 3.2 Equivalent Circuit for Synchronous Machines

For the purposes of short-circuit current calculations, industry standards have established three specific names for values of this variable reactance, called subtransient reactance, transient reactance, and synchronous reactance.

X_d'' = subtransient reactance; determines current during first cycle after fault occurs. In about 0.1 s reactance increases to

X_d' = transient reactance; assumed to determine current after several cycles at 60 Hz. In about 0.5 to 2 s reactance increases to

X_d = synchronous reactance; this is the value that determines the current flow after a steady state condition is reached.

Because most short-circuit interrupting devices, such as circuit breakers and fuses, operate well before steady-state conditions are reached, generator synchronous reactance is seldom used in calculating fault currents for application of these devices.

Synchronous generator data available from some manufacturers includes two values for direct axis subtransient reactance, subtransient reactance X_{dv}'' (at rated voltage, saturated, smaller) and X_{di}'' (at rated current, unsaturated, larger). Because a short-circuited generator may be saturated, and for conservatism, the X_{dv}'' value is used for short-circuit current calculations.

3.2.1.2 Synchronous Motors and Condensers

Synchronous motors are generally used to drive large loads such as compressors, pumps, and M-G sets and to supply capacitive power for power factor improvement. Sometimes synchronous motors are operated near unity power factor and rarely are operated drawing reactive power from system. The motors can have fixed or constant current fields or can have regulators that control bus voltage or motor power factor. Synchronous motors supply current to a fault much as synchronous generators do. When a fault causes system voltage to drop, the synchronous motor receives less power from the system for rotating its load. At the same time, the internal voltage causes current to flow to the system fault. The inertia of the motor and its load acts as a prime mover and, with field excitation maintained, the motor acts as a generator to supply fault current. This fault current diminishes as the magnetic field in the machine decays. The generator equivalent circuit is used for synchronous motors. Again, a constant driving voltage and the same three reactance, X_d'', X_d', and X_d, are used to establish values of current at three points in time.

Synchronous condensers are used as a means of reducing power system transmission losses, reactive power control and controlling voltages in a transmission or distribution system. They are connected to the power system as a motor but are neither connected to a load nor to a prime mover. Modern equipment such as static var compensators (SVCs) is much more common today than synchronous condensers, but the older rotating compensators may still be occasionally encountered in practice. Synchronous condensers are treated in the same manner as synchronous motors.

The most important characteristics of synchronous machines when calculating short-circuit currents are the internal reactances and resistances [14]. The variation of the reactance from a subtransient to a transient to sustained or steady-state impedance controls the ac component of the fault current. The resistance controls the dc rate of decay. For simplification of short-circuit calculation when actual short-circuit reactance values are not available, the multiplying factors given in Table 3.1 are used to calculate the approximate reactance of the machine during short-circuit.

Table 3.1 Synchronous Machine Reactance Multiplying Factors

Type of machine	Medium voltage and high voltage per IEEE Std C37.010	Low voltage per IEEE Std C37.13
First cycle calculations		
Remote Utility	1.0 * Xs	1.0 * Xs
Local generator	$1.0 * X''_{dv}$	$1.0 * X''_{dv}$
Synchronous motor	$1.0 * X''_{dv}$	$1.0 * X''_{dv}$
Interrupting time calculations (3–5 cycles)		
Remote Utility	1.0 * Xs	NA
Local generator	$1.0 * X''_{dv}$	NA

Table 3.1 – *Continued*

Synchronous motor	1.0 * X''_{dv}	NA

3.2.2 Induction Machines

A running induction motor that has a bolted three-phase short circuit suddenly connected across its terminals will contribute currents to the short circuit. Typical fault current vs. time plots are shown in figure 3.3. The plot shows a high initial current decay followed by fairly rapid decay to zero.

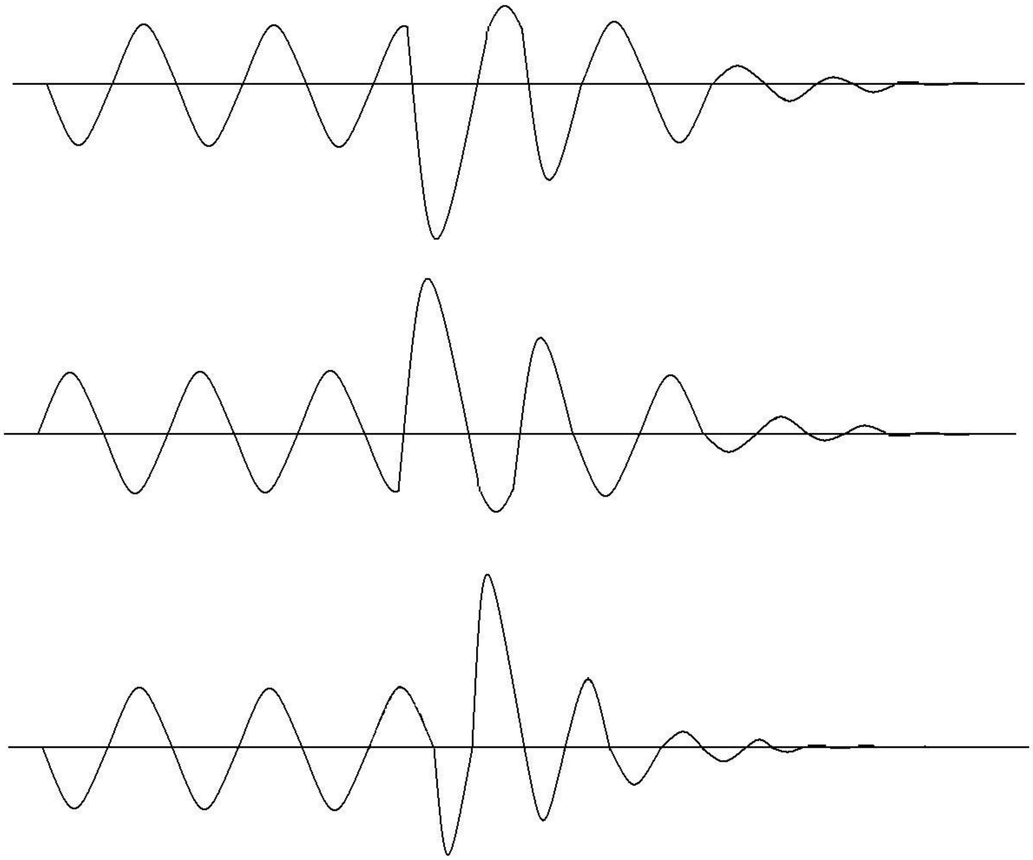


Figure 3.3 Typical Induction Motor Short-Circuit Current Contribution

The current contribution is caused by a stator driving voltage generated by trapped rotor flux. The current to the terminal short circuit is limited by the internal reactance of the motor. The current in two or all three phases is asymmetrical at first, and that each offset current consists of an ac and a dc component. The ac component decays because the rotor flux is not maintained by normal applied voltage. The dc component, a transient not supported by any driving voltage, also decays. The frequency differs initially from system frequency by motor slip and thereafter reduces at a rate dependent on motor mechanical load and combined motor and load inertia. For the first few cycles after the short circuit, the frequency change is usually conservatively considered to be inconsequential.

A squirrel-cage induction motor will contribute current to a power system short circuit. This is generated by inertia driving the motor in the presence of a field flux produced by induction from the stator rather than from a dc field winding. Since this flux decays on loss of source voltage caused by a fault at the motor terminals, the current contribution of an induction motor to a terminal fault reduces and disappears completely after a few cycles. Because field excitation is not maintained, there is no steady-state value of fault current as for synchronous machines.

The initial magnitude of the ac component is calculated using the subtransient motor reactance $X^{''}$. It is accepted practice to substitute the known or estimated locked rotor reactance X_{LR} for $X^{''}$. The initial magnitude of dc component for short-circuit calculations is taken to be equal to the crest value of the initial ac component. This is based on the conservative assumption that the current in one of the phases will have the maximum possible asymmetry.

The equivalent circuit used to represent an induction motor in simplified short-circuit calculations is shown in figure 3.4. For a fault calculation involving different times after the fault, a different equivalent motor reactance would result because induction motor equivalent reactances vary considerably with the motor size and speed.

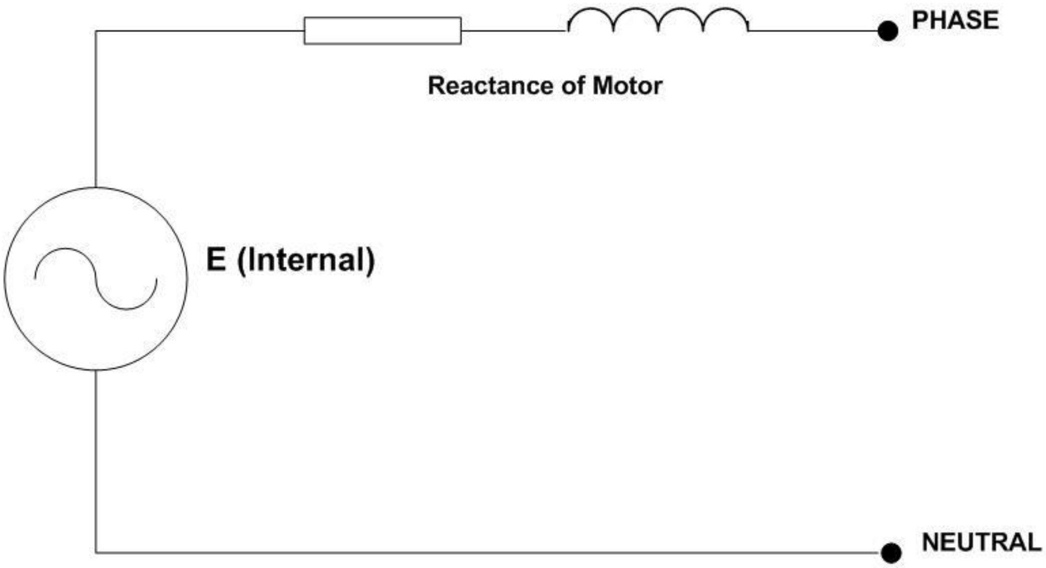


Figure 3.4 Equivalent Circuit For Induction Motor

Short circuits are calculated frequently for fault points separated from contributing induction motor terminals by series impedances. Ideally the value of the multiplying factor used for calculating the value of the impedance for analysis should vary depending on the location of the fault. But for simplified calculations the same multiplying factors are applied whether the fault is close to or remote from the motor, this reasonable assumption also assists in short circuit studied performed using computers as the value of the reactance does not vary based on the location of the fault.

There is a possibility in the power system during a remote fault the nearer power sources partially sustain the voltage at the motor. At the instance of the fault there is reduction in the voltage and the motor contributes to the fault but if the nearby power sources are able to sustain the minimum required voltage the motor would return to normal operation and stop contributing to the fault. The simplified short-circuit calculation method ignore this effect and consider all connected medium and large sized motors continue to contribute current to short circuits for at least four cycles after the short circuit starts.

For longer times after the short circuit, appreciably after four cycles, smaller induction motors are usually omitted from the equivalent circuit because induction motor fault current contribution decay is rapid and approaching zero although the motors remain connected. In addition, some motors nearer the fault may have been disconnected by relays or contactor dropout on depressed voltage due to the nearby fault. The motor dropout effect could be included in interrupting time calculations. However, for a conservative short-circuit current; often it is assumed that the motors do not drop out. When actual short-circuit reactance data is not available the Table 3.2 provides the multiplying factors [14] to be used to calculate approximate short circuit reactance of the machine

Table 3.2 Induction Machine Reactance Multiplying Factors

Type of machine	Medium voltage and high voltage per IEEE Std C37.010	Low voltage per IEEE Std C37.13	Recommended reactance multiplier
First cycle calculations			
Large Induction Motors			
>1000 HP	1.0 * X”	1.67 * X”	1.0 * X”
>250 HP and 2 pole	1.0 * X”	1.67 * X”	1.0 * X”
Medium Induction Motors			
50 to 249 HP	1.2 * X”	1.67 * X”	1.2 * X”
250 to 1000 HP > 2 pole	1.2 * X”	1.67 * X”	1.2 * X”
Small Induction Motors			
< 50 HP		1.67 * X”	1.67 * X”
Interrupting time calculations (3–5 cycles)			
Large Induction Motors			
>1000 HP	1.5 * X”	NA	1.5 * X”

Table 3.2 – *Continued*

>250 HP and 2 pole	1.5 * X”	NA	1.5 * X”
Medium Induction Motors			
50 to 249 HP	3.0 * X”	NA	3.0 * X”
250 to 1000 HP > 2 pole	3.0 * X”	NA	3.0 * X”
Small Induction Motors			
< 50 HP		NA	

For short-circuit current calculations, an induction generator can be treated the same as an induction motor. Wound-rotor induction motors normally operating with their rotor rings short-circuited will contribute short-circuit current in the same manner as a squirrel-cage induction motor. Occasionally, large wound-rotor motors operated with some external resistance maintained in their rotor circuits may have sufficiently low short-circuit time constants that their short-circuit current contribution is not significant and may be neglected. A specific investigation should be made to determine whether to neglect the contribution from a wound-rotor motor.

3.2.3 Electric Utility Systems

The remote generators of an electric utility system are a source of short-circuit current often delivered through a supply transformer. The generator-equivalent circuit can be used to represent the utility system. The utility generators are usually remote from the industrial plant. The current contributed to a short circuit in the remote plant appears to be merely a small increase in load current to the very large central station generators, and this current contribution tends to remain constant. Therefore, the electric utility system is usually represented at the plant by single valued equivalent impedance referred to the point of connection.

Transformers merely change the system voltage and magnitude of current but generate neither. The short-circuit current delivered by a transformer is determined by its secondary voltage rating and reactance, the reactance of the generators and the system to the terminals of the transformer, and the reactance of the circuit from the transformer to the short circuit.

3.2.4 Adjustable Speed ac Induction or dc Motors with Solid-State ac Power Supply Equipment

Some adjustable speed ac induction or dc motors, speed controlled by adjusting the frequency or dc voltage of solid-state ac power supply equipment, can, under certain conditions, contribute current from the motors to a short circuit on the incoming ac electric power system. The design of the power supply equipment determines whether a current can or cannot be “back-feed” from the motors. When it can, the power supply operating mode at the time of the power system short circuit usually determines the magnitude and duration of the back-feed current. For some motors, the duration is limited by power supply equipment protective functions to less than one cycle of ac power frequency. The adjustable frequency or dc voltage power supply manufacturer should be consulted for information on whether adjustable speed ac induction or dc motors can contribute back-feed current to ac power system short circuits, and if so, under what operating conditions and how much.

For large power systems consisting of high number of generators and huge mix of motors at various voltage calculating short-circuit current from all machines would be very tedious and complex process. To simplify this calculation the short-circuit reactance of the rotating machines can be obtained by utilizing the simplified multiplying factors for first cycle and Interrupting short-circuit current calculation given in Table 3.3 which are based on IEEE Std C37.010-1979 and IEEE Std C37.5-1979 [16].

Table 3.3 Rotating-Machine Reactance (Or Impedance) Multipliers

Type of Rotating Machine	First-cycle network	Interrupting network
Large Induction Motors All turbine generators; all hydro generators with amortisseur windings; all condensers	$1.0 * X''_d$	$1.0 * X''_d$
Hydro generators without amortisseur windings	$0.75 * X'_d$	$0.75 * X'_d$
All synchronous motors	$1.0 * X''_d$	$1.5 * X''_d$
Induction Motors		
Above 1000 hp at 1800 r/min or less	$1.0 * X''_d$	$1.5 * X''_d$
Above 250 hp at 3600 r/min	$1.0 * X''_d$	$1.5 * X''_d$
All others, 50 hp and above	$1.0 * X''_d$	$1.5 * X''_d$
All smaller than 50 hp	neglect	neglect

3.3 Short-Circuit Fault Current

Short circuits occur in power system due to various reasons like, equipment failure, lightning strikes, falling of branches or trees on the transmission lines, switching surges, insulation failures and other electrical or mechanical causes. All these are collectively called faults in power systems. A fault usually results in high current flowing through the lines and if adequate protection is not taken, may result in damages in the power apparatus

Short-circuits can occur on a three-phase system in several ways. The protective device or equipment must have the ability to interrupt or withstand any type of short circuit that can occur. The three-phase bolted short circuit is the basic type utilized for selection of equipment. The magnitude of the fault currents depends on the internal impedance of the generator plus the impedance of the intervening circuit. As discussed earlier the impedance of the rotating machine is not constant under short circuit condition. The generator behavior varies with time and as a result for first few cycles of the fault the sub-transient reactance would be utilized, for longer period the transient reactance would be utilized and the actual reactance would be utilized during steady state period.

3.3.1 Nature of Fault Current

The short-circuit current can be both symmetrical, if the envelopes of the peaks of the current waves are symmetrical about the zero axis, as well as asymmetrical, if the envelopes of the peaks of the current waves are asymmetrical about the zero axis. The envelope is the line drawn through the peaks of the waves. figures 3.5 and 3.6 show typical symmetrical and asymmetrical ac waves as 60Hz.

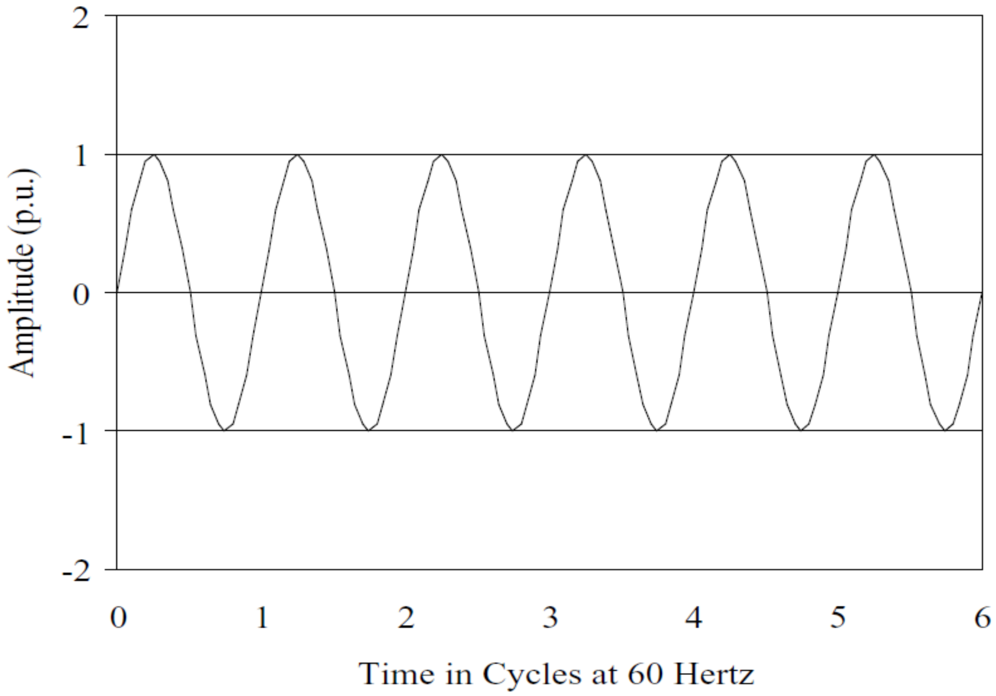


Figure 3.5 Symmetrical AC Current Wave

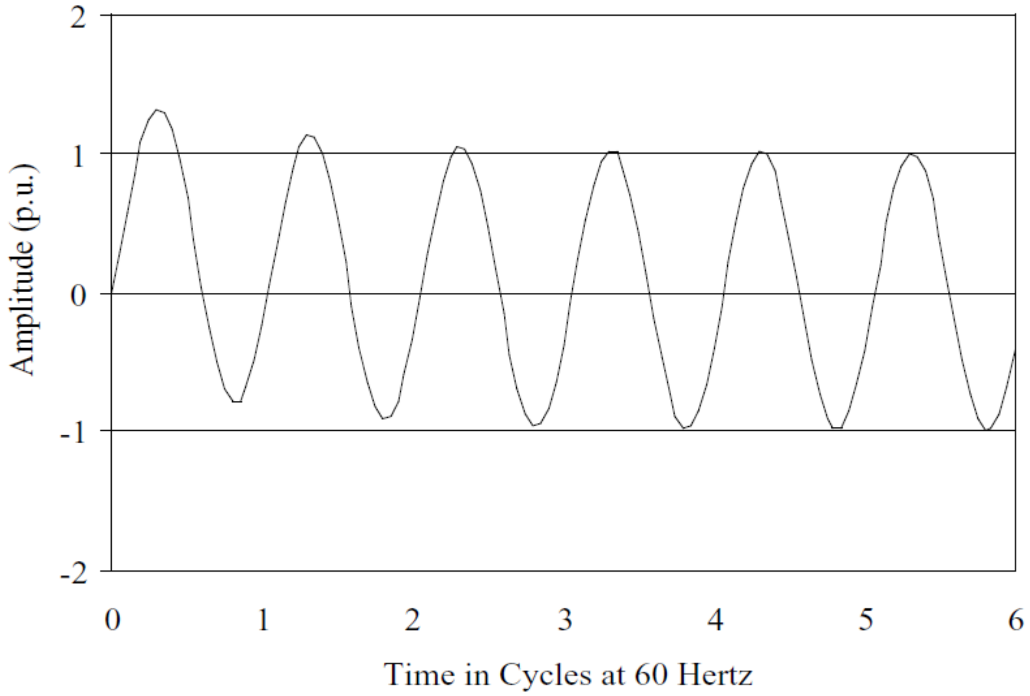


Figure 3.6 Asymmetrical AC Current Wave

In the usual industrial power systems the applied or generated voltages are of sine-wave form. When a short circuit occurs, substantially sine wave short-circuit currents result. In ordinary power circuits the resistance of the circuit is negligible compared with the reactance of the circuit. The short-circuit current power factor is determined by the ratio of resistance and reactance of the circuit only (not of the load). Therefore the short-circuit current in most power circuits lags the internal generator voltage by approximately 90^0.

If in a circuit mainly containing reactance a short circuit occurs at the peak of the voltage wave, the short-circuit current would start at zero and trace a sine wave which would be symmetrical about the zero axis. This is known as symmetrical short-circuit current. If in the same circuit, a short-circuit occurs at the zero point of the voltage wave, the current will start at zero but cannot follow a sine wave symmetrically about the zero axis because such a current would be in phase with the voltage. The wave shape must be the same as that of voltage but 90^0 behind. That can occur only if the current is displaced from the zero axis.

The fact that the pre-fault system current cannot change instantaneously leads to a presence a significant unidirectional component in the fault current depending on the exact instance of the occurrence of the short-circuit. This unidirectional current component often referred to as dc offset, decays with time exponentially.

The amount of offset that will occur in a fault current waveform depends on the time at which the fault occurs on the ac voltage waveform and the network resistances and reactances. The current in a purely reactive network could have any offset from none to fully offset (as shown in figure 3.7), depending on the time of its inception, and the offset would be sustained (not decaying). A fault occurring in a purely resistive system would have no offset in the current waveform. A network containing both resistances and reactances will generally begin with some offset in the current (up to full) and gradually the current will become symmetrical (because of the decay of the offset) around the zero axis.

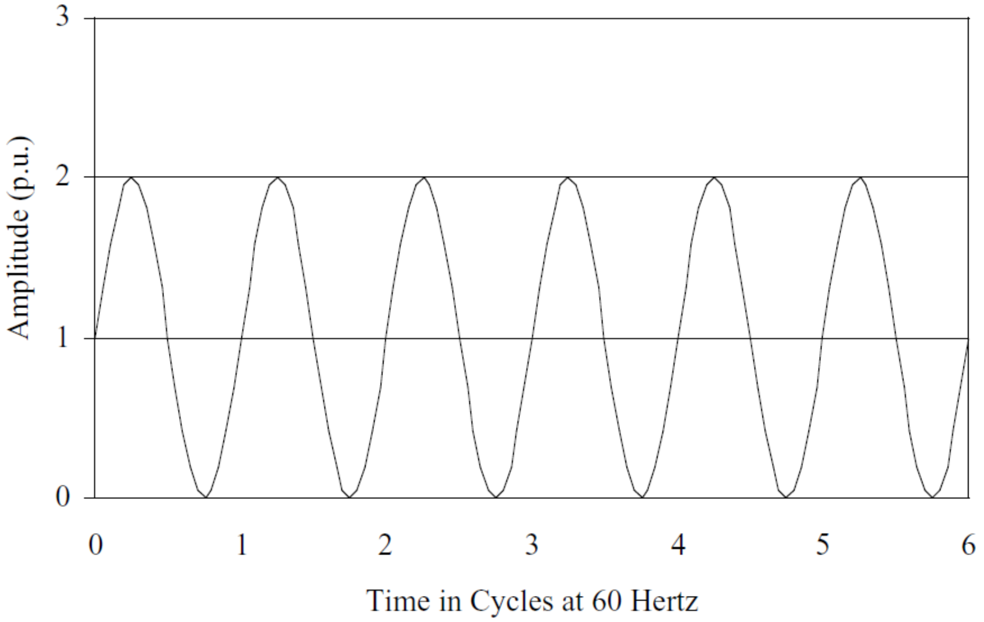


Figure 3.7 Totally Offset AC Current Wave

Similarly for circuits containing both reactance and resistance, the point on the voltage at which the short circuit must produce maximum asymmetry depends on the ratio of the reactance to the resistance of the circuit. Maximum asymmetry is obtained when the short circuit occurs at a time angle equal to $90^0 + \theta$ (measured forward in degrees from zero point of the voltage wave) where tangent θ equals the reactance-to-resistance ratio of the circuit. The short circuit would be symmetrical if the fault occurs 90^0 from that point of the voltage wave.

The asymmetrical alternating current behaves exactly as if there were two component currents flowing simultaneously. One is the symmetrical ac component and the other a dc component. The sum of these two components at any instant is equal to the magnitude of the total asymmetrical ac wave at the same instant. The dc component referred to here is generated within the ac system with no external source of direct current being considered.

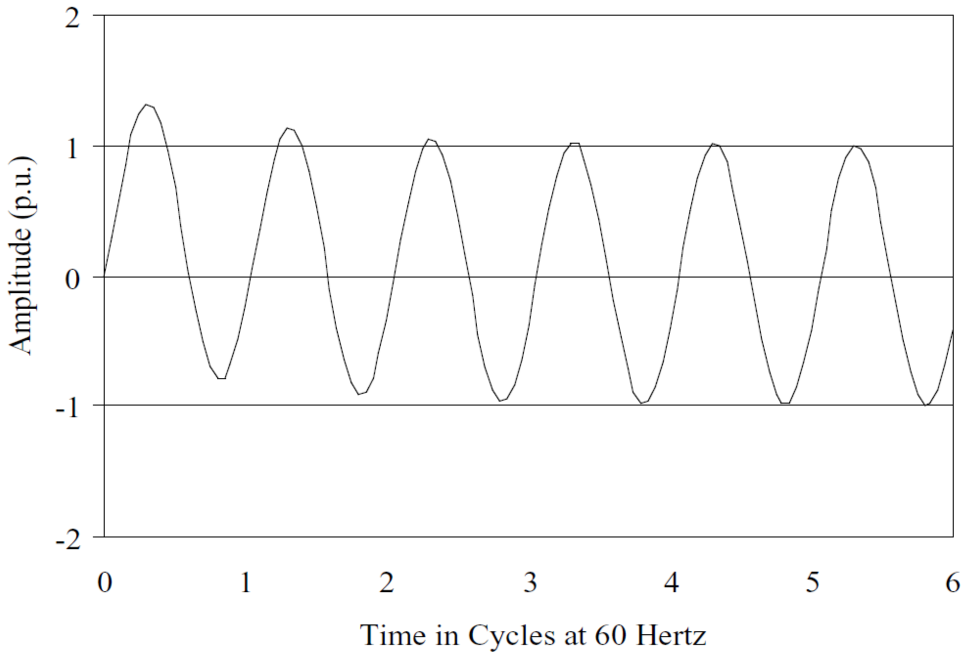


Figure 3.8 Typical AC Short-Circuit Wave

There is no dc voltage in the system to sustain the flow of direct current; therefore the energy represented by the direct component of current will be dissipated as I^2R loss from the direct current flowing through the resistance of the circuit. If the circuit has zero resistance the direct current would flow at a constant value until the circuit was interrupted. However all practical circuits have some resistance, so the dc component decays. The combination of the decaying of dc and symmetrical ac components gives an asymmetrical wave that change to a symmetrical wave when the dc component has disappeared.

3.3.2 Types of Fault Current

Depending upon the nature of the fault current wave form the great majority of short-circuit faults in industrial and commercial power systems can be classified in two categories [17]

- Symmetrical or balanced faults (Three Phase Faults)
- Asymmetrical or un-balanced faults

The asymmetrical faults can be further classified in three major types

- Single Line-to-Ground fault
- Double Line fault
- Double Line-to-Ground fault

3.3.2.1 Three Phase faults

A three-phase bolted fault describes the condition where the three conductors are physically held together with zero impedance between them, just as if they were bolted together. For a balanced symmetrical system, the fault current magnitude is balanced equally within the three phases. While this type of fault does not occur frequently, its results are used for protective device selection, because this fault type generally yields the maximum short-circuit current values. Figure 3.9 provides a graphical representation of a bolted three-phase fault. Because the network is balanced, it is solved on a per- phase basis. The other two phases carry identical current except for the phase shift.

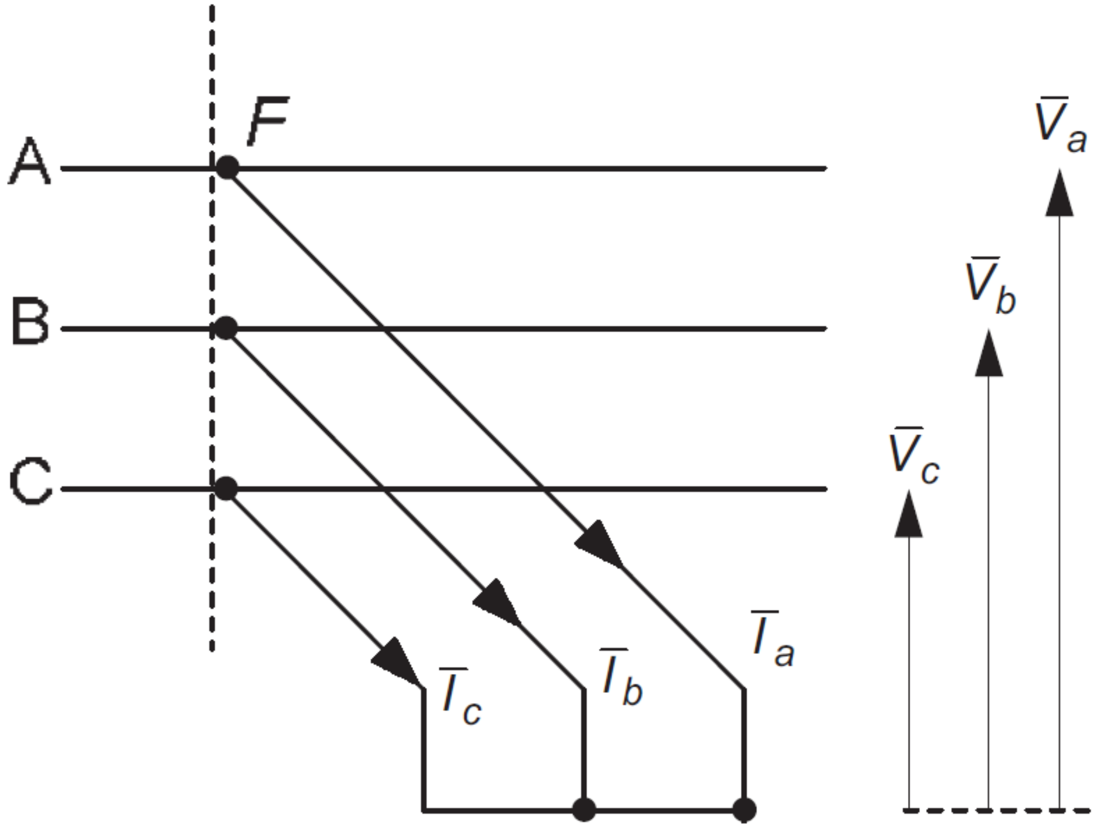


Figure 3.9 Three-Phase or Balanced Fault

The three phase fault earth fault could also occur if the three bolted lines come in contact with ground, still the system would remain balanced even if the fault involved a ground resistance.

3.3.2.2 Single Line-to-Ground fault

Line-to-ground faults, figure 3.10, are the most common type of faults and are usually the least disturbing to the system. The current in the faulted phase can range from near zero to a value slightly greater than the bolted three-phase fault current. The line-to-ground fault current magnitude is determined by the method in which the system is grounded and the impedance of the ground return path of the fault current. Calculation of the exact line-to-ground fault current magnitudes requires the special calculating techniques of symmetrical components. However, close approximations can be made knowing the method of system grounding used. On ungrounded distribution systems, the line-to-ground fault currents are near zero. Line-to-ground fault current magnitudes in distribution systems with resistance grounded system neutrals can be estimated by dividing the system line-to-neutral system voltage by the total value of the system ground-to-neutral resistance. Line-to-ground fault current magnitudes in distribution systems with a solidly grounded system will be approximately equal to the three-phase fault current magnitudes. Determining line-to-ground fault currents on long cable runs or transmission lines will require detailed ground return path impedance data and detailed calculation techniques.

In resistance grounded, medium voltage systems the resistor is generally selected to limit ground fault current to a value ranging between 400 and 2000 amperes. Line-to-ground fault magnitudes on these systems are determined primarily by the resistor itself and a line-to-ground short-circuit calculation is generally not required.

It is customary to perform three phase short-circuit analysis when seeking to determine the maximum possible magnitudes of fault currents. However there are exception when single line-to-ground short-circuit currents can exceed three-phase short-circuit current levels when they occur in the vicinity of

- A solidly grounded synchronous machine
- The solidly grounded wye side of a delta-wye transformer of the three phase core (three leg) design
- The grounded wye side of a delta-wye autotransformer
- The grounded wye, grounded wye, delta-tertiary of a three winding transformer

For systems where any one or more of the above conditions exist, it is advisable to perform a single line-to-ground fault simulation.

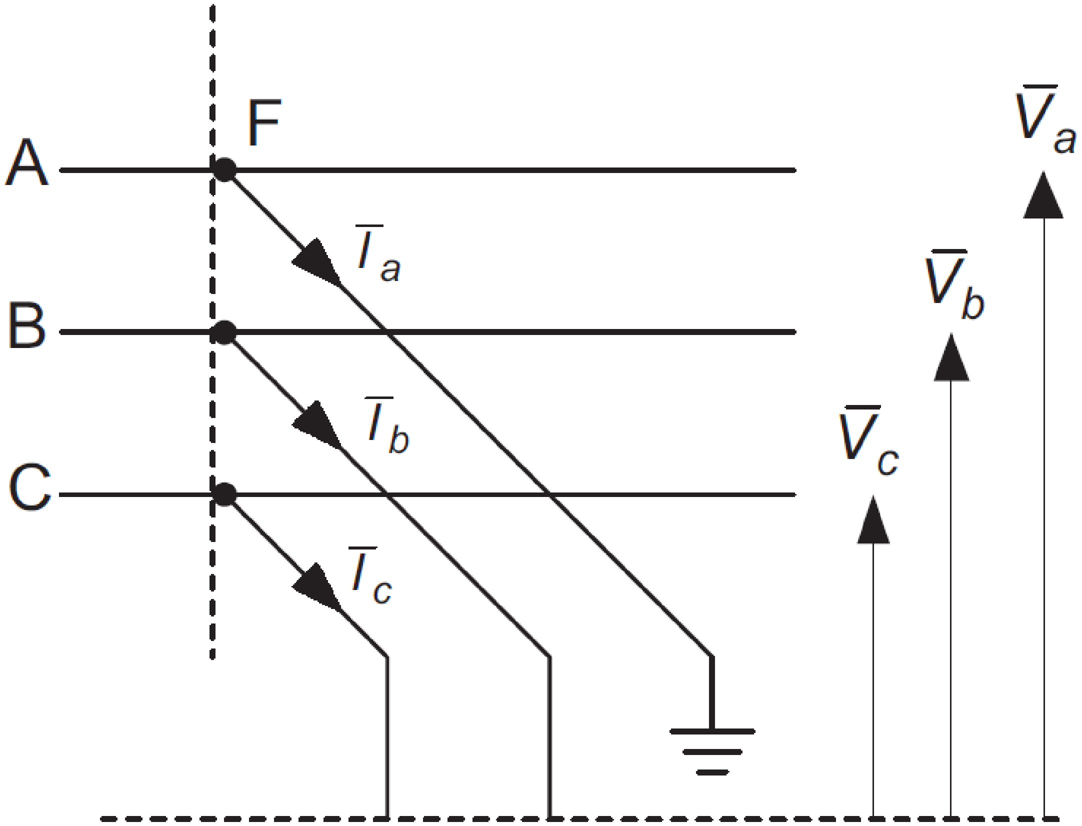


Figure 3.10 Single Line-to-Ground Fault

3.3.2.3 Double Line fault

Bolted line-to-line faults, figure 3.11, are more common than three-phase faults and have fault currents that are approximately 87% of the three-phase bolted fault current. This type of fault is not balanced within the three phases and its fault current is seldom calculated for equipment ratings because it does not provide the maximum fault current magnitude. The line-to-line current can be calculated by multiplying the three-phase value by 0.866, when the impedances are equal. Special symmetrical component calculating techniques are not required for this condition.

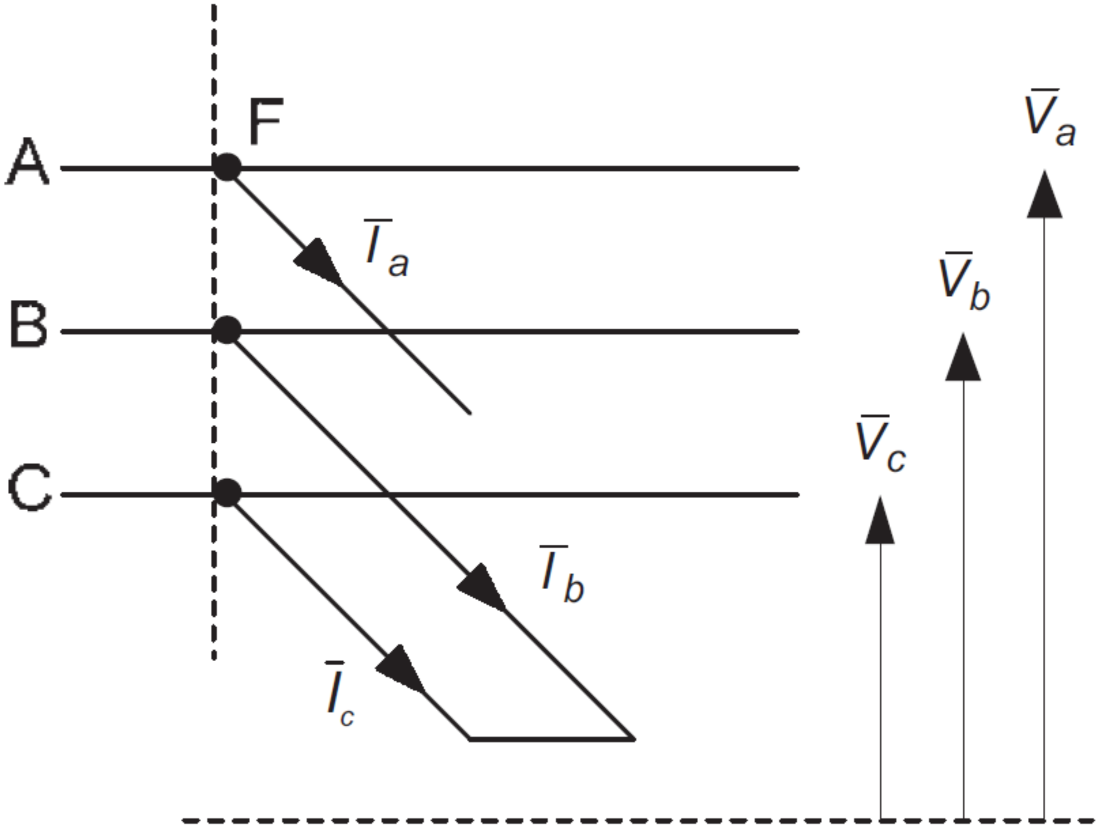


Figure 3.11 Double Line Fault

3.3.2.4 Double Line-to-Ground fault

Line-to-line-to-ground faults, figure 3.12, are typically line-to-ground faults that have escalated to include a second phase conductor. This is an unbalanced fault. The magnitudes of double line-to-ground fault currents are usually greater than those of line-to-line faults, but are less than those of three-phase faults. Calculation of double line-to-ground fault currents requires the use of symmetrical components analysis. The impedance of the ground return path will affect the result, and should be obtained if possible.

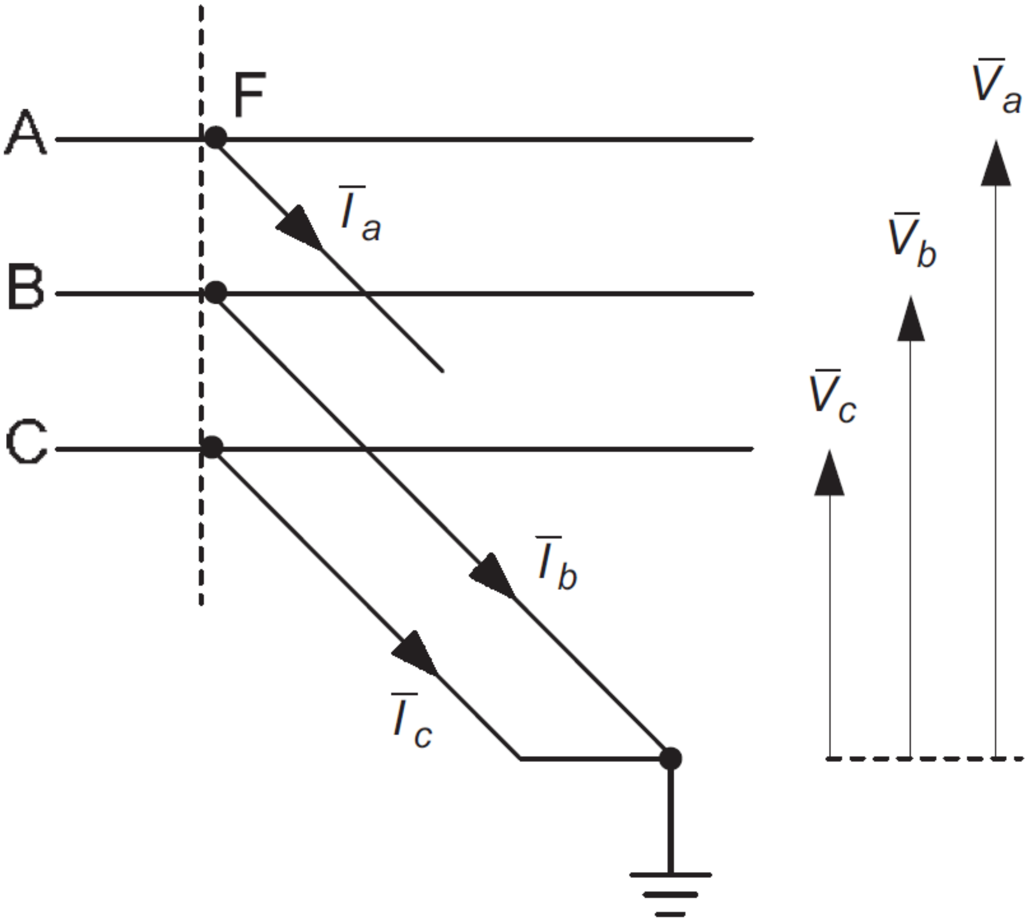


Figure 3.12 Double Line-to-Ground Fault

These types of short circuits are also referred to as “shunt faults,” since all four exhibit the common attribute of being associated with fault currents and MVA flows diverted to paths different from the prefault “series” ones.

3.3.2.5 Other Faults

- Open Circuit Faults

There are two types of open circuit faults that can occur in a system depending on the number of conductors involved in the fault.

  - One line open – Any one of the three phases may be open (figure 3.13)
  - Two line open – Any two of the three of the phases may be open

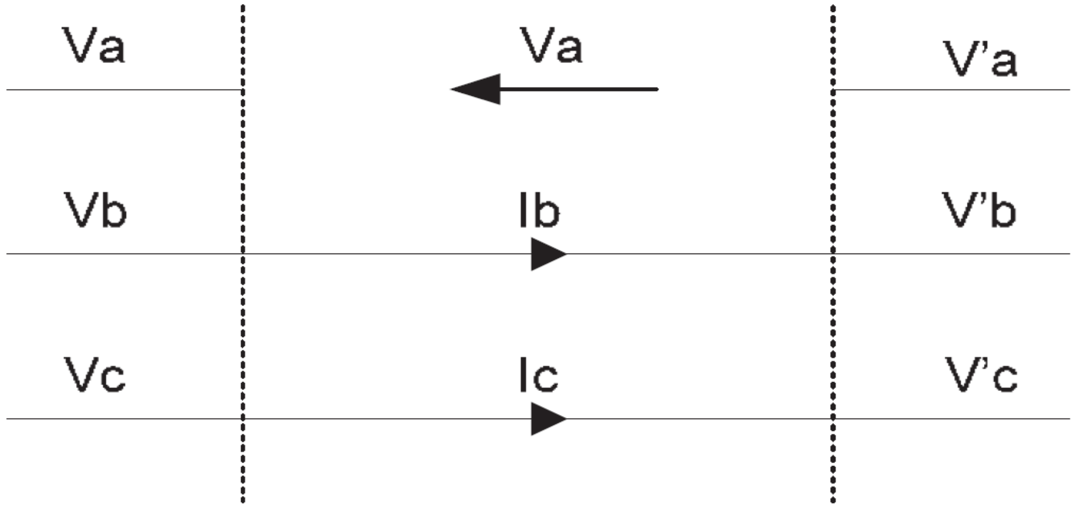


Figure 3.13 One Line Open Fault

- Unequal impedances - Unbalanced line impedance discontinuity.

These faults are termed as series faults because the above unbalances are associated with a redistribution of the prefault load current. Series faults are of interest when assessing the effects of snapped overhead phase wires, failures of cable joints, blown fuses, failure of breakers to open all poles, inadvertent breaker energization across one or two poles and other situations that result in the flow of unbalanced currents.

- Cross-Country Faults - two faults affecting the same circuit, but in different locations and possibly involving different phases.
- Arcing Short-Circuit

The breakdown of the gap between two conductors causes a luminous discharge and this phenomenon is called as arcing short circuit. The short-circuit might at times include the ground path too. The magnitude of the current is limited by the resistance of the arc and impedance of the ground path. They are more common in particularly in low-voltage systems. These type of faults usually draw lower amount of short-circuit current, but sustained arcing generate large amount heat and increase system damage. The low levels of arcing short circuit current in low-voltage systems become important in designing adequate system protection.

CHAPTER 4

SHORT-CIRCUIT CURRENT CALCULATION

There are two types of short-circuit studies of interest to the power engineer. The first type of study determines the first-cycle (momentary) and contact-parting (interrupting) short-circuit current duties (i.e., asymmetrical RMS or peak currents) at the buses of the power system, which are used to select the short-circuit withstand and interrupting capabilities of switchgear. To insure safety of personnel and to prevent damage of power system apparatus, this type of short-circuit study is performed under worst-case assumptions. These assumptions include selecting the worst-case fault location at the switchgear bus (which receives all possible short-circuit current contributions) and fault type (usually a bolted, three-phase fault).

The second type of short-circuit study determines the subtransient and transient short-circuit currents that an overcurrent protective device will sense, in order to initiate the prompt removal of the affected portion of the power system by its circuit interrupter. These short-circuit currents are necessary to properly select the instantaneous and time delay settings of the overcurrent protective devices.

The maximum calculated short-circuit current values are used for selecting interrupting devices of adequate short-circuit rating, to check the ability of components of the system to withstand mechanical and thermal stresses, and to determine the time-current coordination of protective relays. The minimum values are used to establish the required sensitivity of protective relays. Minimum short-circuit values are sometimes estimated as fractions of the maximum values. If so, it is only necessary to calculate the maximum values of short-circuit current. For calculating the maximum short-circuit current, the industrial electric power system should have the largest expected number of connected rotating machines (usually with the system at full future load).

Ohm’s law, I = E/Z [16], is the basic relationship used in determining I, the short-circuit current, where E is the driving voltage of the source, and Z is the impedance from the source to the short circuit including the impedance of the source. Most industrial systems have multiple sources supplying current to a short circuit since each motor can contribute. One step in short-circuit current calculation is the simplification of the multiple-source system to the condition where the basic relationship applies.

The following constraints [14] are common to all of the techniques used in the short circuit calculation

- The ac source frequency must be constant. In power system short-circuit analysis; it is reasonable to assume constant system frequency for the fault duration except for very rare and special cases.
- The impedance coefficients R, L, and C must be constant (saturated values). Again, for the majority of short-circuit calculations this restraint causes no difficulty since the maximum fault current is of concern and the fault resistance is taken to be zero when the equipment rating is evaluated. There are few scenarios where the above constraints are violated, for example during an arc fault the resistance of the arc is not constant as the value .This variation would in turn reduce the effect of impedance of the current wave and as result harmonic terms would be introduced which will not be reflected when a constant value of R is used in simplified calculations. A similar non-linearity exists electromagnetic elements. When the flux density of these elements are pushed into the saturation region the value of L drops significantly resulting in the appearance of harmonic components in the current which would not be reflected using the simplified calculation.
- The driving voltage and its phase angle are assumed to be constant. In reality, however, the machine’s internal driving voltage varies with machine loading and time. During a fault, the machine’s magnetic energy or internal voltage is reduced faster than

it can be replaced by energy supplied by the machine’s field. The rate of decay differs for each source. In addition, the angles between machines begin to change as some accelerate and others slow down. Solving a system with many varying driving voltage sources becomes cumbersome. The same current can be determined by holding the voltage constant and varying the machine impedance. This interchange helps to simplify the mathematics.

- The fault current source must be sinusoidal. Most voltages and currents used for transmission and utilization of electric power are generated by the uniform rotation of an armature in a magnetic field; the resulting steady-state voltage is periodic and has a waveform that is nearly a pure sine wave or one that can be resolved into a series of sine waves.

4.1 Equivalent Voltage Source at Fault Location

The method used for calculation is based on the introduction of an equivalent voltage source at the short-circuit location. The equivalent voltage source is the only active voltage of the system. All network feeders, synchronous and asynchronous machines are replaced by their internal impedances. In all cases, it is possible to determine the short-circuit current at the short-circuit location with the help of an equivalent voltage source. Operational data and load of consumers, tap-changer position of the transformers, and excitation of generators are dispensable; additional calculations about all the different possible load flows at the moment of short circuit are superfluous. Shunt admittance (for example, line capacitances and passive loads) are not to be considered when calculating short-circuit currents in the transmission system.

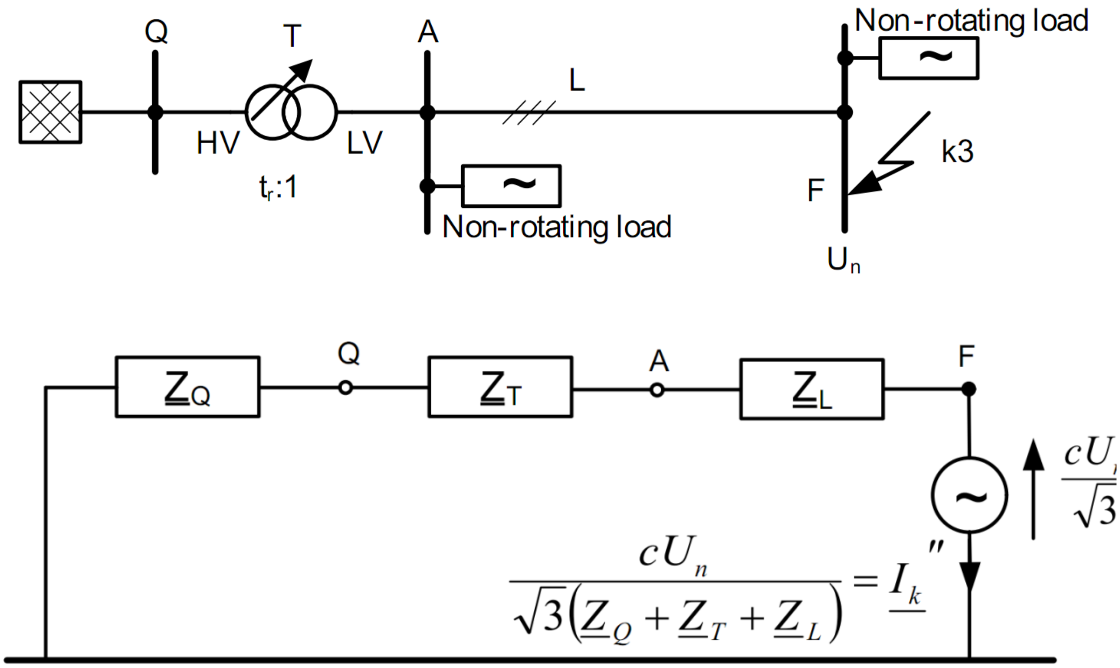


Figure 4.1 Illustration of Equivalent Voltage Source at Fault

The network reduction techniques make use of the various concepts of network theorems to determine the equivalent voltage source at the fault.

4.1.1 Linearity

Linearity is the most fundamental concept to be discussed and is a powerful extension of Ohm's Law. The simplified network is said to be linear for the chosen excitation and response function if the plot response of the magnitude versus the source excitation magnitude is a straight line for a linear element. When linear dc circuits are involved, the current will double if the voltage is doubled. The linear characteristic also holds for ac circuits provided the frequency of the driving voltage is held constant. In a similar manner, it is possible to predict easily the response of a constant impedance circuit (i.e., constant R, L, and C elements) to any magnitude of dc source excitation or fixed frequency sinusoidal excitation based on the known response at any other level of excitation.

An important limitation of linearity is that the excitation source, if not independent, must be linearly dependent on another (independent or dependent) source or network variable.

Ultimately in a linear circuit, all variables, including source, network, and load voltages and currents are related to each other by a set of coefficients. This restraint, in effect, forces a source to behave with a linear response.

4.1.2 Superposition

Superposition is possible as a direct result of linearity and hence is subject to the same restraints. The superposition theorem states that if a network consists of linear elements and has several dc or fixed frequency ac excitation sources (i.e., voltages), the total response (i.e., current) can be evaluated as the sum of the currents caused by each voltage source acting separately with all other source voltages reduced to zero or, similarly, all other current sources open circuited. Note that this sum will be a simple algebraic sum in dc circuits and will be a vector sum in ac circuits.

4.1.3 Thevenin Equivalent Circuit

This powerful circuit analysis tool is based on the fact that any active linear network, however complex, can be represented by a single voltage source equal to the open-circuit voltage across any two terminals of interest, in series with the equivalent impedance of the network viewed from the same two terminals with all sources in the network inactivated (i.e., voltage sources zero and current sources open). The validity of this representation requires only that the network be linear. The existence of linearity is, therefore, a necessary restraint. (Note that Thevenin equivalents can also be formed for multiphase power systems.)

Using the simple Thevenin equivalent it would be easy to examine the response of the circuit as the value of the load impedance is varied. Caution, however, is required to ensure that equipment models or buses of interest are not “absorbed” by the process of forming a Thevenin equivalent. Once absorbed, relevant data pertaining to individual contributions to total short-circuit current and bus voltages are unrecoverable without completely resolving the entire circuit without using an equivalent. The Thevenin equivalent circuit solution method is equally valid for complex impedance circuits and is the basis for making short-circuit calculations.

4.1.4 Norton Equivalent Circuit

A Norton equivalent that consists of a current source (triangle) in parallel with equivalent impedance can alternately be developed for the Thevenin equivalent circuit. This representation is often used for computer solutions, but generally not for “by hand” solutions in power system analysis work.

4.1.5 Millman's Theorem

A direct result of Norton’s equivalent is Millman’s theorem, which states that when any number of voltage sources of arbitrary generated voltage and finite internal impedance different from zero are connected in parallel, the resultant voltage across the parallel combination is the ratio of the algebraic sum of the currents that each source individually delivers when short circuited to the algebraic sum of the internal admittances. Millman’s theorem can be used to simplify calculations in polyphase circuits and has other applications.

4.1.6 Reciprocity

The general reciprocity theorem states that in networks consisting of linear circuit elements, the ratio of excitation to response when only one excitation is applied is constant when the positions of excitation and response are interchanged. Specifically, this means that the ratio of the voltage applied in one branch to the resulting current in a second branch of a network is the same as the ratio of the voltage applied in the second branch to the resulting current in the first branch.

4.1.7 The Sinusoidal Forcing Function

It is a most fortunate truth that the sources (i.e., driving voltage) of electrical networks, in general, have a sinusoidal character and may be represented by a sine wave. There are two important consequences of this circumstance. First, although the response (i.e., current) for a complex R, L, C network represents the solution to at least one second-order differential equation, the steady-state result will be a sinusoid of the same frequency as the excitation and differs only in magnitude and phase angle.

The second important item is that when the sinusoidal current is forced to flow in a general impedance network of R, L, and C elements, the voltage drop across each element will have a sinusoidal shape of the same frequency as the source. The sinusoidal character of all the circuit responses makes the application of the Superposition technique to a network with multiple sources surprisingly manageable. The necessary manipulation of the sinusoidal terms is easily accomplished using the laws of vector algebra.

The only restraint associated with the use of the sinusoidal forcing function concept, is that the circuit must be comprised of linear elements. While most circuits contain nonlinearities, it is usually possible to restrict an analysis to a certain range of operating conditions where linear characteristic hold.

4.1.8 Phasor Representation

Phasor representation allows any sinusoidal forcing function to be represented as a phasor in a complex coordinate system in the manner shown in figure 4.2. The expression for the phasor representation of a sinusoid may assume any of the following shorthand forms:

Exponential: $Ee^{j\Phi}$

Rectangular: $E(\cos\Phi + j\sin\Phi)$

Polar: E/Φ

These three forms are related as shown below.

$$Ee^{j\Phi} = E(\cos\Phi + j\sin\Phi) = E\angle\Phi$$

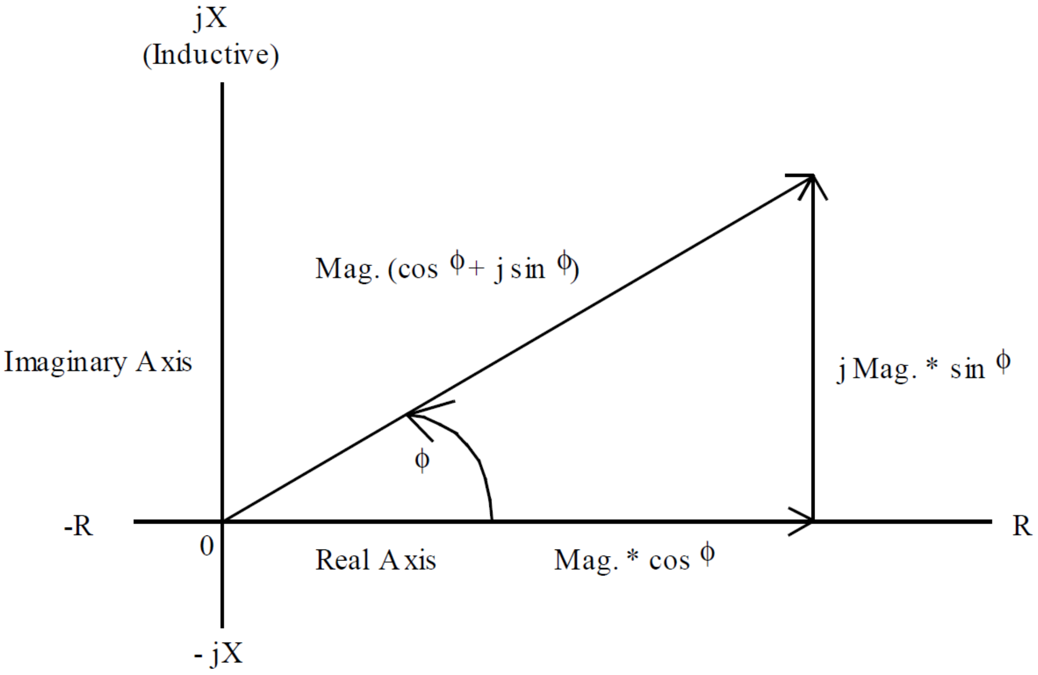


Figure 4.2 Phasor Representation

The network impedances can be represented as phasors using vectorial relationships and the circuit current responses can be obtained through the simple vector algebraic manipulation of the quantities involved. The need for solving complex differential equations in order to determine the steady-state circuit response is completely eliminated.

4.1.9 Fourier Representation

This tool allows any non-sinusoidal periodic function to be represented as the sum of a dc component and a series (infinitely long, if necessary) of ac sinusoidal functions. The ac components have frequencies that are an integral “harmonic” of the fundamental frequency. The general mathematical form of the so-called “Fourier Series” is given below

$$f(t) = F_0 + \sum_{n=1}^{\infty} \sqrt{2}\,F_n \cos(n2\pi f_0 t + \theta_n)$$

Where F_0 is a dc term, F_1 is a fundamental frequency term, and F_n are called "harmonics" of the fundamental and have frequency of n2π f_0. Each harmonic may have some nonzero phase angle θ_N.

The importance of the Fourier representation is that the response to the original driving function can be determined by first appropriately solving for each harmonic component driving function and then summing all the individual solutions to find the total response by superposition. Because each of the component response solutions is readily obtained, the most difficult part of the problem becomes the modification of reactance and capacitance of the network for each harmonic and the solution of the component driving function. The individual harmonic voltages can be obtained in combination with numerical integration approximating techniques through several well-established mathematical procedures.

4.1.10 Equivalence

The Equivalence Theorem states that at any given frequency, any passive four-terminal network can be replaced by an equivalent star or delta network. This fact is very useful in short-circuit calculations to reduce a system consisting of many current loops and voltage nodes to a simple equivalent circuit.

- Star-Delta Transformation

$$Z_A = Z_b + Z_c + \frac{Z_b\,Z_c}{Z_a} = \frac{Z_a\,Z_b + Z_b\,Z_c + Z_c\,Z_a}{Z_a}$$

$$Z_B = Z_a + Z_c + \frac{Z_a\,Z_c}{Z_b} = \frac{Z_a\,Z_b + Z_b\,Z_c + Z_c\,Z_a}{Z_b}$$

$$Z_C = Z_a + Z_b + \frac{Z_a\,Z_b}{Z_c} = \frac{Z_a\,Z_b + Z_b\,Z_c + Z_c\,Z_a}{Z_c}$$

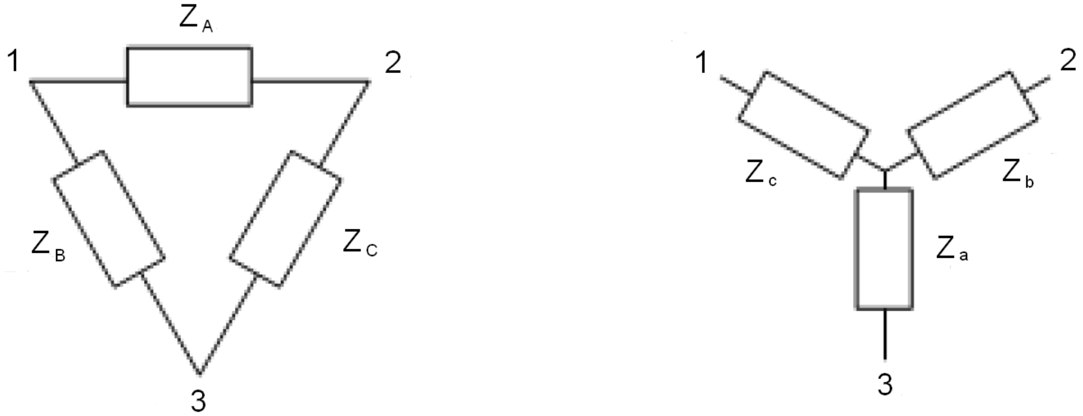


Figure 4.3 Star-Delta Impedance Representation

- Delta-Star Transformation

$$Z_a = \frac{Z_B \, Z_C}{Z_A + \, Z_B + \, Z_C}$$

$$Z_b = \frac{Z_A \, Z_C}{Z_A + \, Z_B + \, Z_C}$$

$$Z_c = \frac{Z_A \, Z_C}{Z_A + \, Z_B + \, Z_C}$$

4.1.11 Parallel Impedances

When two or more impedances are paralleled as shown in figure 4.4, then the equivalent impedance Z_{eq} can be calculated using the formula given below

$$Z_{eq} = \frac{1}{\frac{1}{Z_a} + \frac{1}{Z_b} + \frac{1}{Z_c} + \frac{1}{Z_d} + \ldots}$$

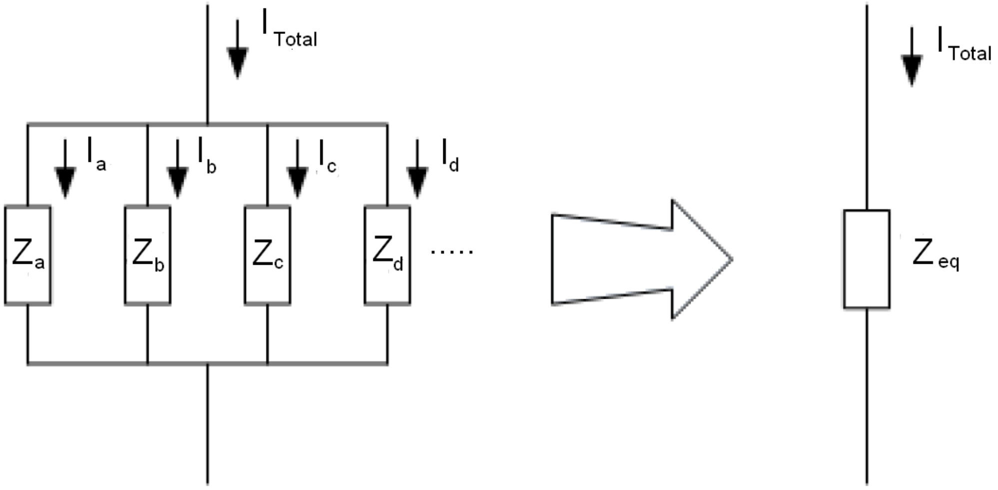


Figure 4.4 Parallel Impedance Representation

4.2 Application of Symmetrical Components

An unbalanced fault condition is the most common circuit condition that invalidates the single-phase (or positive sequence) equivalent circuit condition methods for calculating short-circuit current. The use of symmetrical components is the analytical technique most commonly used under these circumstances. Unbalanced faults, such as line-to-ground faults, line-to-line faults, and double line-to-ground faults require the use of symmetrical components for the calculation of the short-circuit currents. Symmetrical components are used to reduce an unbalanced system of phasors into three balanced systems of phasors designated as positive, negative, and zero sequence components. Figure 4.5 is an illustration of the system of symmetrical components. The subscripts A, B, and C represent the three phases of voltage and the subscripts 1, 2, and 0 represent the positive, negative, and zero sequence components.

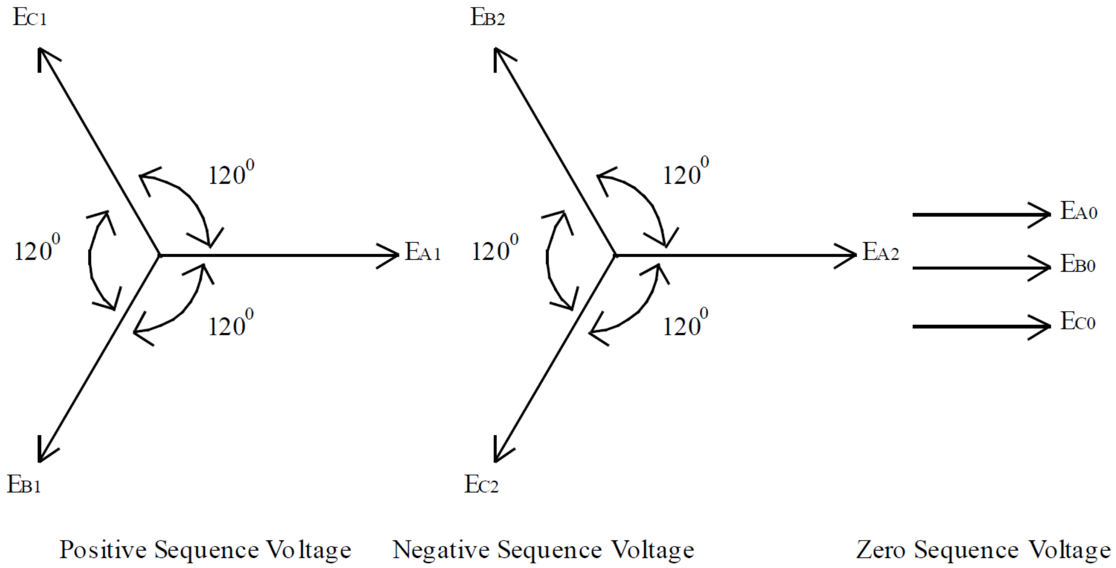


Figure 4.5 Symmetrical Component Representation

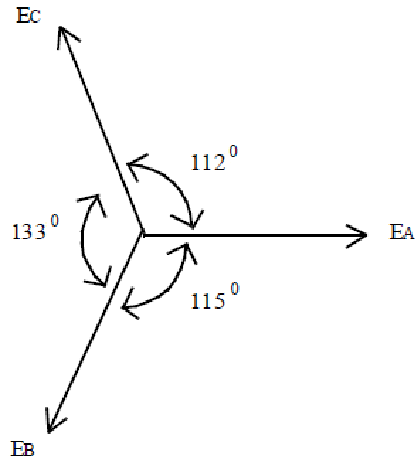
Any three-phase set of unbalanced voltage phasors (or current phasors) can be resolved into three balanced or symmetrical sets of phasors, i.e., positive sequence symmetrical components, negative sequence symmetrical components, and zero sequence components, as shown in figure 4.6.

Symmetrical component techniques allow the user to solve for voltages and currents in balanced sequence networks, and then convert the solution back to actual currents and voltages. The relationship between the phase quantities in terms of their symmetrical components is given below. Values of current can be substituted in place of the voltage in the equation without any conversion factors. The equations are normally given as a set of three to represent the individual phases are given below

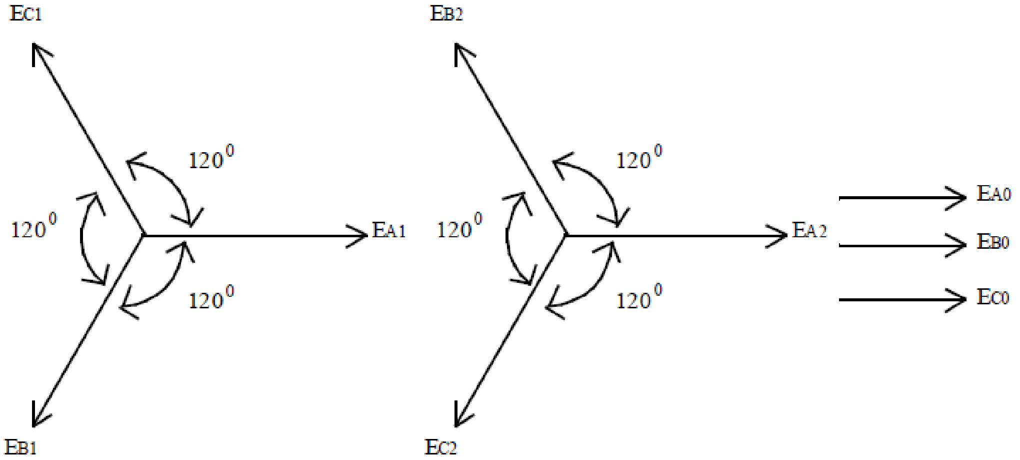
$E_a = E_{a0} + E_{a1} + E_{a2} = E_{a0} + E_{a1} + E_{a2}$

$E_b = E_{b0} + E_{b1} + E_{b2} = E_{a0} + E_{a1}\angle 240 + E_{a2}\angle 120$

$E_c = E_{c0} + E_{c1} + E_{c2} = E_{a0} + E_{a1}\angle 120 + E_{a2}\angle 240$



Unbalanced set of three phase voltages



Positive Sequence Voltage Negative Sequence Voltage Zero Sequence Voltage

Figure 4.6 Symmetrical Component of Unbalanced Phasors

When using symmetrical components it is convenient to define an operator “a” such that:

$$a = 1\angle 120 = -0.5 + j0.866$$

$$a^2 = 1\angle 240 = -0.5 - j0.866$$

Note that vector “a” is an operator with unit length and is oriented 120 degrees in counterclockwise rotation from reference axis. Figure 4.7 shows the property of a_0, a_1, and a_2 and so on.

Using the operator “a” we can rewrite the voltage equation as given below

$E_a = E_{a0} + E_{a1} + E_{a2}$

$E_b = E_{a0} + a^2Ea1 + aE_{a2}$

$E_c = E_{a0} + aE_{a1} + a^2E_{a2}$

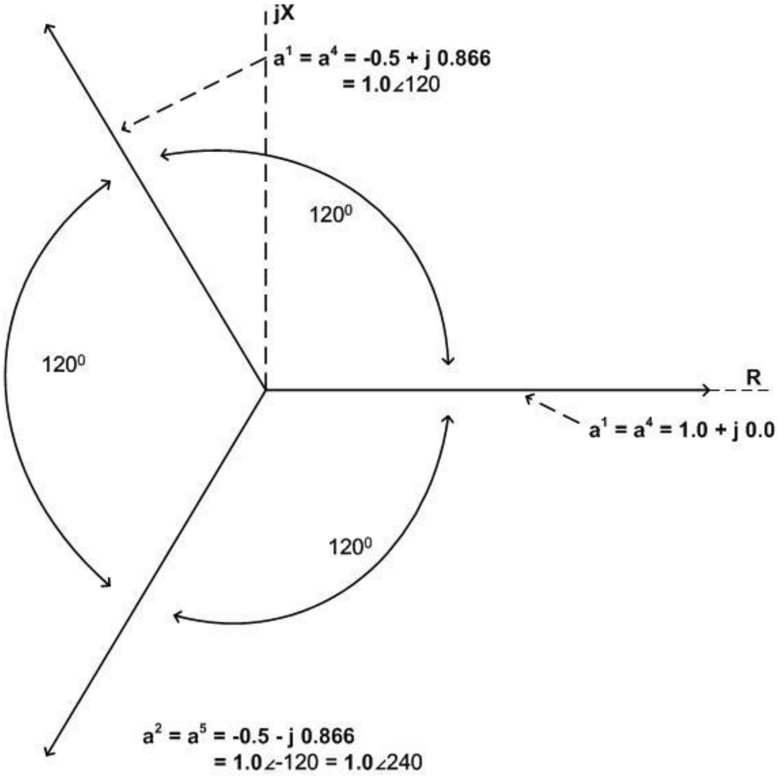


Figure 4.7 Operator “a” Representation

It could be represented in matrix form as give below

$$\begin{matrix} E_A \\ E_B \\ E_C \end{matrix} = \begin{matrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{matrix} \quad \begin{matrix} E_{a0} \\ E_{a1} \\ E_{a2} \end{matrix}$$

Similarly the sequence components can be determined from the phase quantities as defined below

$$\begin{matrix} E_{a0} \\ E_{a1} \\ E_{a2} \end{matrix} = \frac{1}{3} \begin{matrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{matrix} \begin{matrix} E_A \\ E_B \\ E_C \end{matrix}$$

The equations above were written for the sequence voltages. A similar set of equations can be written for the sequence current by interchanging the voltage symbol for a current symbol. Note that if the zero sequence quantity, I_{a0} (or V_{a0}), equals zero then the vector sum of $I_A + I_B + I_C$ (or $V_A + V_B + V_C$) equals zero.

In a grounded power system, the zero sequence impedance completes the circuit by allowing the current to flow in the system neutral or in ground. The magnitude of current in the return path is $3I_{a0}$. Where $3I_{a0} = I_n = I_a + I_b + I_c$. When $3I_{a0} = 0 = I_a + I_b + I_c$, no current flows in the neutral. Note that a three-phase three-wire (ungrounded) system will require $I_{a0}=0$ because no neutral (or return) path exists for current flow.

It is interesting to note that the delta winding of a delta-wye or wye-delta connected transformer or delta connected loads provide no current path to neutral and no zero sequence currents will exist in delta connected systems. However, it can be shown that zero sequence circulating currents can exist in the delta winding of a transformer but not pass through the transformer. The typical representation of a delta-delta transformer is shown in figure 4.8. Zero sequence components in one phase is always in phase with zero sequence components of other two phases as a result they do not cancel out but instead appear in the neutral conductor of the circuit. Since the delta winding of the transformer does not have any neutral path the zero sequence impedance of the delta winding appears to be infinite. As a result the delta winding does not draw zero sequence current from the lines. But the presence of voltage unbalance in the lines causes the zero sequence current to appear in the limbs of the delta winding and since they do not have path to flow they create a circulating current within the delta winding of the transformer.

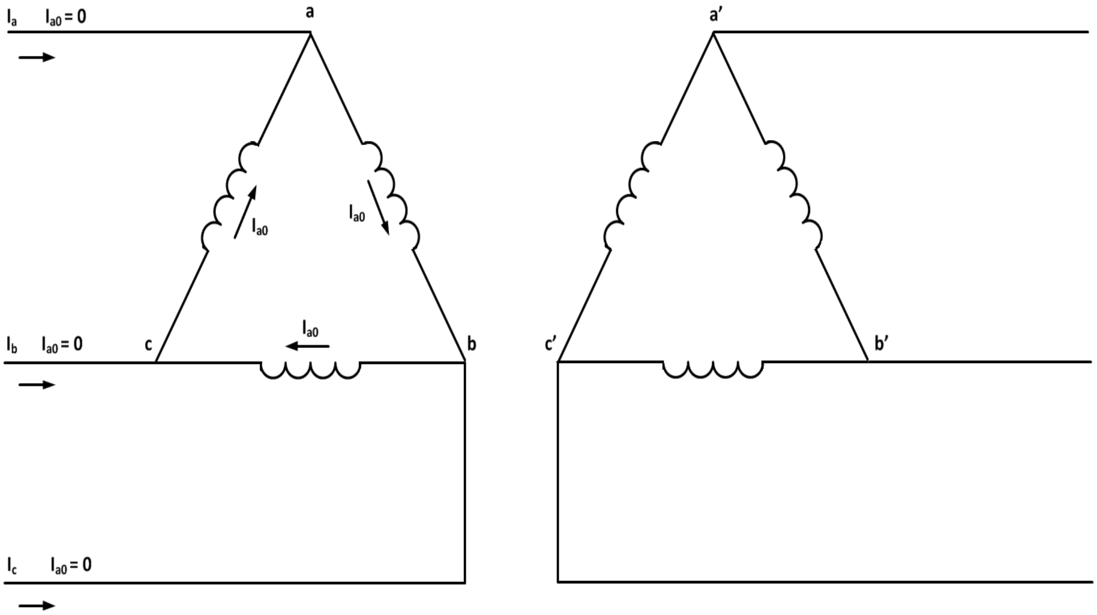


Figure 4.8 Delta-Delta Transformer With Circulating Zero Sequence Currents

4.2.1 Connection of Sequence Networks

The connections of the sequence networks for three-phase, line-to-ground, line-to-line, and double line-to-ground faults are given in figure 4.9, figure 4.10, figure 4.11, and figure 4.12. The diagrams show the direction and location of the sequence currents and the sequence voltages. It is important to recognize the defined positive directions for current flow and voltage polarity. Attention to the defined convention is necessary so that the correct phase values can be obtained from the sequence values.

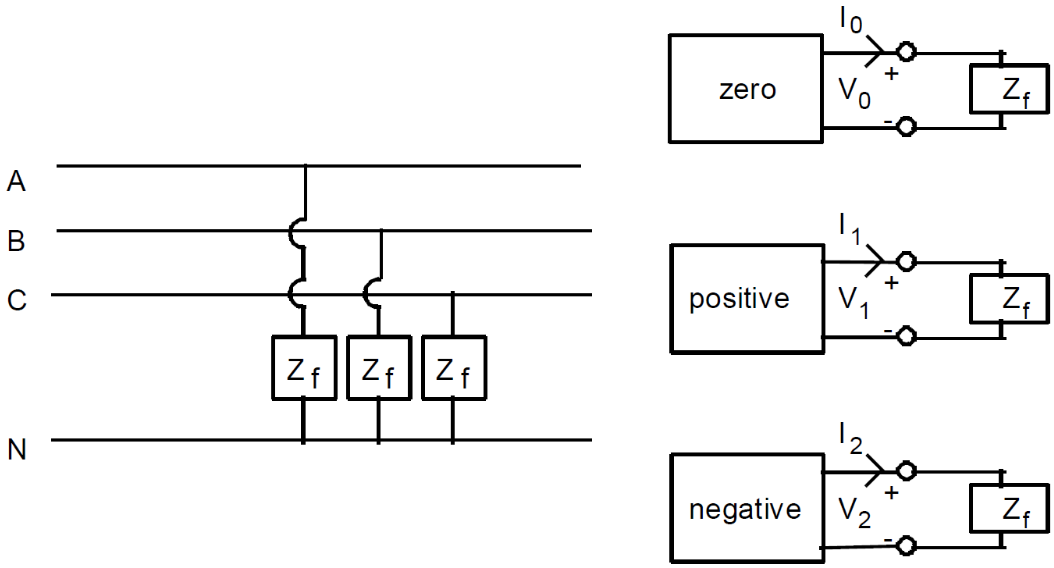


Figure 4.9 Sequence Network for Three Phase Fault

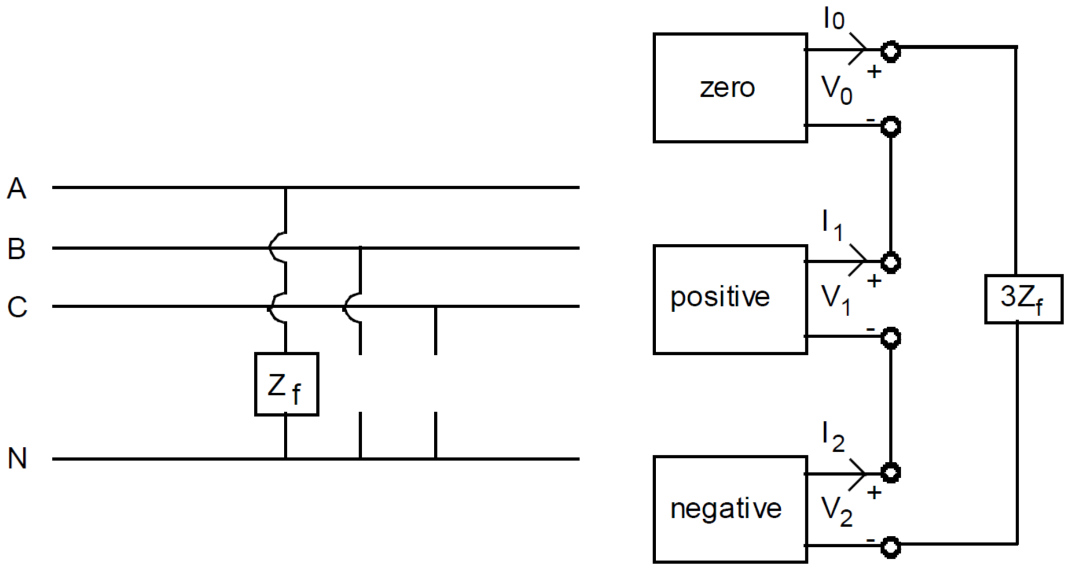


Figure 4.10 Sequence Network for Line-to-Ground Fault

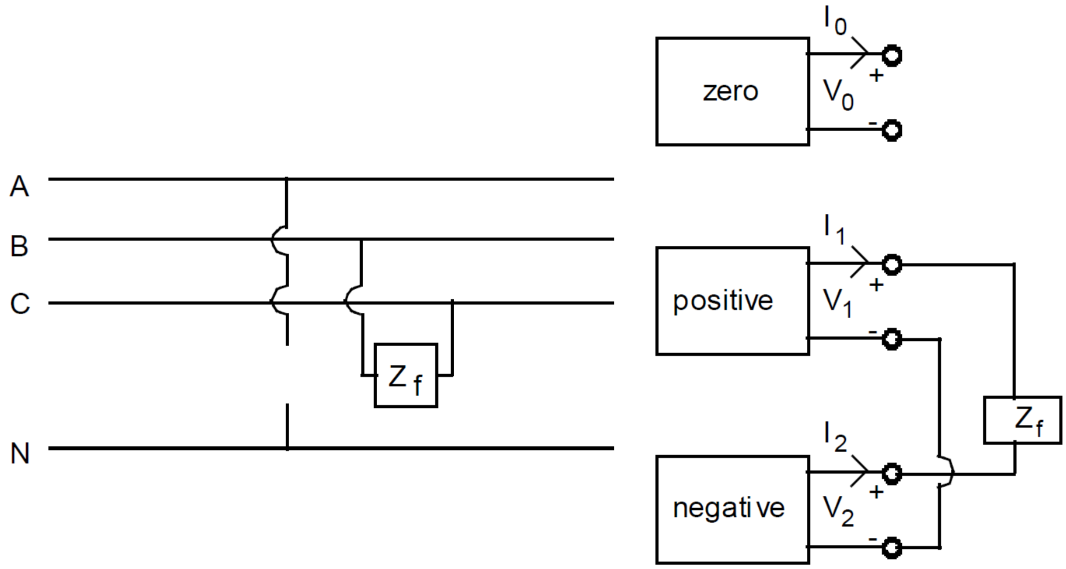


Figure 4.11 Sequence Network for Line-to-Line Fault

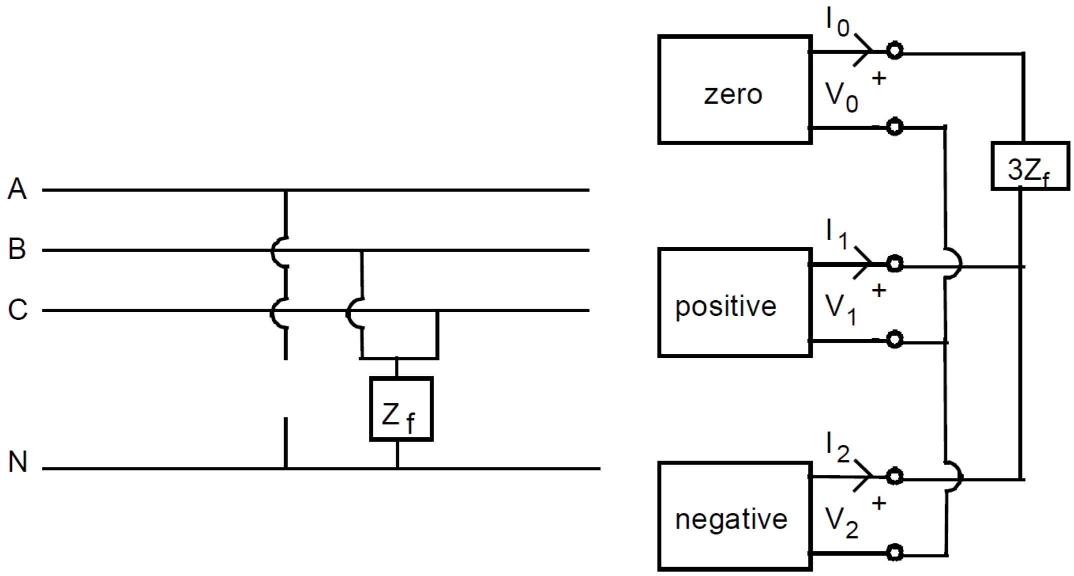


Figure 4.12 Sequence Network for Line-to-Line-to-Ground Fault

4.2.2 Procedure to Calculate Fault Currents

Some of the most important items in an unbalanced fault calculation are the sequence component one-line diagrams and the connection of the sequence networks for different types of faults. The negative sequence diagram is basically the positive sequence diagram with no voltage source(s) and with some impedances of the synchronous machine being changed.

Often the assumption that the negative sequence impedances are the same as the positive sequence impedances is used. This is a fairly good assumption except for rotating machines where the negative sequence impedance is constant and the positive sequence impedance changes with the time period being studied (to account for ac decay). For first cycle calculations, the negative sequence impedance and positive sequence impedance are similar in magnitude.

The zero sequence diagram is more complex and the impedances may not be as readily available. The type of grounding on generators and transformers must be included in the zero sequence diagrams. Transformer winding configurations, manner of grounding, and zero sequence impedances are important and have to be correctly represented or the results will be meaningless.

The steps in performing an unbalanced fault calculation are as follows:

- Obtain sequence impedances on the apparatus such as generators, motors, and transformers and circuits such as cables, duct, and lines
- Convert impedances to a per-unit value on a common VA base
- Construct each of the three sequence impedance networks for the electrical system that is under study
- Reduce the sequence networks to simplify calculations (as appropriate)
- Connect the sequence network for the type of fault desired
- Calculate the sequence currents
- Calculate the fault and line currents

For most short circuit current magnitude calculations at medium and high voltage and for few low voltages, when the reactance is much larger than the resistance, it is sufficiently accurate, conservative and simpler to ignore resistance and use reactance alone. Usually system nominal voltage at the point of short circuit is considered as this will generate the maximum possible short-circuits currents. Certain cases use higher than nominal voltage when the full load system voltage is observed to be above nominal.

The size and complexity of modern industrial power system make longhand short-circuit calculations impractically time consuming. Computers are generally used to perform major short circuit studies. Initially iterative methods similar to load flow analysis were used to perform short circuit studies. The development of a fast method of assembling Z-bus (driving point and transfer impedance) matrix and use of matrix axis discarding technique assisted in the development of easy and efficient algorithms to perform short circuit studies. Most of the commercial software packages make use of this technique to perform short-circuits studies.

CHAPTER 5

VALIDATION OF CIRCUIT BREAKER INTERRUPTING CAPABILITY

The validation of the circuit breaker interrupting capability through short circuit analysis would be explained using IEEE 13 Bus Industrial Bus System.

5.1 IEEE 13 Bus Industrial System

Figure 5.1 gives a pictorial representation of IEEE 13 Bus Industrial System

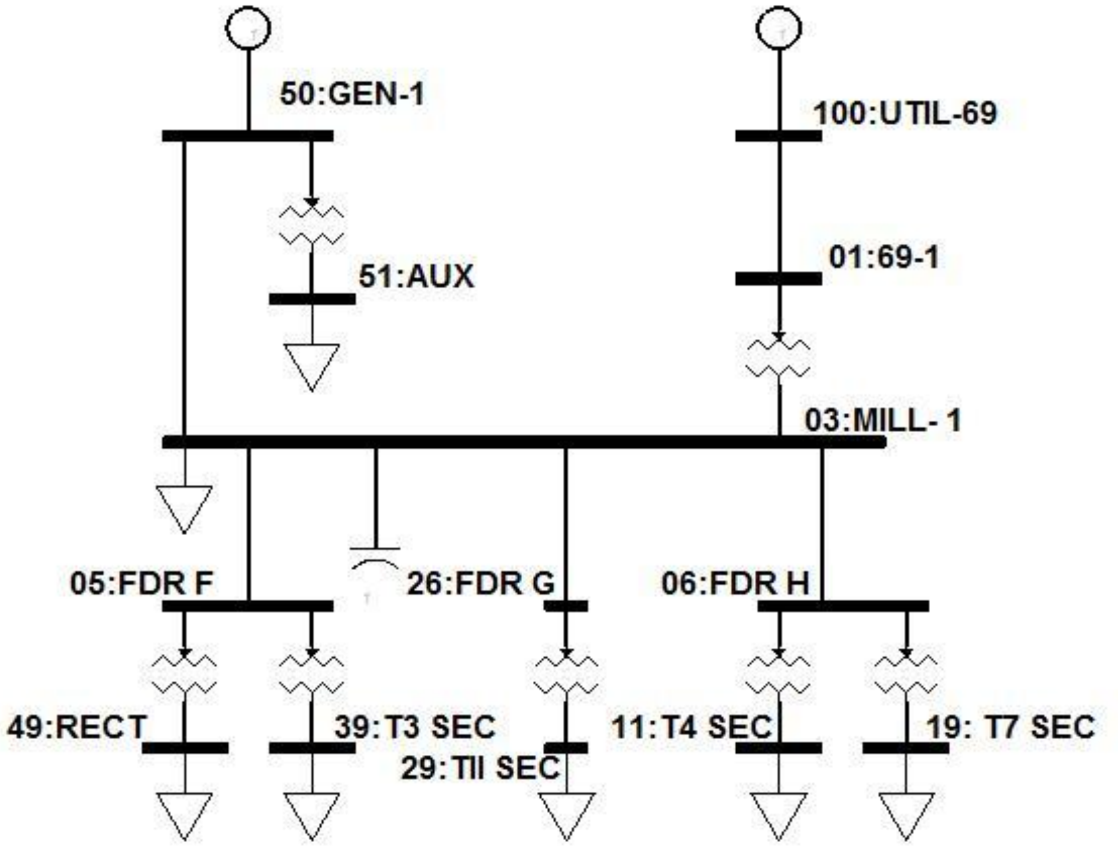


Figure 5.1 IEEE 13 Bus Industrial Distribution System

The data for the system is given in the tables below.

Table 5.1 Per-Unit Line and Cable Impedance Data (base values: 13.8 kV, 10,000 kVA)

From	To	R	X
100: UTIL-69	01:69-1	0.00139	0.00296
03:MILL-1	50:GEN-1	0.00122	0.00243
03:MILL-1	05:FDR F	0.00075	0.00063
03:MILL-1	26:FDR G	0.00157	0.00131
03:MILL-1	06:FDR H	0.00109	0.00091

Table 5.2 Transformer Data

From	To	Voltage	Tap	KVA	%R	%X
01:69-1	03:MILL-1	69:13.8	69	15000	0.4698	7.9862
50:GEN1	51:AUX	13.8:0.48	13.45	1500	0.9593	5.6694
05:FDR F	49:RECT	13.8:0.48	13.45	1250	0.7398	4.4388
05:FDR F	39:T3 SEC	13.8:4.16	13.11	1725	0.7442	5.9537
26:FDR G	29:T11 SEC	13.8:0.48	13.45	1500	0.8743	5.6831
06:FDR H	11:T4 SEC	13.8:0.48	13.8	1500	0.8363	5.4360
06:FDR H	19:T7 SEC	13.8:2.4	13.11	3750	0.4568	5.4810

Table 5.3 Generation, Load, and Bus Voltage Data (from power flow study results)

Bus	V_{mag} (p.u)	δ (deg)	P_{gen} kW	Q_{gen} kvar	P_{load} kW	Q_{load} kvar
100:UTIL-69	1.000	0.00	7450	540	-	-
01:69-1	0.999	-0.13	-	-	-	-
03:MILL-1	0.994	-2.40	-	-	2240	2000
50:GEN1	0.995	-2.39	2000	1910	-	-
51:AUX	0.995	-3.53	-	-	600	530
05:FDR F	0.994	-2.40	-	-	-	-
49:RECT	0.980	-4.72	-	-	1150	290
39:T3 SEC	0.996	-4.85	-	-	1310	1130
26:FDR G	0.994	-2.40	-	-	-	-
06:FDR H	0.994	-2.40	-	-	-	-
11:T4 SEC	0.979	-3.08	-	-	370	330
19:T7 SEC	1.001	-4.69	-	-	2800	2500
29:T11 SEC	0.981	-4.16	-	-	810	800

The IEEE system consists of 13 buses and is representative of a medium-sized industrial plant. The plant is fed from a utility supply at 69 kV and the local plant distribution system operates at 13.8 kV. The utility connection is simulated using two generators connected at buses 50:GEN-1 and 100:UTIL-69 with 2 MW and 7.45 MW capacity respectively. The auxiliary transformer is connected between 50:GEN-1 and 50:Aux busses and the auxiliary load is connected to 50:Aux bus. A 13.8 kV load is connected to the 03:MILL-1 bus which also has a capacitor bank attached to it. The system also has 5 loads connected at various low voltage levels. It does not have any in-plant generating units. Under normal operating condition the voltage at all the buses is close to 1 p.u as a result of which we would consider 1 p.u. to perform the short circuit analysis under worst case condition.

5.2 Circuit Breaker Interrupting Capability Calculation

The circuit breaker interrupting capability is the maximum short circuit current that they can safely interrupt. If the breaker circuit is applied with short-circuit current higher than the interrupting capability, it may result in failure of the breaker to safely interrupt the fault. As a result of this, the precise calculation of maximum short circuit current becomes very important process in the selection of the circuit breaker.

The power system analysis software Seimens PTI PSS/E was utilized to perform the analysis. The simulation software performs the short circuit analysis on ANSI or IEC standards based on the user selection. The short-circuit analysis module allows the user to analyze the system for various types of faults. It generates a report for each analysis, which can be reviewed to infer the required results. The software allows the user to work with Graphical interface based on one line diagram. The analysis can be run and the results can be reviewed from the graphical interface shown in figure 5.2.

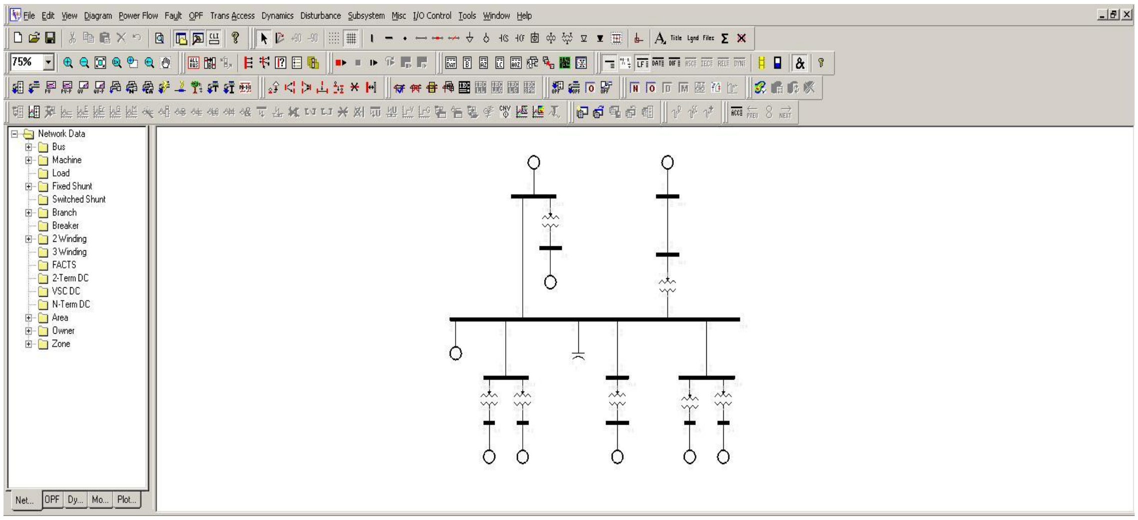


Figure 5.2 PSSE Graphical User Interface

The procedure used to calculate the maximum short-circuit current is as given below

- Prepare the system data by first modeling the entire rotating machine loads as generators with impedance.
- Convert all the equipment impedances to common base as used for conducting the study (This thesis uses 100 MVA base).
- Input the data and simulate the short circuit at the bus near to the Circuit Breaker for which the maximum current needs to be calculated.
- The fault current calculated at the bus of concern is taken as the magnitude of the fault current when the fault occurs next to the Circuit breaker.
- Now by applying KCL on the fault current and the branch contributions, the maximum short circuit current can be calculated.

Note: The maximum short-circuit current calculated in the above procedure of using KCL can sometimes give lesser value than the fault contribution to the circuit breaker from the branch. So always the calculated current needs to be compared with the branch current contribution to select the maximum short-circuit current.

Table 5.4 lists the results of the short circuit study performed using the IEEE 13 bus test system. It can be seen that the at some circuit breaker locations the maximum short circuit current using the branch currents is high and at other locations the current calculated using the procedure explained above gives a higher value. It can be seen that in larger systems with more redundant design each bus would have more branches and the location where the normal calculation provides higher values is reduced. But always a comparative study is useful in determining the maximum short circuit current for a circuit breaker as this would assist in determining the rating with more accuracy.

Table 5.4 Short Circuit Current at Various Circuit Breaker Locations

Bus Name	CB Location	Branch Current	New Procedure
100:UTIL-69	System Connection	61.92	117.42
	System Distribution Line	117.42	61.92
01:69-1	System Distribution Line	61.91	117.46
	Distribution Transformer HV Side	117.47	61.9
03 :MILL- 1	Distribution Transformer LV Side	298	630
	In-plant Distribution Line	159.57	768.43
50:GEN-1	Generator Side	125	803.6
	In-plant Distribution Line	769	159.6
	Auxiliary Transformer HV Side	34	894.6
51 :AUX	Auxiliary Transformer LV Side	14050	962
05:FDR F	49:RECT Transformer HV Side	51.95	876.86
	39:T3 SEC Transformer HV Side	72.31	856.5
49:RECT	49:RECT Transformer LV Side	23852	1426
39:T3 SEC	9:T3 SEC Transformer LV Side	2808	240
26:FDR G	9:T11 SEC Transformer HV Side	49.85	876.83
06:FDR H	11:T4 SEC Transformer HV Side	21.36	907.43
	19: T7 SEC Transformer HV Side	149.51	779.28
11:T4 SEC	11:T4 SEC Transformer LV Side	12135.66	596.6
19: T7 SEC	19: T7 SEC Transformer LV Side	3582.96	903.07
29:T11 SEC	29:T11 SEC Transformer LV Side	23843.51	1368.8

Let's consider the Bus 03:MILL1, which is connected to the bus 01:69-1 on the upstream through a transformer and to the bus 06:FDR H on the downstream. For a circuit breaker placed on the LV side of the transformer close to bus 03:MILL1 the largest value branch current is 298 A and for a circuit breaker placed on the in-plant distribution line close to the bus 03:MILL1 the largest value of branch current is 159.7 A, but when the short circuit current is calculated using the procedure explained above the value of currents are 630 and 768.43 A respectively. This is due to the fact that the short circuit current for the upstream circuit breaker calculated using the above procedure would take into account the contribution from 50:GEN 1 and the load buses 05:FDR F, 26:FDR G and 06:FDR H. Similarly circuit breaker connected close to bus 50:GENL on the in-plant distribution line between buses 50:GENL and 03:MILL1, the branch current is 769 A but the current calculated by the above procedure is 159.6 A, this variation is due to the fact that the procedure considers fault next to circuit breaker and in effect cancels the downstream contribution which is considered in the branch current.

CHAPTER 6

CONCLUSION

A method for validation of the interrupting capability of the circuit breaker through short-circuit analysis is presented in this thesis. Its procedure has been explained by using an IEEE 13 Bus Industrial Distribution System. The validation makes use of the basic network concept of Kirchoff's Current Law to determine the exact current at any point. It should be noted that usual technique of determining the branch currents which are used in commercial software is not completely avoided instead the explained technique makes use of the result obtained from the usual short circuit studies and extends it to applying KCL to the existing network and determines more precisely the current seen by the circuit breaker. The values obtained from the method are always compared with the branch currents which ensure that the maximum current seen by the circuit breaker is obtained from the study.

Once a precise value of the short circuit current is obtained from this procedure, it allows the engineer to design new plant as well as plan expansion of existing power plants with greater degree of accuracy. It also gives the engineer a better idea for planning future loads in the system. This method would allow engineer to reduce the cost of the protective equipment and cost of design.

In future, an extension to the current study would be to evaluate the feasibility to use a similar technique in commercial distribution system protection design. And also to create a program that would use the procedure explained on the usual short-circuit results to determine the maximum short circuit current.

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BIOGRAPHICAL INFORMATION

Vijayanand Appanaickenpatti Ramachandran received his Bachelor’s degree in Electrical and Electronics Engineering from ANNA University Chennai India in 2005 and his Master’s degree in Electrical Engineering from the University of Texas At Arlington in 2011. Prior to his master’s program he worked with Infosys Technologies Limited from 2005 to 2009. He is currently working with AES Corporation, a company focused with power generation and distribution with power plants spread around the world, with his interests in transformer design, testing, SCADA and optimal power flow.