



PDHonline Course E204 (4 PDH)

Introduction to Short Circuit Analysis

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Course Content

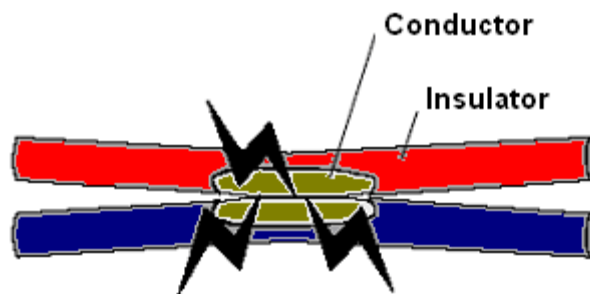
A short circuit is a low-resistance connection established by accident or intention between two points in an electric circuit. This excessive electric current potentially causes circuit damage, overheating, magnetic stress, arcing, fire or explosion. The amount of current that is available in a short circuit is determined by the capacity of the system voltage sources and the impedances of the system, including the fault.

In circuit analysis, the term *short circuit* is used by analogy to designate a zero-impedance connection between two nodes. This forces the two nodes to be at the same voltage. In an ideal short circuit, this means there is no resistance and no voltage drop across the short. The electrical opposite of a *short circuit* is an open circuit, which is infinite resistance between two nodes.

What causes a short circuit?

Several scenarios can lead to a short circuit;

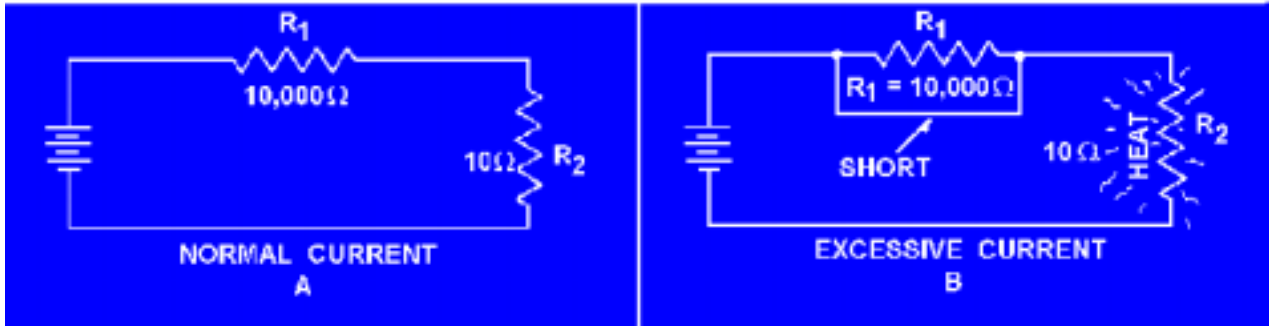
#1: When two bare conductors touch, a short circuit occurs. In figure below, a short is caused due to broken insulation.



Another type of short circuit occurs when some conductive object such as tool or an animal, accidentally gets into an overhead power line. If the object touches both the lines at the same time, the electricity has a short circuit path available to return to the source before it goes to the customer's electric service. If the object is connected to the ground, the earth can act as a short circuit path.

#2: In the figure below, a short is caused by improper wiring. Note the effect on current flow. Since the resistor has in effect been replaced with a piece of wire, practically all the current flows through the short and very little current flows through the resistor. Electrons flow through the short (a path of almost zero resistance) and the remainder of the circuit by passing through the 10-ohm resistor and the battery. The amount of current flow increases greatly because its resistive path has decreased from 10,000 ohms to 10 ohms. Due to the excessive current flow the 10-ohm resistor becomes heated. As it attempts to dissipate

this heat, the resistor will probably be destroyed.



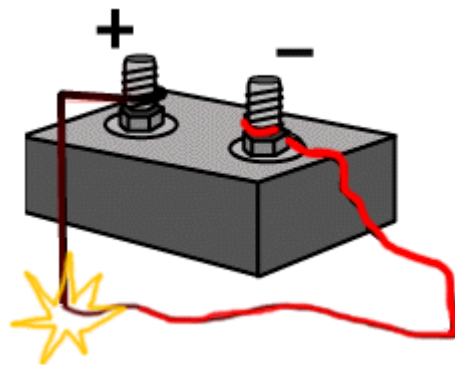
Normal and short circuit conditions

It might happen that electricians may have connected temporary grounds or other conductors between phases/neutral and/or ground for safety purposes during installation and testing. If these temporary conductors are unintentionally left connected when the circuit is energized, a short circuit results, producing what's called a "bolted fault".

Workers who take voltage measurements or perform other work on energized equipment can also unintentionally bridge or short-out conductors in the equipment, creating a short circuit. Short circuits have occurred when someone placed a wrench across the switchboard bus bars accidentally.

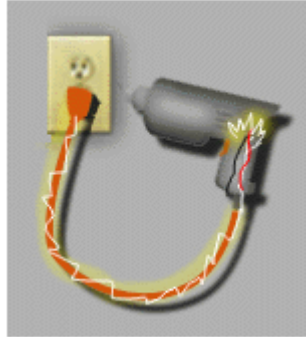
It might happen that water leak or some other form of contamination creates a conductive path between phases/neutral and/or ground. The air insulation will break down and produce a short circuit arc.

#3: In the figure below, a short circuit is caused by connecting a wire to the positive and negative terminals of a battery. With low resistance in the connection, a high current flows, causing the cell to deliver a large amount of energy in a short time.



Caution: Actually performing this experiment could result in the rapid buildup of heat, damage to the wire or cell, a release of toxic fumes, and/or an explosion of the battery possibly resulting in fire and/or personal injury. Do not attempt this.

#4: Short circuit can occur due to faulty wiring in the appliance. In the picture below, the source is the outlet, the path is an extension cord and the load is the drill. If the wire inside the drill comes loose and touches the other wire, a new path exists where the current can return to the source without going through a load the drill motor.



What are common types of short circuits?

There are several types of short circuits: a bolted fault, arcing faults and ground faults:

Bolted Fault: A bolted fault is a short circuit of very high magnitude characterized by all three phases “bolted” together to create a zero impedance connection. Normally, short circuit calculations are performed on a bolted 3-phase fault condition because this establishes a “highest current” condition.

Arcing Fault: An arcing fault results from a gap between two electrodes (such as loose wire on a terminal block). Arc welding is a common example of the practical application of the heating due to arcing. The power supply for an arc welder can supply very high currents that flow through the welding rod and the metal pieces being welded. The point of contact between the rod and the metal surfaces gets heated to the melting point, fusing a part of the rod and both surfaces into a single piece.

Ground Fault: Ground faults normally occur either by accidental contact of an energized conductor with normally grounded metal, or as a result of an insulation failure of an energized conductor. The residual current devices (RCD's) often known by other names, e.g., earth leakage circuit breakers (ELCB) detect a very much lower level of electricity flowing to earth and immediately switch the electricity off. Normal protective devices such as fuses and circuit breakers do not offer the same level of personal protection against faults involving current flow to earth.

Why is a short circuit dangerous?

A short circuit always involves the flow of uncontrolled current that isn't restrained by the normal load resistance. When a short circuit occurs, resistance of a circuit or the resistance of a part of a circuit drops in

value to almost zero ohms. Ohm's Law demonstrates the relationship of current, voltage, and resistance. For example, a 240 volt motor with 24 ohms of resistance would normally draw 10 amps of current.

$$I = V / Z$$

$$I = 240 / 24$$

$$I = 10 \text{ amps}$$

When a short circuit develops, resistance drops almost to zero. Say if resistance drops to 24 milliohms, current will be 10,000 amps.

$$I = 240 / 0.024$$

$$I = 10,000 \text{ amps}$$

This increased flow of current quickly heats the conductors and equipment, since heating is a function of current squared.

Potential Hazards

One of the major hazards of short circuit is "Arc Flash" which is established when current begins passing through ionized air. Large volumes of ionized gases, along with metal from the vaporized conductors, are rapidly expelled. As the arc runs its course, electrical energy continues to be converted into extremely hazardous forms of energy. All of these events usually occur in less than 0.2 seconds. The potential affects are:

- 1) **Intense Heat:** The electrical current flowing through the ionized air creates tremendously high levels of heat energy. This heat is transferred to the plasma, which rapidly expands away from the source of supply.
Tests have shown that heat densities at typical working distances can exceed 40cal/cm² and the temperatures can exceed 20,000°F. At typical arc fault durations of less than one second, a heat density of only 1.2cal/cm² on exposed flesh is enough to cause a second-degree burn.
- 2) **Thermo-acoustic Shock Wave:** As the conductive element that caused the arc is vaporized; the power delivered to the arc fault rises rapidly. This corresponds to a rapid rise in surrounding pressure. The resultant shock wave can create impulse sound levels well beyond OSHA's allowable limits. Forces from the pressure wave can rupture ear drums, collapse lungs or cause fatal injuries.
- 3) **Molten Metal:** At high fault current levels, plasma jets are formed at the electrodes. Vaporized and molten electrode material is ejected at high velocity from these jets, reaching distances of several feet away. Since the molten metal is typically over 1000° C, it's a potential ignition source for conventional clothing. As copper vaporizes, it expands by a factor of about 67,000. This rapid expansion will result in near-explosive forces on any nearby equipment or workers. The force of the explosion also causes a

significant amount of shrapnel to be accelerated away from the source. These particles can impact a nearby worker at high velocity, resulting in physical trauma.

- 4) **Blinding Light:** As the arc is established, an extremely bright flash of light occurs. The light can cause immediate vision damage and increase the potential for future vision deterioration.
- 5) **Toxic Smoke:** Also expelled into the atmosphere are toxic combustion byproducts and copper oxides formed when the cooling copper vapor combines with oxygen.
- 6) **Contact with Energized Components:** The explosive nature of an arc fault increases the possibility that an energized conductor or components will make contact with workers in the area.

Because of the intense heat and destruction produced by an uncontrolled electrical arc, it's important to de-energize the circuit as quickly as possible after a short circuit.

OSHA is using the requirements of NFPA 70E, the industry's consensus standard for electrical safety, to judge whether the employer "acted reasonably" in protecting its workers from arc flash hazards. In many cases, this has resulted in employers facing substantial fines after arc flash events. OSHA 29 CFR Part 1910 contains many other sections that pertain to electrical safety and arc flash hazards.



Why do you need Short Circuit Study?

The primary objective of short circuit study is to provide necessary over current protection devices in the distribution system that will prevent injury to personnel, minimize damage to system components, and limit the extent and duration of service interruptions during equipment failures, overload or short circuit conditions. It is important to estimate or calculate the value of prospective current likely to occur under short circuit conditions and ensure that the protective devices provided to interrupt that current are rated to withstand and interrupt it.

Because the short circuit calculations are life-safety related, they're mandated by 110.9 of the National Electrical Code which states that "Equipment intended to interrupt current at fault levels shall have an interrupting rating sufficient for the nominal circuit voltage and the current that is available at the line

terminals of the equipment. Equipment intended to interrupt current at other than fault levels shall have an interrupting rating at nominal circuit voltage sufficient for the current that must be interrupted”.

Article 240 of the National Electric code provides the general requirements for overcurrent protection. Parts I through VII are for protective devices not more than 600 volts nominal. Part VIII is for supervised industrial applications operating at less than 600 volts and part IX is for overcurrent protection greater than 600 volts, nominal. Several other sections of the National Electrical Code relate to proper overcurrent protection.

These sections include, among others:

- 110-9 Interrupting Rating
- 110-10 Component Protection
- 230-65 Service Entrance Equipment
- 240-1 Conductor Protection
- 250-95 Equipment Grounding Conductor Protection
- 517-17 Health Care Facilities - Selective Coordination

Compliance with these code sections can best be accomplished by conducting a short circuit study and a selective coordination study. Once the short circuit levels are determined, the engineer can specify proper interrupting rating requirements, selectively coordinate the system and provide component protection.

What is Coordination of protective devices?

The diagram of a simple electrical system resembles a tree-like configuration. The main power source corresponds to the tree trunk, and the primary feeder circuits and branch circuits correspond to large and small tree branches. To minimize damage and the extent of the power outage, breakers and fuses are located at strategic points in the system — usually at the main power entrance and the start of each primary and branch circuit.

If the fault occurs near the end of a branch circuit, the fuse or breaker immediately upstream from that fault should open before any other protective devices do, which would limit the resulting power outage to only the portion of the circuit downstream of the protective device. Similarly, if the fault occurs on a primary feeder, the fuse or breaker for that feeder should open before any other upstream protective devices. Selecting and setting the time-current characteristics of protective devices so they'll operate in this manner is called **“coordination.”**

When the branch breaker and main breaker aren't coordinated, the main breaker will trip when a fault occurs on a small branch circuit, exposing the entire facility to a complete power outage. Conversely, if the branch breaker were coordinated with the upstream breakers and fuses, only the branch breaker immediately upstream of the fault should trip.

How do you select & install the protection devices?

To select the appropriate fuse and breaker/relay settings, it's necessary to perform a short circuit and coordination analysis for the electrical system. The process begins with developing a single line diagram for the electrical distribution system. Equipment and conductor impedances, operating voltage, load values, starting currents, equipment ratings, and interrupting characteristics of the protective devices are represented on the diagram followed by calculating the short circuit path impedance using equations or software program. (Refer part-3 for an example).

The short circuit calculation will identify any interrupting equipment that may be inadequately rated for the available short circuit current. Using the results of the analysis of the system, it's then possible to choose optimum time-current settings for relays and breakers and plot the results. Engineers use the following general concepts when making these determinations:

- 1) Over current protective devices should be selected to ensure that the short circuit current rating of the system components is not exceeded should a short circuit or high -level ground fault occurs.
- 2) In order to properly select equipment, short circuit levels at all locations in the electrical system need to be calculated to ensure that equipment is applied within its rating.
- 3) It is important to coordinate protective devices by choosing a main fuse or breaker with slower operating characteristics than the feeder breakers.
- 4) The fault current or overload should always be interrupted by the first protective device upstream — on the source side — of the fault location. In general, the protective device furthest downstream should have the lowest trip setting (in amperes) and be the one that operates fastest for a given current level.
- 5) Normal transformer inrush current and motor starting current should never cause a protective device to operate.
- 6) Over current devices should interrupt the current as quickly as possible after an overload or short circuit occurs.
- 7) Only listed products (such as UL listed) applied in accordance with their listing shall be considered to meet the requirements.

Which areas of the power distribution system are critical for short circuit calculations?

The fundamental logic applied to calculate the short circuit current value is that “the short circuit current is related to the short circuit path impedance and system power”. Unfortunately we never know when and where a short circuit will occur. Accordingly estimating the short circuit path impedance can be very complex. In addition, although the generator or system power may be known, other consumers on the system add to that power under short circuit conditions. For example, as a motor decelerates, it acts like a

generator and contributes to the power driving the short circuit current. It is difficult to determine the likely number of motors or other consumers contributing power at the time the short circuit occurs. Consequently to determine precisely the total power driving the short circuit can be very difficult. Apart from these complications, when a generator experiences a short circuit current, it responds in a non-linear fashion. In effect the generator impedance changes as the short circuit current develops; this again affects the short circuit current at any point in time.

To obtain reliable, coordinated operation and assure that system components are protected from damage, it is necessary to first calculate the available fault current at various critical points in the electrical system. The critical points in the system include:

- ❖ Service Entrance
- ❖ Panel Boards
- ❖ Motor Control Centers
- ❖ Motor Starters
- ❖ Transfer Switches
- ❖ Load Centers

Normally, short circuit studies involve calculating a bolted 3-phase fault condition.

How do you calculate short circuit current?

Although a short circuit produces uncontrolled flow of current, the resulting current isn't infinite. There are number of factors that determine the magnitude of fault current. The key factors used to calculate the amount of short circuit current include:

- 1) Operating voltage, often referred to as electrical pressure
- 2) System impedance or the resistance to current flow

In simple form, the equation for determining short circuit current is derived from Ohm's Law and is expressed as $I = V / Z$, where I is current, V is voltage, and Z is impedance. The voltage used in the calculation is the rated operating voltage of the circuit. The impedance value used is the sum of all the equipment and conductor impedances from the source(s) of power to the point in the circuit where the short circuit is postulated. Since the voltages, impedances, and resulting currents are vector quantities, these calculations can become very complex. Certain IEEE (Institute of Electrical and Electronic Engineers) publications detail how to calculate these currents if they are substantial. Most engineers now use commercially available software to model the system and perform these calculations to conform to the ANSI/IEEE 399 Standard, "Recommended Practice for Power Systems Analysis".

Before we discuss the short circuit calculation procedure, it is important to understand some basic elementary terminology and fundamentals. This is defined in next section, part-2.

PART-2

BASIC TERMINOLOGY

Direct Current: *Direct current* (DC) is electricity flowing in a constant direction, and/or possessing a voltage with constant polarity. In DC circuits, the polarity of the voltage source does not change over time. By convention, we show DC current flow as originating at the positive terminal of the source, traveling through the circuit and returning to the negative terminal. Common DC sources include batteries, photocells, fuel cells, rectifiers and the common DC machines are motors and generators.

Alternating Current: Alternating current (AC) unlike Direct current (DC) flow first in one direction then in the opposite direction in a sine (or sinusoidal) waveform. 60 cycle AC currents change direction 60 times per second and one cycle = 1/60 second = 0.0167 second.

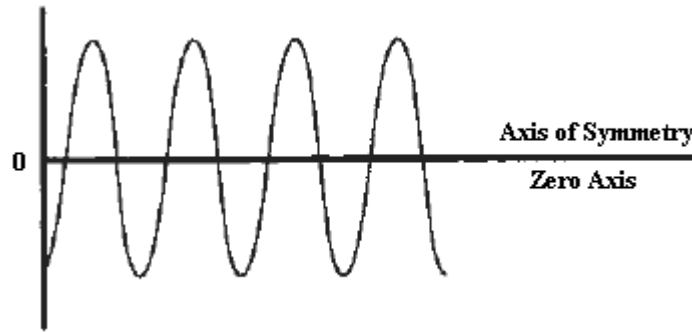
RMS or Effective Current: Since an alternating current varies continuously from 0 to maximum to 0 first in one direction and then in the other, it is not readily apparent just what the true current value really is.

The current at any point on a sine wave is called the "Instantaneous Current". The current at the top of the wave is called the "Peak" or "Crest" current. It is also possible to determine the "Arithmetic average value" of the alternating current, but none of these values correctly relate alternating current to direct current. RMS means root mean square and is the square root of the average of all the instantaneous currents squared. Root mean square (RMS) values equate AC to DC equivalents.

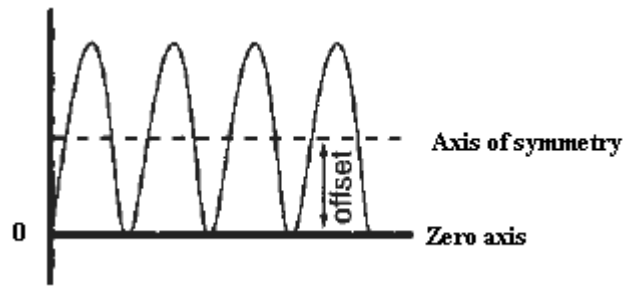
Effective value of AC equals effective value of DC. It is possible to say that the RMS value of a sinusoidal current (AC) represents that direct current (DC) value which, in an equal time, produces the same heating effects.

- Effective Current: $I = 0.707 I_{\max}$
- Effective Voltage: $E = 0.707 E_{\max}$
- Average Current: $I_{\text{av}} = 0.636 I_{\max} = 0.9 I$
- Average Voltage: $E_{\text{av}} = 0.636 E_{\max} = 0.9 E$

Symmetrical Current: A symmetrical current wave is symmetrical about the zero axis of the wave. This wave has the same magnitude above and below the zero-axis.



Asymmetrical Current: An asymmetrical current wave is not symmetrical about the zero-axis. The axis of symmetry is displaced or offset from the zero axis, and the magnitude above and below the zero axis are not equal. The axis of symmetry of an offset wave resembles a DC current.



The asymmetrical currents can be readily handled, if considered to have an AC component and a DC component. Both of these components are theoretical. The DC component is generated within the AC system and has no external source.

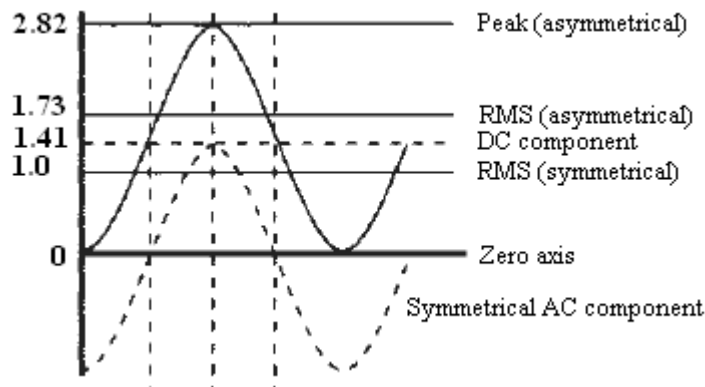


Figure above shows a fully offset asymmetrical current with a steady DC component as its axis of symmetry. The symmetrical component has the zero-axis as its axis of symmetry. *If the RMS or effective value of the symmetrical current is 1, then the peak of the symmetrical current is 1.41. This is also the effective value of the DC component.*

We can add these two effective currents together by the square root of the sum of the squares and get the effective or RMS value of the asymmetrical current.

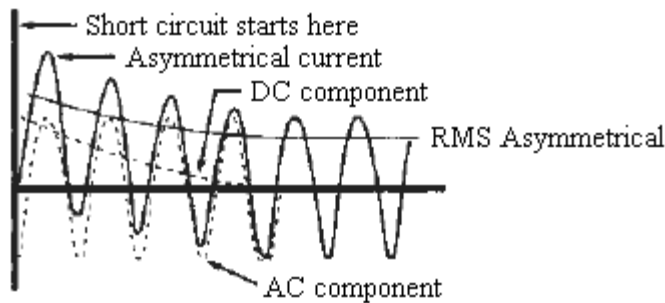
$$I_{asm} = \sqrt{I_{dc}^2 + I_{sym}^2}$$

$$I_{asm} = \sqrt{(1.41)^2 + 1^2} = \sqrt{3} = 1.73$$

Total Current: The term total current is used to express the total or the sum of the AC component and the DC component of an asymmetrical current. Total current and TOTAL ASYMMETRICAL CURRENT have the same meaning and may be expressed in peak or RMS amperes.

Overcurrent: An over current is a current that exceeds the ampere rating of the conductors (cable), equipment (motors, instruments) or other devices. Overcurrents include short circuits and overloads. They can occur as a result of normal conditions such as motor starting, or abnormal conditions such as a fault.

Decay: Unfortunately fault currents are neither symmetrical nor fully asymmetrical but somewhere in between. The DC component is usually short lived and is said to decay.



In the above diagram the DC component decays to zero in about four cycles. The rate of decay is called “Decrement” and depends upon the circuit constants. *The DC components would never decay in a circuit having reactance but zero resistance, and would remain constant forever. In a circuit having resistance but zero reactance the DC component would decay instantly.* These are theoretical conditions and all practical circuits have some resistance and reactance, and the DC component disappears in a few cycles.

Since fault currents are neither symmetrical nor fully asymmetrical so what actually is the available short circuit current! We can say that short circuit current normally takes on an asymmetrical characteristic during the first few cycles of duration and it is symmetrical after about 4 cycles, and we can properly talk about the available short circuit current in RMS symmetrical amperes after the DC component becomes zero. We can also determine current at 1, 2, 3 cycles of any other time after the short circuit started. The accepted practice is to use the current which is available 1/2 cycle after the short circuit starts.

Closing Angle: A short circuit fault can occur at any point on the voltage wave of the circuit. The voltage wave resembles the current wave and the two waves may be in phase or out of phase. The magnitude and

symmetry of the current wave on a short circuit depends on the point of the voltage wave at which the short occurs. In laboratory tests it is possible to pick the point on the voltage wave where the fault occurs by closing the circuit at any desired angle on the voltage wave. We can say that we pick the closing angle to produce the current conditions which we wish. This is called 'controlled closing'.

Random Closing: In real life, faults occur at any and every point on the voltage wave and in a laboratory this can be duplicated by closing the circuit at random. This is known as random closing. The following is true of a short circuit having negligible resistance:

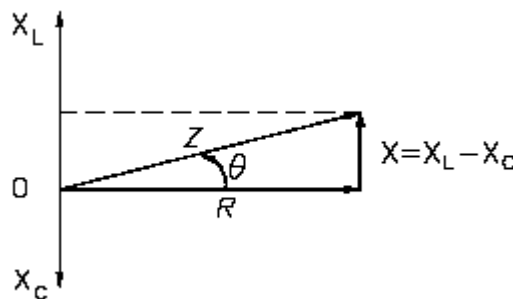
- 1) If the fault occurs at zero voltage the current wave is fully asymmetrical, thus the maximum value of short circuit current is obtained.
- 2) If the fault occurs at maximum voltage the current wave is completely symmetrical, and a minimum value of short circuit current is obtained.
- 3) Most natural faults occur somewhere between these two extremes.

Impedance: Every practical circuit contains resistance (R) and inductive reactance (X). These are electrically in series. Their combined effect is called "Impedance (Z)". *Impedance* is defined as the total opposition to current flow in a circuit. The mathematical representation for the magnitude of impedance in an AC circuit is

$$Z = \sqrt{R^2 + X^2}$$

Where

- Z = impedance (Ω)
- R = resistance (Ω)
- X = net reactance (Ω)



Relationship between Resistance, Reactance and Impedance

The current through a certain resistance is always in phase with the applied voltage. Resistance is shown on the zero-axis. The current through an inductor lags applied voltage by 90°; inductive reactance is shown

along the 90° axis. Current through a capacitor leads applied voltage by 90° ; capacitive reactance is shown along the -90° axis. Net reactance in an AC circuit is the difference between inductive and capacitive reactance. The mathematical representation for the calculation of net reactance when X_L is greater than X_C is

$$X = X_L - X_C$$

Where

- X = net reactance (Ω)
- X_L = inductive reactance (Ω)
- X_C = capacitive reactance (Ω)

Equation below is the mathematical representation for the calculation of net reactance when X_C is greater than X_L .

$$X = X_C - X_L$$

Impedance is the vector sum of the resistance and net reactance (X) in a circuit. The angle θ is the phase angle and gives the phase relationship between the applied voltage and the current. Impedance in an AC circuit corresponds to the resistance of a DC circuit. The voltage drop across an AC circuit element equals the current times the impedance.

Equation below is the mathematical representation of the voltage drop across an AC circuit.

$$V = IZ$$

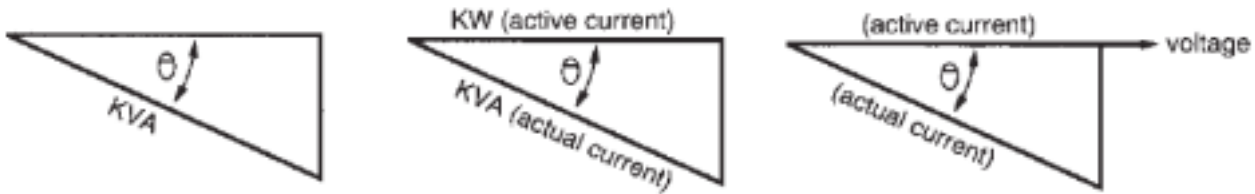
Where

- V = voltage drop (V)
- I = current (A)
- Z = impedance (Ω)

The phase angle θ gives the phase relationship between current and the voltage

Power Factor: Power factor is defined as a ratio of real power (KW) to apparent power (KVA).

$$PF = \frac{KW}{KVA} = \frac{\text{Real Power}}{\text{Apparent Power}}$$



The active current is in phase with the voltage. The actual current, as read on an ammeter, lags the voltage by an amount equal to the phase angle.

Power Factor = $\cos\theta$

The power factor is said to be 1 or unity or 100% when the current and the voltage are in phase i.e. when $\theta = 0$ degrees ($\cos 0^\circ = 1$). The power factor is 0 when θ is 90 degrees ($\cos 90^\circ = 0$).

X/R Ratio: In the impedance diagram above, the resultant angle θ is between the voltage and current waves and is called the “Phase Angle”. The voltage leads the current or the current lags the voltage by an amount equal to the phase angle.

The X/R value is determinant as to how long a short circuit current will remain on a circuit, if uninterrupted by an overcurrent protective device. Mathematically it is given by

$$\frac{X}{R} = \tan \theta$$

If a circuit has an X/R ratio less than the value specified for the proof testing of a given breaker type, the circuit breaker can be evaluated by direct comparison of it’s short circuit rating with the calculated symmetrical fault current. When the circuit X/R ratio is above the specified value, multiplying factors must be applied to the calculated symmetrical short circuit current to properly evaluate the device rating.

The X/R ratio determines the power factor of a circuit and the table below shows the short circuit power factor relationships

Short Circuit Power Factor %	Short Circuit X/R Ratio	Multiplying Factor		
		Maximum 1 phase RMS Amperes at ½ Cycle	Average 3 phase RMS Amperes at ½ Cycle	Maximum Peak Amperes at ½ Cycle
0	Infinite	1.732	1.394	2.828
5	19.974	1.568	1.301	2.625
10	9.9501	1.436	1.229	2.455
20	4.8990	1.247	1.127	2.183
30	3.1798	1.130	1.066	1.978
50	1.7321	1.026	1.013	1.694
100	0.0	1.000	1.000	1.414

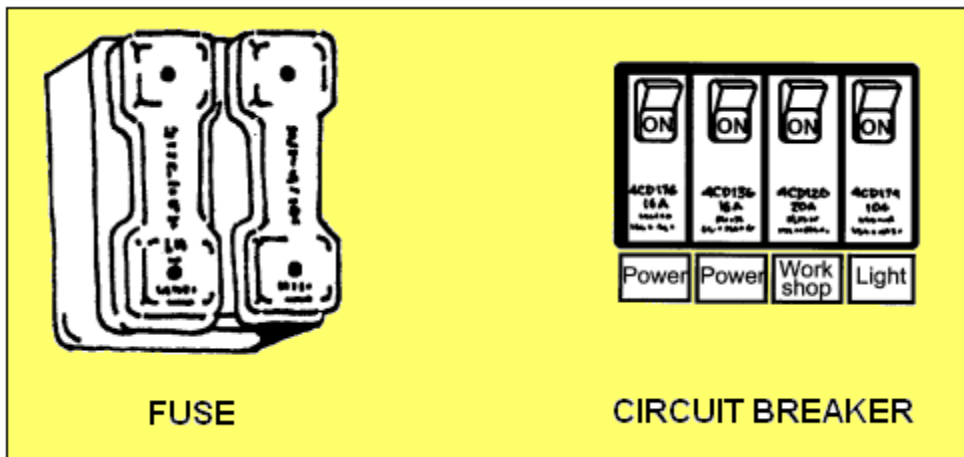
Withstand Rating: The energy of a fault can be measured by the formula; Thermal Energy = I^2t . For example, if a short circuit is 10,000 amps (I) for .01 second, $I^2t = 1,000,000$. A short circuit of 7,500 amps can melt a #8 copper wire in 0.1 second. The maximum specified value of Voltage and Current that equipment can safely “handle” is known as its “Withstand Rating”.

A short circuit current translates into Mechanical Force (I^2) and Thermal Energy (I^2t) which can destroy equipment and create hazardous conditions. Therefore, for equipment protection, the ‘withstand rating’ should never be less than the available short circuit current at the equipment location. In reality such conditions cannot always be avoided. Hence, the current-limiting ability of fuses is utilized to reduce the short circuit current of a value LESS THAN the equipment ‘withstand rating’.

Interrupting Rating: The maximum specified value of short circuit current that an overcurrent protective device (fuse or circuit breaker) can safely open or clear is known as its “Interrupting Rating”. For circuit breakers there are numerous ratings ranging from 10,000 up (i.e. 10,000, 14,000, 22,000, 42,000, 65,000 etc). In the case of modern current-limiting fuses (Class R, J and L) there is one rating; 200,000 amperes RMS. Older fuse types (Class H and K) have 10,000, 50,000 or 100,000 ampere ratings. The Interrupting Ratings of over-current protective devices must never be exceeded if serious damage is to be avoided. Hence, the use of One- Time or Renewable, 10,000 ampere Class H fuses can create serious concern. Extreme caution must be exercised so that there 10,000 ampere rating is not exceeded. This problem is eliminated with the application of 200,000 ampere rated fuses.

Overcurrent Protective Devices

Distribution equipment such as circuit breakers and fuses are common overcurrent protective devices that have interrupting or withstand ratings defined as the maximum RMS values of symmetrical current.



There are 3 types of circuit breakers:

- 1) Low voltage power circuit breakers – used primarily in draw-out switchgear. They have replaceable contacts and are designed to be maintained in the field.

- 2) Molded case circuit breakers are primarily used in panel boards and switchboards where they are fix-mounted. Molded case circuit breakers are rated in amperes at a specific ambient temperature. This ampere rating is the continuous current the breaker will carry in the ambient temperature for which it is calibrated in open air. According to the National Electric Code, all overcurrent devices may be loaded to a maximum of 80% of their continuous ampere rating, unless they are specifically listed for 100%.
- 3) Insulated case circuit breakers- These utilize the characteristics of design from both classes. They are primarily used in fix mounted switchboards.

Circuit breakers shall be capable of being opened and closed manually. They can be operated electrically or pneumatically only if means for manual operation are also provided. They must clearly indicate whether they are open (off) or closed (on). Where circuit breaker handles are operated vertically, the “up” position of the handle shall be the “on” position.

Circuit breakers shall be marked such that their ampere rating is visible after installation, and shall be permitted to be made visible by the removal of a trim or cover. Every circuit breaker having an interrupting rating other than 5000 amperes shall have its interrupting rating shown on the circuit breaker. They shall be marked with a voltage rating not less than the nominal system voltage that is indicative of their capability to interrupt fault currents between phases or phase to ground.

An adjustable trip circuit breaker is a circuit breaker that has an external means for adjusting the current setting (long time pickup setting). The rating of the circuit breaker is the maximum setting possible.

Making Capacity and Breaking Capacity: The performance of a circuit-breaker under short circuit conditions is mainly defined by:

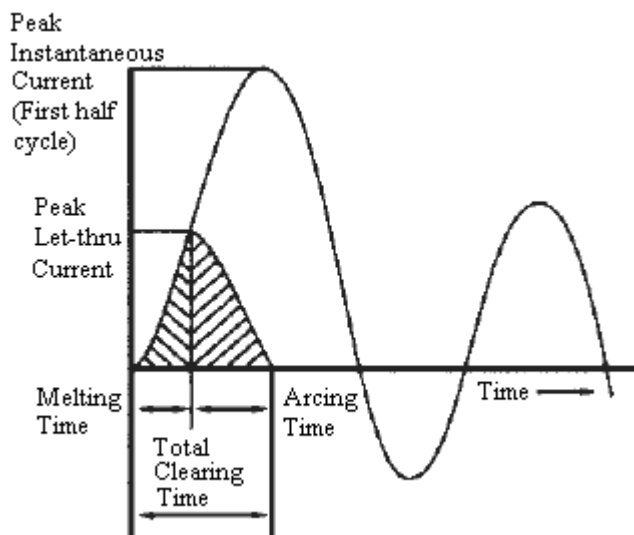
- 1) Breaking capacity (I_{cu})
- 2) Making capacity (I_{cm})

The “breaking capacity” is defined with reference to the RMS value of the symmetrical component of the short circuit current. *The “making capacity”* is defined with reference to the maximum peak value of the prospective short circuit current. Since each element with impedance modifies the short circuit current on the load side, and since a circuit breaker is an element with an impedance of its own, the *“prospective current”* is defined as the current flowing when the protection device is replaced by an element with null impedance. The making capacity of every circuit-breaker or switch intended to be capable of being closed, if necessary, on short-circuit, should not be less than the maximum value of the short-circuit current at the point of installation; on alternating current this maximum value corresponds to the peak value allowing for maximum asymmetry.

A circuit breaker can't interrupt a circuit at the instant of inception of a short. Instead, due to the relay time delay and breaker contact parting time, it will interrupt the current after a period of five to eight cycles, by which time the DC component will have decayed to nearly zero and the fault will be virtually symmetrical. Maximum thermal and mechanical stress on the equipment occurs during these first few cycles. It is

therefore important to concentrate on what happens during the first half cycle when the current values are essentially asymmetrical. Fault analysis is required to calculate and compare symmetrical and asymmetrical current values in order to select a protective device to adequately protect a piece of electrical distribution equipment.

Current Limitation: The significant reduction of available short circuit current, in a circuit, by use of a device that prevents this short circuit current from reaching its maximum value, is called “Current Limitation”. Fuses which perform this function are known as Current Limiting. Current Limiting fuses operate in less than 1/2 cycle, thus interrupting the short circuit current before it can achieve its maximum value. The resultant reduction (refer to shaded segment of figure below) is substantially less than the maximum value of available short circuit current.



This figure shows the current-limiting action of these fuses. The “Melting time” is the time required to melt the fusible link. The “Arching time” is the time required for the arc to burn back the fusible link and reduce the current to zero. “Total Clearing Time” is the sum of the melting and arcing times and is the time from fault initiation to extinction.

Let-Thru Current: The maximum instantaneous or peak current which passes through the fuse is called the let-thru current. The let-thru current of a current-limiting fuse varies with the design, ampere rating and available short circuit current. This value can be expressed in RMS amperes also. The value of let-thru current is used in determination of electrical equipment protection, as required by the NEC, Article 110-10 and CEC 14-200.

Do the protection devices prevent short circuits?

No. A common misconception is that fuses and circuit breakers will prevent short circuits or equipment failure. In reality, these protective devices are reactive and only operate after a failure has initiated. The real job of overcurrent protective devices is to limit the damage and effect of a short circuit. They minimize the

damage at the point of failure, minimize or prevent injury, prevent damage to other equipment, and minimize the extent of the resulting power outage. If they're designed and adjusted to act very quickly, only a small amount of damage will occur as a result of the fault energy.

Protective Devices Settings

Circuit breaker and fuse operating characteristics are graphically represented by time-current curves. From these curves, you can tell how long it will take for the protective device to interrupt at any value of current. *These protective devices are typically designed to interrupt the current more quickly for higher current values and slower for lower current values.* For example, a bolted fault is interrupted more quickly than an overload.

Although fuse manufacturers offer a variety of fuse types, each with its own curve shape and current rating, fuses are non-adjustable devices. If a different operating characteristic or current rating is needed, you must replace the fuse with a more compatible type. Smaller molded case breakers typically aren't adjustable either and must similarly be replaced if a different operating characteristic or trip value is necessary. Most relays and electronically controlled breakers, however, are designed with considerable flexibility. They offer a wide range of field-adjustable trip settings and operating curves.

PART -3

SHORT CIRCUIT CALCULATIONS

The short circuit currents can be calculated on the basis of the impedance represented by the "circuit". This impedance may be calculated after separately summing the various resistances and reactance's in the fault loop, from (and including) the power source to the fault location. Mathematically the short circuit impedance (Z_{sc}) is given by relation:

$$Z_{sc} = \sqrt{(\sum R)^2 + (\sum X)^2}$$

Where

- Z_{sc} is the total impedance
- $\sum R$ = the sum of series resistances
- $\sum X$ = the sum of series reactances

The calculation of short circuit currents (I_{sc}) is based on the Ohm's law:

$$I_{sc} = \frac{V_n}{\sqrt{3} * Z_{sc}}$$

Where

- I_{sc} is the short circuit current (for three phase fault)
- V_n is the nominal network voltage at no-load (this is 3 to 5% greater than the on-load voltage across the terminals).
- Z_{sc} is the total impedance

The short circuit currents values shall be different for the different type of faults as discussed below.

MAIN TYPES OF SHORT CIRCUIT FAULTS

Various types of short circuits can occur in electrical installations. Short circuits can be:

- 1) Three phase short circuit
- 2) Phase to phase short circuit clear of earth
- 3) Phase to neutral short circuit clear of earth
- 4) Phase-to-earth fault (one or two phases)

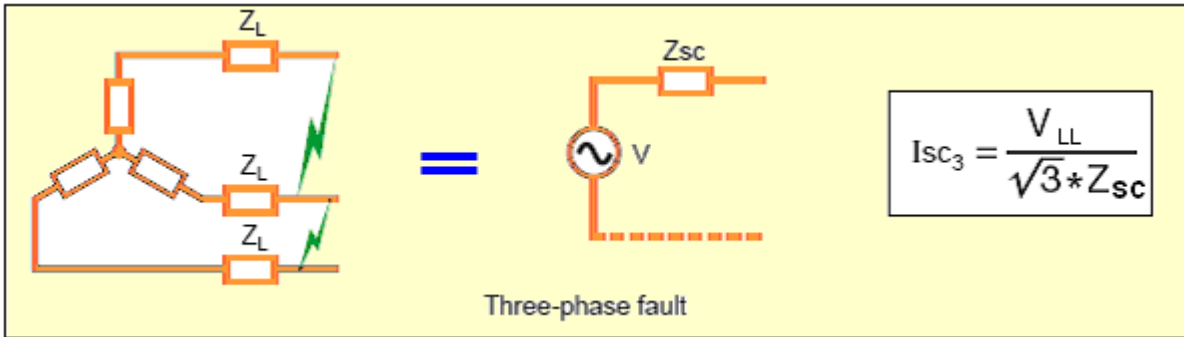
In electrical systems, the three phase short circuit condition generally causes the highest fault currents.

However, the majority incidents of short circuit occur between a phase and neutral and between a phase and earth (ground). It is also possible for short circuits to arise between neutral and earth conductors, and

between two conductors of the same phase. Such short circuits can be dangerous, particularly as they may not immediately result in a large current flowing and are therefore less likely to be detected. Possible effects include unexpected energization of a circuit presumed to be isolated.

1) Three-phase short circuit

This fault involves all three phases.



Short circuit current I_{sc3} is equal to:

$$I_{sc3} = \frac{V_{LL}}{\sqrt{3} * Z_{sc}}$$

Where

- I_{sc3} is the short circuit current for three phase fault
- V_{LL} is line to line voltage
- Z_{sc} is the total impedance (Z_L shown on the diagram is the line impedance)

Calculation of the short circuit current requires only calculation of Z_{sc} and is given by

$$Z_{sc} = \sqrt{(\sum R)^2 + (\sum X)^2}$$

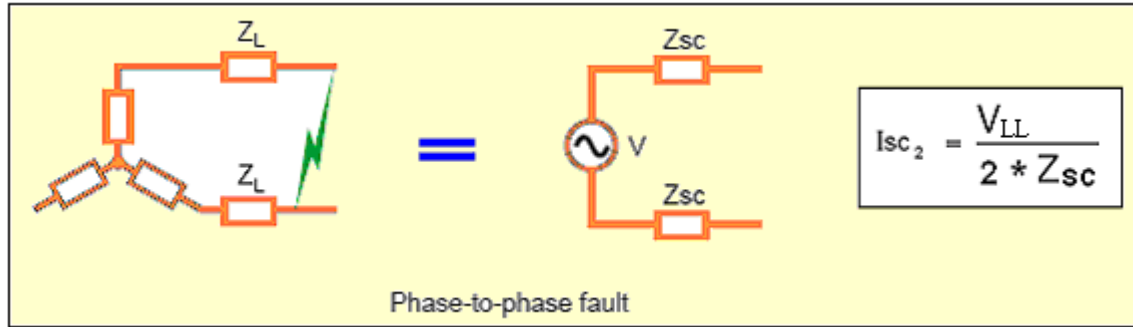
Where

$\sum R$ = the sum of series resistances

$\sum X$ = the sum of series reactances

2) Phase-to-phase short circuit clear of earth

This is a fault between two phases, supplied with a phase-to-phase voltage V_{LL} . In this case, the short circuit current I_{sc2} is less than that of a three-phase fault:

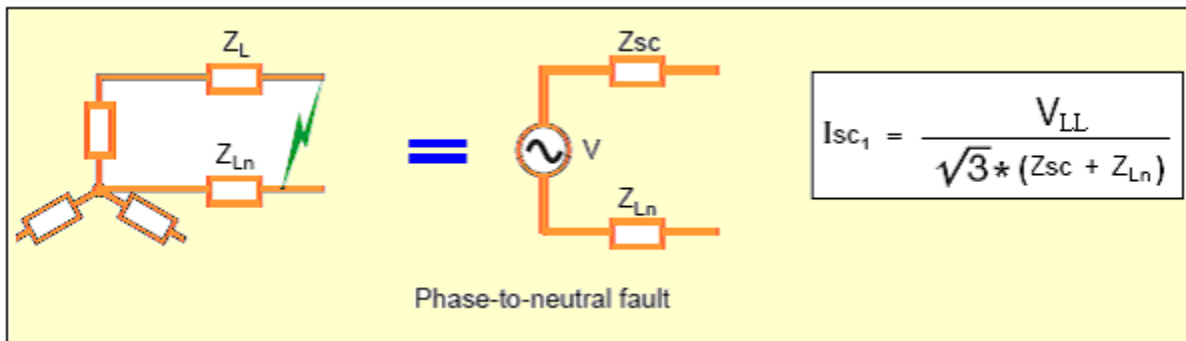


$$I_{sc2} = \frac{V_{LL}}{2 * Z_{sc}} = \frac{\sqrt{3} I_{sc3}}{2} \approx 0.86 I_{sc3}$$

For a fault occurring near rotating machines, the impedance of the machines is such that I_{sc2} is close to I_{sc3} .

3) Phase-to-neutral short circuit clear of earth

This is a fault between one phase and the neutral, supplied with a phase-to-neutral voltage



The short circuit current I_{sc1} is:

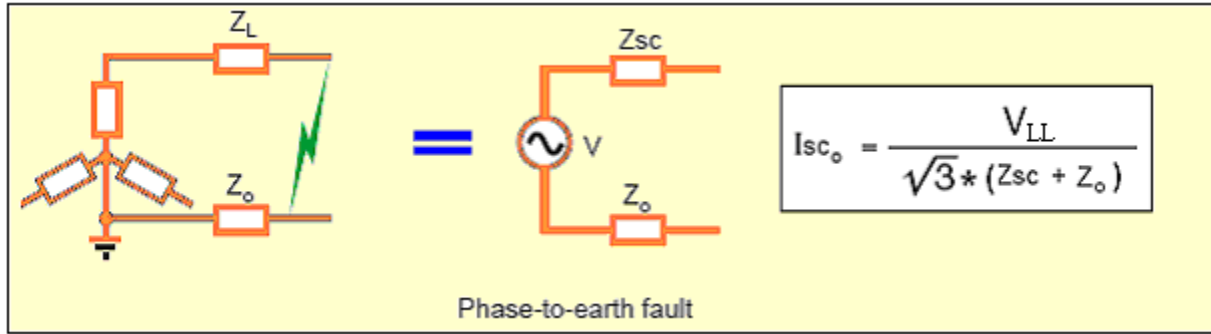
$$I_{sc1} = \frac{V_{LL}}{\sqrt{3} * (Z_{sc} + Z_{Ln})}$$

In certain special cases of phase-to-neutral faults, the zero-sequence impedance of the source is less than Z_{sc} (for example, at the terminals of a star-zigzag connected transformer or of a generator under sub-transient conditions).

In this case, the phase-to-neutral fault current may be greater than that of a three-phase fault.

4) Phase-to-earth fault (one or two phases)

This type of fault brings the zero-sequence impedance Z_0 into play.



The short circuit current I_{sc0} is:

$$I_{sc0} = \frac{V_{LL}}{\sqrt{3} * (Z_{sc} + Z_o)}$$

Except when rotating machines are involved (reduced zero-sequence impedance), the short circuit current I_{sc0} is less than that of a three phase fault. Calculation of I_{sc0} may be necessary, depending on the neutral system (system earthing arrangement), in view of defining the setting thresholds for the zero-sequence (HV) or earth fault (LV) protection devices.

Summarizing, the maximum available current for AC circuits is calculated for a three-phase bolted fault. This is generally considered as the fault which generates the highest currents (except for particular conditions). When there are no rotary machines, or when their action has decreased, this value represents also the steady state short circuit current and is taken as reference to determine the breaking capacity of the protection device. Minimum available current is calculated for a line to line arcing fault.

In real field conditions, the statistics indicate that the most common type of short circuit faults relate to

- ❖ Phase-to-earth (80% of faults)
- ❖ Phase-to-phase (15% of faults) - This type of fault often degenerates into a three phase fault
- ❖ Three-phase (only 5% of initial faults)

Although 3-phase faults are only 5% in occurrence, it is practice to analyze short circuit for three phase bolted faults.

IMPEDANCE METHOD

Total fault current at any location in the power system includes contributions from all sources such as network impedances, transformers, motors, generators, cables and miscellaneous elements like capacitors, switchgear, rectifiers etc. The amount of impedance between the source and the short circuit location has a direct effect on the amount of short circuit current that will flow during a fault. *If the utility increases circuit conductor size, replaces the service transformer with a larger unit, or installs a new generating station near the customer, the available short circuit current will increase.* If little impedance exists between the source

of power and the location of the postulated fault, the resulting short circuit can be very large, possibly more than 100,000A.

The extract below describes the methodology for estimating short circuit currents and also discusses in detail the data needed for each type of circuit component and how to obtain the data. An important element of this analysis is to determine if circuit protective devices are sized and set correctly. *Sizing of circuit protective devices can only be done when maximum available short circuit current is known. Setting of the devices can only be done when minimum available short circuit current is known.* This extract below is taken from Mine Safety and Health Administration (MSHA's) website www.msha.gov.

Distribution Network Impedances

Generally speaking, points upstream of the power source are not taken into account. Available data on the upstream network is therefore limited to that supplied by the power distributor, i.e. only the short circuit power in MVA. Thus the first step in analyzing a power system is to get the data for the power available at the site, the utility data. The power company will be able to supply this information for the point in the power system where their responsibility for the power system ends and the customer's responsibility starts. A common location for this point is the secondary of a pole or pad mounted transformer. If the customer is responsible for the transformer, the transition point would be the primary of the transformer. Sometimes a pole mounted disconnect will be the transition point. The power company will specify where in the system their responsibility ends.

To calculate the short circuit currents; it is necessary to know the network short circuit power (kVA_{SC}), the line to line voltage (V_{LL}) and X/R. Short circuit kVA is the power available at a bolted three phase fault, which means all three phases connected together with no added impedance. X/R is the ratio of reactance to resistance in the supply. In a MV network the rated voltage is the unique parameter usually known. The short circuit power can indicatively vary from 250MVA to 500MVA for systems up to 30kV. When the voltage level rises, the short circuit power can indicatively vary between 700MVA and 1500MVA. The voltage values of the MV distribution network and the relevant short circuit power values accepted by the Standard IEC 60076-5 are reported in table below:

Distribution Network Voltage (kV)	Short circuit apparent power (MVA) (European Practice)	Short circuit apparent power (MVA) (North American Practice)
7.2 – 12 – 17.5 - 24	500	500
36	1000	1500
52 – 72.5	3000	5000

Short circuit kVA and X/R may need to be derived from other data.

When Utility Company Provides the Short circuit Current

Short circuit current (I_{SC}) is sometimes supplied by the power company rather than short circuit kVA. This current is the current in one phase of a three phase bolted fault. The short circuit kVA can then be calculated from the short circuit current using the following equation.

$$kVA_{SC} = \frac{\sqrt{3} * I_{SC} * V_{LL}}{1000} \quad (\text{Eq. 1})$$

If you're not doing these calculations every day, it is sometimes hard to remember when to include the square root of three factor. *Power in a three phase circuit is three times the single phase power or three times the current in one phase times the line to neutral voltage (V_{LN}). The line to neutral voltage is the line to line voltage divided by the square root of three.*

$$kVA_{SC} = \frac{3 * I_{SC} * V_{LN}}{1000} = \frac{3 * I_{SC}}{1000} * \frac{V_{LL}}{\sqrt{3}} = \frac{\sqrt{3} * I_{SC} * V_{LL}}{1000} \quad (\text{Eq. 2})$$

When Utility Company Provides the Power Factor instead of X/R

Power factor (PF) is sometimes specified instead of X/R. This must be the short circuit power factor. Power factor is defined as the cosine of the angle between voltage and current. X/R is the tangent of this same angle. X/R can be found from power factor by taking the tangent of the inverse cosine of the power factor.

$$X / R = \tan(\cos^{-1} PF) \quad (\text{Eq. 3})$$

When Utility Company Provides neither the X/R nor the Power Factor

When neither X/R nor power factor are specified, it is usually safe to assume the impedance of the utility is all reactance and X/R is infinite. Unless there are many miles of transmission line, the impedance of the utility will be mainly reactance in the generator. This is all the data needed for the utility. From this data, the impedance (Z), resistance (R), and reactance (X) can be calculated manually as follows:

Calculating Impedance (Z)

Impedance is calculated from V_{LL} and short circuit kVA.

$$Z = \frac{V_{LL}^2}{kVA_{SC} * 1000} \quad (\text{Eq. 4})$$

Calculating Resistance (R) and Reactance (X)

Resistance and reactance are then calculated from the impedance using X/R.

$$\text{Since: } Z = \sqrt{X^2 + R^2} \quad (\text{Eq. 5})$$

$$R = \frac{Z}{\sqrt{1 + (X/R)^2}} \quad (\text{Eq. 5a}) \quad \text{and} \quad X = R * (X/R) \quad (\text{Eq. 5b})$$

Resistance and reactance are calculated at the voltages for the points in the circuit where the short circuit currents are calculated. For example, even though the utility voltage may be 69 kilovolts (kV), if the short circuit currents are being calculated further down the circuit where the voltage is 2400 volts, the resistance and reactance will be calculated at 2400 volts. Calculate resistance and reactance for the utility at the utility voltage and work down through a circuit, encountering transformers. Applying the conservation of energy, energy into the transformer (V_1^2/R_1) equals energy out of the transformer (V_2^2/R_2).

$$R_2 = R_1 * \frac{V_2^2}{V_1^2} \quad (\text{Eq. 6})$$

Where:

- R_2 = resistance at secondary voltage
- R_1 = resistance at primary voltage
- V_2 = secondary voltage
- V_1 = primary voltage

TRANSFORMERS

Transformers are specified by output voltage (V), kVA rating, percent impedance (%Z), and X/R ratio. All this information, with the exception of X/R, is usually on the transformer nameplate. If X/R is not specified on the nameplate, a value of 4.9 is typical and can be used in calculations. Impedance (Z) is calculated from V, kVA, and %Z.

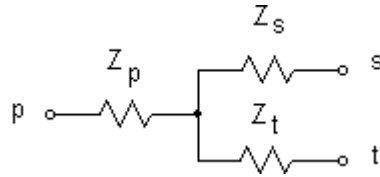
$$Z = \frac{\%Z * V^2}{kVA * 100,000} \quad \text{Or} \quad Z = \frac{\%Z}{100} * \frac{V^2}{VA} \quad (\text{Eq. 7})$$

Resistance and reactance are then calculated from Z and X/R as they were for the utility network. Again, these resistances and reactance's are for a short circuit at the secondary of the transformer. If the short circuit is at a point further down the circuit and after another transformer, the voltage at the short circuit should be used in equation 7. Alternatively, the calculated resistances and reactance's can be converted to the new voltage by multiplying by the ratio of the voltages squared.

Three Winding Transformers

The most common three winding transformers are usually specified like two separate transformers with no inter-winding impedance. When three winding transformers have separate inter-winding impedance specified, it is usually specified as reactance (X) and resistance (R) in ohms. Three sets of X and R must

be supplied; primary-secondary (ps), primary-tertiary (pt), and secondary-tertiary (st). X_{ps} and R_{ps} are measured in the primary with the secondary short circuited and the tertiary open. X_{pt} and R_{pt} are measured in the primary with the tertiary short circuited and the secondary open. X_{st} and R_{st} are measured in the secondary with the tertiary short circuited and the primary open. The three winding transformer is modeled as follows.



The impedances are related by the following formulas.

$$Z_{ps} = Z_p + Z_s \quad (\text{Eq. 8a})$$

$$Z_{pt} = Z_p + Z_t \quad (\text{Eq. 8b})$$

$$Z_{st} = Z_s + Z_t \quad (\text{Eq. 8c})$$

$$Z_p = 0.5 * (Z_{ps} + Z_{pt} - Z_{st}) \quad (\text{Eq. 8d})$$

$$Z_s = 0.5 * (Z_{ps} + Z_{st} - Z_{pt}) \quad (\text{Eq. 8e})$$

$$Z_t = 0.5 * (Z_{pt} + Z_{st} - Z_{ps}) \quad (\text{Eq. 8f})$$

In the equations, all impedances must be referred to a common voltage. Note that X_{st} and R_{st} are measured at the secondary voltage. If all impedances are to be at the primary voltage, X_{st} and R_{st} must be transferred.

CABLES

The impedance value of the cables and other connection elements (overhead lines, bus-bar etc) depends on different factors (constructional techniques, temperature, etc....) which influence the line resistance and the line reactance. These two parameters expressed per unit of length are given by the manufacturer of the cable. The impedance is generally expressed by the following formula:

$$Z = (R + X) * L$$

Where

- Z = Line impedance
- R = Line resistance
- X = Line reactance

- L = Length of the cable

Cable Resistance

The resistance per unit length is calculated as

$$R = \rho / A \quad (\text{Eq. 9a})$$

Where

- A = Cross-sectional area of the conductor
- ρ = conductor resistivity; however the value used varies, depending on the calculated short circuit current (minimum or maximum).

The resistance values are generally given for a reference temperature of 20°C. Cables operating temperature has an effect on the resistance of a cable. Most cables have a rated operating temperature of 90 °C. Aerial cable is rated 75 °C. The cables have higher resistances at their rated operating temperature ratings than at ambient temperature. The resistance at rated operating temperature can be calculated from the resistance at ambient temperature using the following formula.

$$R_2 = R_1 [1 + \alpha(T_2 - T_1)] \quad (\text{Eq. 9b})$$

Where:

- R_2 = resistance at operating temperature
- R_1 = resistance at ambient temperature
- T_2 = rated operating temperature
- T_1 = ambient temperature
- α = temperature coefficient of resistivity which depends on the type of material (for copper it is 3.95×10^{-3} corresponding to temperature T_1 at 20 °C)

When calculating maximum available current, the resistance of the cable at ambient temperature should be used. However, the current that causes the cable to reach its highest temperature may not be the maximum available current. If the cable is initially at a temperature between ambient and its rated operating temperature and a short circuit occurs, it is possible that the cable will reach a higher final temperature at a current lower than the maximum available current.

Cable Reactance

Reactance of most cables is published by the manufacturer. The reactance in ohms per 1000 feet of aerial cables with one foot spacing can be found with the following formula.

$$X_L = 0.02298 * \ln\left(\frac{1}{GMR}\right) \quad (\text{Eq. 10})$$

GMR is the geometric mean radius in feet. It can be calculated by multiplying the wire outside diameter (OD) in inches by .03245.

$$GMR \cong R * e^{-0.25} \cong 0.3894 * D \cong 0.03245 * d \quad (\text{Eq. 11})$$

Where:

- R = wire radius in feet
- D = wire diameter in feet
- d = wire diameter in inches

The reactance of aerial cable depends on the spacing between wires. *For overhead lines, the reactance increases slightly in proportion to the distance between conductors and therefore in proportion to the operating voltage.* Reactance at spacings other than one foot can be calculated with the following formula.

$$X_{new} = X_{old} \left[1 + \frac{\ln(\text{spacing})}{\ln\left(\frac{1}{GMR}\right)} \right] \quad (\text{Eq. 12})$$

The following average values can be used:

X = 0.3 ohm /km (LV lines)

X = 0.4 ohm / km (MV or HV lines)

In general, a cable with a large cross sectional area has small impedance.

MOTORS

For a motor the resistance is considered to be negligible and the reactance value may be listed on the name plate along with the horsepower rating. Motors have two values of reactance; sub-transient and transient.

- 1) Sub-transient reactance is the reactance of the motor during the first cycle of the short circuit.
- 2) Transient reactance is the reactance of the motor during the remainder of the short circuit.

The sub-transient and transient reactances are usually given in per unit values and will vary depending on whether the motor is induction, 6-pole synchronous, or 8- to 14-pole synchronous. It also varies between induction motors rated less than or equal to 600 volts and induction motors rated greater than 600 volts. *Induction motors do not contribute to a short circuit after the first cycle.* The typical values of sub-transient and transient reactance for are tabulated below.

Type of Motor	Sub-transient Reactance (per unit)	Transient Reactance (per unit)
---------------	------------------------------------	--------------------------------

Type of Motor	Sub-transient Reactance (per unit)	Transient Reactance (per unit)
DC	0.15	0.30
6-pole Synchronous	0.15	0.23
8- to 14-pole Synchronous	0.20	0.30
Induction ≤600 Volts	0.25	-
Induction >600 Volts	0.17	-

The actual value of reactance can be found with the following formula.

$$X = \frac{X_{PU} * V^2}{746 * HP} \quad (\text{Eq. 13})$$

Where:

- X_{PU} = per unit reactance
- V = voltage
- HP = horsepower

Sub-transient reactance should be used to calculate maximum available short circuit current. Minimum available short circuit current does not usually include contributions from motors, but when it does, transient reactance should be used in the calculation.

Asynchronous motor

When an asynchronous motor is cut from the network, it maintains a voltage across its terminals that disappear within a few hundredths of a second. When a short circuit occurs across the terminals, the motor supplies a current that disappears even more rapidly, according to time constants in the order of:

- 20 ms for single-cage motors up to 100 kW
- 30 ms for double-cage motors and motors above 100 kW
- 30 to 100 ms for very large HV slip ring motors (1,000 kW)

In the event of a short circuit, an asynchronous motor acts like a generator to which impedance (sub transient only) of 20 to 25% is attributed. Consequently, the large number of LV motors, with low individual outputs, may be a source of difficulties in that it is not easy to foresee the average number of motors running that will contribute to the fault when a short circuit occurs. Individual calculation of the reverse current for each motor, taking into account the line impedance, is therefore a tedious and futile task. Also when a fault condition occurs, power system voltage will drop dramatically. All motors that are running at

that time will not be able to sustain their running speed and as those motors slow in speed, the stored energy within their fields will be discharged into the power line. *The nominal discharge of a motor will contribute to the fault a current equal to up to four times its full load current.*

Common practice, notably in the United States, is to take into account the combined contribution to the fault current of all the asynchronous LV motors in an installation. This reduces the impedance at that point. Adding impedances in parallel is most easily done by first converting resistance and reactance to conductance and susceptance, adding the conductances and susceptances, and converting the conductance and susceptance back to resistance and reactance. Conductance, susceptance, resistance, and reactance are related by the following formulas.

$$G = \frac{R}{R^2 + X^2} \quad (\text{Eq. 14a}) \quad -B = \frac{X}{R^2 + X^2} \quad (\text{Eq. 14b})$$

$$R = \frac{G}{G^2 + B^2} \quad (\text{Eq. 14c}) \quad X = \frac{-B}{G^2 + B^2} \quad (\text{Eq. 14d})$$

Where:

- R = resistance
- X = reactance
- G = conductance
- B = susceptance

When sizing the transformer for motor loads, the fault current contribution from the motors is typically not considered for sizing. However, the motor contribution must be considered when sizing all branch circuit fuses and circuit breakers. The interrupting capacity ratings of feeder breakers must equal or exceed the total short circuit capacity available at the point of application.

GENERATORS

Generators impedance calculations are not straightforward. The impedance of the generator, which is constituted practically by the reactance, only, has no definite value, but it varies instant by instant, because the magnetic flux does not reach immediately the steady state configuration. If the reactances are not available from the generator nameplate, the following values can be indicated as order of quantity for the various reactances:

- 1) Sub-transient reactance: the values vary from 10% to 20% in turbo-alternators (isotropic machines with smooth rotor) and from 15% to 30% in machines with salient pole rotor (anisotropic);
- 2) Transient reactance: it can vary from 15% to 30% in turbo-alternators (isotropic machines with smooth rotor) and from 30% to 40% in machines with salient pole rotor (anisotropic);

3) Synchronous reactance: the values vary from 120% to 200% in turbo-alternators (isotropic machines with smooth rotor) and from 80% to 150% in machines with salient pole rotor (anisotropic).

Table below lists typical values of reactance for DC and four types of AC generators. The four types are two-pole turbine, four-pole turbine, salient pole with dampers and salient pole without dampers.

Type of Generator	Sub-transient Reactance (per unit)	Transient Reactance (per unit)
DC	0.15	0.30
2-Pole Turbine	0.09	0.15
4-Pole Turbine	0.14	0.23
Salient Pole with Dampers	0.20	0.30
Salient Pole without Dampers	0.30	0.30

Reactance is calculated with the following formula.

$$X = \frac{X_{PU} * V^2}{1000 * kVA} \quad (\text{Eq. 15})$$

Where:

- X_{PU} = per unit reactance
- V = voltage
- kVA = kilovolt-ampere rating

CAPACITORS

A shunt capacitor bank located near the fault location will discharge, thus increasing the short circuit current. This damped oscillatory discharge is characterized by a high initial peak value that is superposed on the initial peak of the short circuit current, even though its frequency is far greater than that of the network. Depending on the timing between the initiation of the fault and the voltage wave, two extreme cases must be considered:

- If the initiation of the fault coincides with zero voltage, the short circuit discharge current is asymmetrical, with a maximum initial amplitude peak
- Conversely, if the initiation of the fault coincides with maximum voltage, the discharge current superposes itself on the initial peak of the fault current, which, because it is symmetrical, has a low value

It is therefore unlikely, except for very powerful capacitor banks, that superposition will result in an initial peak higher than the peak current of an asymmetrical fault.

It follows that when calculating the maximum short circuit current, capacitor banks do not need to be taken into account. However, they must nonetheless be considered when selecting the type of circuit breaker.

During opening, capacitor banks significantly reduce the circuit frequency and thus affect current interruption.

Capacitors are specified by kVAR on their nameplates. This is kVA reactive. If no tolerance is specified, 15% may be used. Capacitors will feed a short circuit just like motors and generators. The following formula calculates reactance for a capacitor using a tolerance of 15%.

$$X = \frac{V^2 * 1.15}{kVAR * 1000} \quad (\text{Eq. 16})$$

Where:

- V = voltage
- kVAR = kilovolt-amperes reactive

What about special cases?

Other elements may add some impedance. This is the case for harmonics filters and inductors used to limit the short circuit current. They must, of course, be included in calculations, as well as wound-primary type current transformers for which the impedance values vary depending on the rating and the type of construction. Below are some special cases that must be handled carefully.

- 1) What if there is a rectifier in the circuit? Efficiency is the only rating needed for rectifiers. If no efficiency rating is specified, 99% can be assumed. Current through the rectifier is reduced by the factor Efficiency (%) / 100.
- 2) What if there is an automatic transfer switch? If the system involves one or more transfer switches, the short circuit and coordination studies must consider various possible operating parameters, such as source and load configurations for these switches.
- 3) What if there is an emergency generator? If the system includes one or more emergency generators, it will have a similar number of transfer switches. Each of the possible operating scenarios must then be considered when performing the short circuit and coordination studies.
- 4) What if the system is supported by a UPS or back-up battery? An uninterruptible power supply requires special attention when performing a short circuit and coordination study. Since a UPS and battery represent a load during normal operation but a source during utility outage situations, the protective devices must be sized for either condition. Manufacturer recommendations must be considered.

- 5) What if there is co-generation? Co-generation can present special difficulties since available fault current can be high with a generating unit connected directly to the system. Often the addition of a cogeneration facility will require that protective equipment be replaced with higher rated equipment.
- 6) What about other miscellaneous equipment? Certain devices (circuit breakers, contactors with blow-out coils, direct thermal relays, etc.) have an impedance that must be taken into account, for the calculation of short circuit current, when such a device is located upstream of the device intended to break the given short circuit and remain closed (selective circuit breakers). For LV circuit breakers, for example, a reactance value of 0.15 mΩ is typical, while the resistance is negligible. For breaking devices, a distinction must be made depending on the speed of opening. Certain devices open very quickly and thus significantly reduce short circuit currents. This is the case for fast-acting, limiting circuit breakers and the resultant level of electro-dynamic forces and thermal stresses, for the part of the installation concerned, remains far below the theoretical maximum.

MINIMUM AVAILABLE CURRENT

Minimum available current is calculated for a line to line arcing fault using the following formula.

$$I_{MIN} = \frac{0.95 * V_{LL}}{2 * Z_{MAX}} \quad (\text{Eq. 17})$$

Where:

- V_{LL} = line to line voltage
- Z_{MAX} = maximum impedance

This formula is used for AC and the DC output from a three phase rectifier. The factor of 0.95 accounts for voltage fluctuations. The maximum impedance is calculated from the maximum resistances and reactances for all the elements in the circuit. For AC circuits, the current is further reduced by multiplying by an arcing fault factor, K_A . This factor is listed in table below for various voltages.

Voltage (V)	K_A
$V \leq 480$	0.85
$480 < V \leq 600$	0.90
$600 < V \leq 1040$	0.95
$1040 < V$	1.0

For DC circuits the arc voltage depends on the current. First, the current is calculated with Equation 17. If the calculated current is greater than or equal to 600 amperes, the arc voltage is 60 volts. If the calculated current is less than 600 amperes, the arc voltage is calculated with the following formula

$$V_{ARC} = e^{\left[\frac{(1842-I)}{303} \right]} \quad (\text{Eq. 18})$$

Where:

- I = initially calculated current

The voltage is then reduced by the arc voltage and the available current is recalculated.

MAXIMUM AVAILABLE CURRENT

Maximum available current for AC circuits is calculated for a three-phase bolted fault using the following equation.

$$I_{MAX-AC} = \frac{V_{LL}}{\sqrt{3} * Z_{MIN}} \quad (\text{Eq. 19})$$

Where:

- V_{LL} = line to line voltage
- Z_{MIN} = minimum impedance

Maximum available current for DC circuits is calculated for a line to line bolted fault using the following equation.

$$I_{MAX-DC} = \frac{V_{LL}}{2 * Z_{MIN}} \quad (\text{Eq. 20})$$

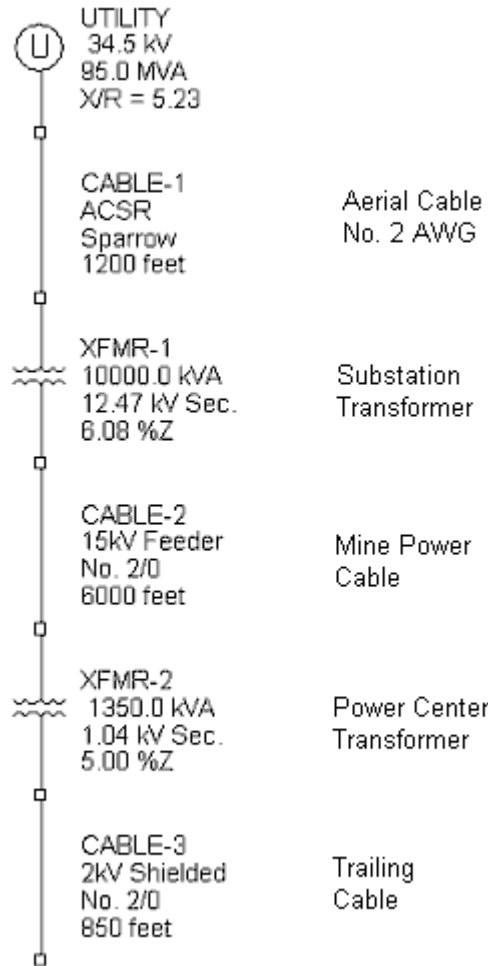
Where:

- V_{LL} = line to line voltage
- Z_{MIN} = minimum impedance

EXAMPLE

A mine is supplied 95 MVA of power at 34.5 kV with an X/R ratio of 5.23. The power travels 1200 feet through number 2, ACSR aerial cable with three-foot spacing to a substation. The substation has a secondary voltage of 12.47 kV and is rated 10 MVA with 6.08% impedance. The power then travels 6000 feet through number 2/0, 15 kV, mine power feeder cable to an underground power center. The power center has a secondary voltage of 1040 volts and is rated 1350 kVA with 5.0% impedance. Power then travels 850 feet through number 2/0, 2 kV, shielded trailing cable to a continuous miner. If a short circuit

occurs on the continuous miner at the point where the trailing cable ends, what are the minimum and maximum available short circuit currents?



Step -1: Starting at the utility, calculate the impedance using equation 4. Remember to use the voltage at the short circuit, 1040 volts.

$$Z = \frac{V_{LL}^2}{kVA * 1000} = \frac{1040^2}{95,000 * 1000} = 0.0114 \Omega$$

From the impedance and X/R ratio, find X and R.

$$R = \frac{Z}{\sqrt{1 + (X / R)^2}} = \frac{.0114}{\sqrt{1 + 5.23^2}} = 0.0021 \Omega$$

$$X = R * (X / R) = 0.0021 * 5.23 = 0.0112 \Omega$$

Step-2: Now, find the reactance and minimum and maximum resistance for the aerial cable. The GMR must first be found with Equation 11. From manufacturer's specifications, the O.D. of number 2, ACSR wire is 0.316 inch.

$$GMR \cong 0.03245 * d = 0.03245 * 0.316" = 0.0103'$$

The reactance is then found with Equation 10.

$$X_L = 0.02298 * \ln\left(\frac{1}{GMR}\right) = 0.02298 * \ln\left(\frac{1}{0.0103}\right) = 0.105 \Omega$$

Since this is the impedance for one-foot spacing, you must correct for three-foot spacing using Equation 12.

$$X_{new} = X_{old} \left[1 + \frac{\ln(spacing)}{\ln\left(\frac{1}{GMR}\right)} \right] = 0.105 * \left[1 + \frac{\ln(3)}{\ln\left(\frac{1}{0.0103}\right)} \right] = 0.1304 \Omega$$

The reactance of 1000 feet of number 2, ACSR aerial cable is 0.1304Ω. The reactance for 1200 feet is 1.2 * 0.1304 = 0.1565Ω. This needs to be converted from the overhead line voltage to the voltage at the short circuit.

$$X = 0.1565 * \frac{1.04^2}{34.5^2} = 0.0001 \Omega$$

From the manufacturer's specifications, the resistance of number 2, ACSR aerial cable is 1.753 Ω per mile at 75 °C. The resistance of 1200 feet is 0.3984 Ω at 75 °C. Multiplying by the ratio of the voltages squared gives a maximum resistance of 0.0004 Ω. To get the minimum resistance, the resistance at 75°C must be converted to the resistance at 20 °C using Equation 9.

$$R_{20} = \frac{R_{75}}{1 + \alpha(75 - 20)} = \frac{0.0004}{1 + 0.00393 * 55} = 0.0003 \Omega$$

Step -3: The next component in the system is the substation. First, find the impedance using Equation 7.

$$Z = \frac{\%Z * V^2}{kVA * 100,000} = \frac{6.08 * 1040^2}{10,000 * 100,000} = 0.0066 \Omega$$

The X/R ratio is not specified for the substation. A value of 4.9 can be assumed. Using this value and the impedance, find X and R.

$$R = \frac{Z}{\sqrt{1 + (X/R)^2}} = \frac{.0066}{\sqrt{1 + 4.9^2}} = 0.0013 \Omega$$

$$X = R * (X/R) = 0.0013 * 4.9 = 0.0065 \Omega$$

Step -4: Next is the 6000 feet of number 2/0, 15 kV, power feeder cable. From manufacturer's specifications, reactance of 1000 feet of this cable is 0.038 Ω . The reactance of 6000 feet at 1040 volts is calculated as follows:

$$X = 6 * .038 * \frac{1040^2}{12,470^2} = 0.0016 \Omega$$

From manufacturer's specifications, resistance of this cable at 20°C is 0.0792 Ω per 1000 feet. Resistance of 6000 feet at 1040 volts would be:

$$R_{MIN} = 6 * 0.0792 * \frac{1040^2}{12,470^2} = 0.0033 \Omega$$

The maximum resistance will be at 90 °C, the rated operating temperature of mine power feeder cable.

$$R_{MAX} = R_{MIN} * [1 + \alpha(90 - 20)] = 0.0033 * (1 + 0.00393 * 70) = 0.0042 \Omega$$

Step -5: The power center is the next component in the circuit. First find the impedance.

$$Z = \frac{\%Z * V^2}{kVA * 100,000} = \frac{5 * 1040^2}{1350 * 100,000} = 0.0401 \Omega$$

The X/R ratio is not specified for the substation. A value of 4.9 can be assumed. Using this value and the impedance, find X and R.

$$R = \frac{Z}{\sqrt{1 + (X/R)^2}} = \frac{0.0401}{\sqrt{1 + 4.9^2}} = 0.0080 \Omega$$

$$X = R * (X/R) = 0.0080 * 4.9 = 0.0393 \Omega$$

Step -6: Last is the 850 feet of number 2/0, 2 kV, shielded cable. From manufacturer's specifications, reactance of 1000 feet of this cable is 0.031 Ω . The reactance of 850 feet is 0.85 * 0.031 = 0.0264 Ω . From manufacturer's specifications, resistance of this cable at 20°C is 0.0839 Ω per 1000 feet. The minimum resistance (R_{MIN}) of 850 feet is 0.85 * 0.0839 = 0.0713 Ω . The maximum resistance is the resistance at the 90 °C rated operating temperature of mine power feeder cable.

$$R_{MAX} = R_{MIN} * [1 + \alpha(90 - 20)] = 0.0713 * (1 + 0.00393 * 70) = 0.0909 \Omega$$

Step-7: Now that all the resistances and reactances are calculated, we total them and calculate impedances and available currents.

Component	Minimum Resistance (Ω)	Maximum Resistance (Ω)	Reactance (Ω)
Utility	0.0021	0.0021	0.0112
Aerial Cable	0.0003	0.0004	0.0001
Substation	0.0013	0.0013	0.0065
Power Feeder Cable	0.0033	0.0042	0.0016
Power Center	0.0080	0.0080	0.0393
Trailing Cable	0.0713	0.0909	0.0264
Total	0.0863	0.1069	0.0851

$$Z_{MIN} = \sqrt{R_{MIN}^2 + X^2} = \sqrt{0.0863^2 + 0.0851^2} = 0.1212 \Omega$$

$$Z_{MAX} = \sqrt{R_{MAX}^2 + X^2} = \sqrt{0.1069^2 + 0.0851^2} = 0.1366 \Omega$$

$$I_{MIN} = \frac{0.95 * K_A V_{LL}}{2 * Z_{MAX}} = \frac{0.95 * 0.95 * 1040}{2 * 0.1366} = 3436 \text{ Amperes}$$

$$I_{MAX} = \frac{V_{LL}}{\sqrt{3} * Z_{MIN}} = \frac{1040}{1.732 * 0.1212} = 4954 \text{ Amperes}$$

The I_{MAX} and I_{MIN} values shall be used to size and set the circuit protective devices (circuit breakers and/or fuses). Sizing of circuit protective devices shall be done on maximum available short circuit current (I_{MAX}) and the setting of the devices shall be done on minimum available short circuit current (I_{MIN}).

Different types of circuit breakers have different settings that are available for long and short time delays, as well as ground fault tripping and instantaneous and inverse-time trips. For circuit breakers, time current curves are available. Selection of these settings changes how fast the circuit breaker reacts to a particular overcurrent. A reasonable design strategy would be to then specify electrical switchgear that has a “standard” rating above this calculated value. Using this approach however you must ensure that the standard rating used, is standard for the specific country where it is intended to purchase the switchgear. Standards do vary from country to country. In general, North American standards are different from the rest

of the world and the North American standard RMS symmetrical current ratings for low voltage circuit breakers are 14, 18, 22, 25, 30, 35, 42, 50, 65, 85, 100, 125, 150 and 200 kA. Further information is available in the National Electric Code. Other resources include manufacturer's guides for selecting protective devices for the appropriate application.

Conclusion

The "impedance" method is used to calculate fault currents at any point in an installation with a high degree of accuracy. Accurate calculations of available short circuit currents can be made without a power systems specialization in electrical engineering. Symmetrical components and the per-unit system can be left for more advanced analyses. Hand calculations can still be tedious though. A computer program can make the calculations simpler.