The Importance of the X/R Ratio in Low-Voltage Short Circuit Studies

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Introduction

In some short circuit studies, the X/R ratio is ignored when comparing the short circuit rating of the equipment to the available fault current at the equipment. What is not always realized is that when low-voltage gear is tested, it is tested at a certain X/R ratio. The X/R ratio is important because it determines the peak asymmetrical fault current. The asymmetrical fault current can be much larger than the symmetrical fault current. The purpose of this article is to introduce such terms as the X/R ratio and asymmetrical fault current and to relate the importance of the X/R ratio to the rating of low-voltage equipment.

Purpose of a Short Circuit Study

The purpose of a short circuit study is to determine whether or not electrical equipment is rated properly for the maximum available fault current that the equipment may see. The study is performed using computer software first by modeling the system (conductors, transformers, generators, utility sources, etc.) and then by simulating faults.

There are essentially four types of faults: three-phase, single line-to-ground, double line-to-ground, and line-to-line. Each of these types of faults can result in different magnitudes of fault current. In all types, however, there is a common element: an abnormally low-impedance path for current to flow. Such a condition can lead to extremely high currents.

By Ohm's Law, voltage equals current times impedance (resistance). Therefore, when the impedance becomes very low and the voltage does not change, the current becomes very high. Large electrical currents produce a lot of heat transfer, which increases the temperature of cables, transformers, etc. The increase in temperature can cause insulation damage. These currents also produce high magnetic forces, which can actually bend buses in switchgear. High fault currents cause magnetic forces that are proportional to the square of the fault current.

Obviously, fault conditions are undesirable. Therefore, protective devices like circuit breakers and fuses are used to remove the short-circuited part of the system from the power source(s). These devices are meant to interrupt very large electrical current. However, there are limits to how many amps they can interrupt. As was stated in the first paragraph of this section, the purpose of a short circuit study is to make sure that each protective device can open the highest calculated fault current that the device can see.

Depending upon whether the equipment is low voltage or medium voltage, there is a different process of comparing the fault current to the equipment rating. We will only discuss only low voltage gear, which is equipment rated at 600 volts or less.

Electrical devices (i.e., power circuit breakers, fuses, molded-case circuit breakers, transfer switches) have one of two types of ratings depending upon the type of device. The first type of rating is an interrupt rating. Devices that would have such a rating include circuit breakers and fuses. An interrupt rating refers to the maximum fault current that a device can interrupt.

The second type of rating is a withstand rating. Devices with withstand ratings are not intended to interrupt fault current, but rather to "ride through" a fault without damage. The rating reflects the device's ability to hold up during a fault.

In the following section, we will discuss fault currents in some more detail.

X/R Ratio and Asymmetrical Fault Current

In the previous section, we used Ohm's Law to say that if the voltage remains constant and the impedance decreases, the fault current increases. This is true. However, it does not take into account the dynamics of AC electrical systems. We must remember that a fault is a sudden event. Any time a sudden event occurs, the electrical system requires some time to adapt. Such a response is called a transient, which means that it lasts for only a short time.

In AC electrical systems, impedance has two components. The first is called reactance (X). Reactance depends on two things: (1) the inductance and (2) the frequency. Inductance reflects how hard it is to change the current. All conductors have some inductance, but a more useful example of a component having inductance is a coil of wire. Frequency is fixed at either 60 or 50Hz, depending upon where in the world the electrical system is, so the reactance is solely dependent upon the inductance.

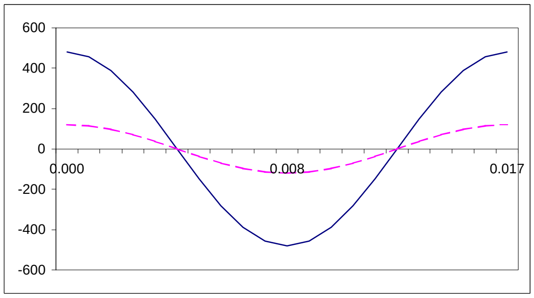
The second component of impedance is the familiar resistance (R). Resistance is a measure of how hard it is for current to flow. When current flows through a material having resistance, heat is transferred from the material to the surroundings.

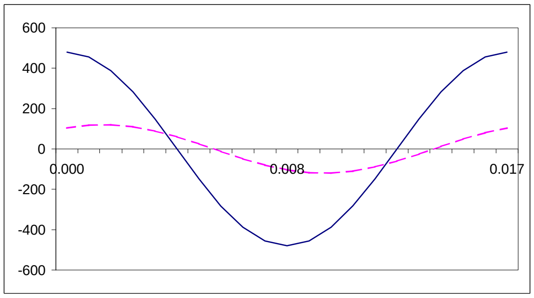
The resistance and reactance of a circuit establishes a power factor. The power factor (p.f.) is given by the following equation:

$$p.f. = \cos(\tan^{-1}(X/R))$$

If the power factor is unity (1), then the impedance only has resistance. If the power factor is zero, then the impedance only has reactance.

The power factor also determines how much the voltage and current waveforms (sine waves) are out of phase. Remember that both voltage and current are sine waves in linear AC electrical systems. For purely resistive systems, the voltage and current are in phase. For purely reactive systems, the voltage and current are 90-degress (one-quarter of a cycle) out of phase, with the voltage leading the current. Figure 2 below illustrates this.





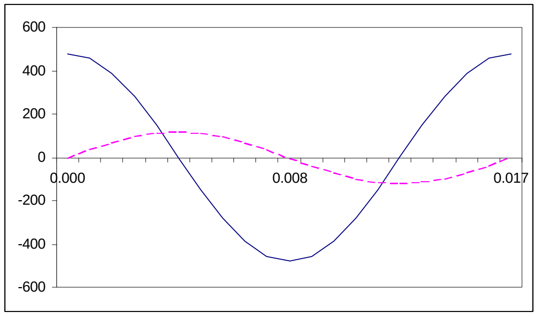


Figure 2. Effect of power factor upon voltage (-------) and current (- - - - - -) waveforms.

The above equation means that the power factor and X/R ratio are related. Therefore, power factor and X/R ratio are different ways of saying the same thing. Please note that as power factor decreases, the X/R ratio increases.

Right after a fault occurs, the current waveform is no longer a sine wave. Instead, it can be represented by the sum of a sine wave and a decaying exponential. Figure 3 below illustrates this phenomenon.

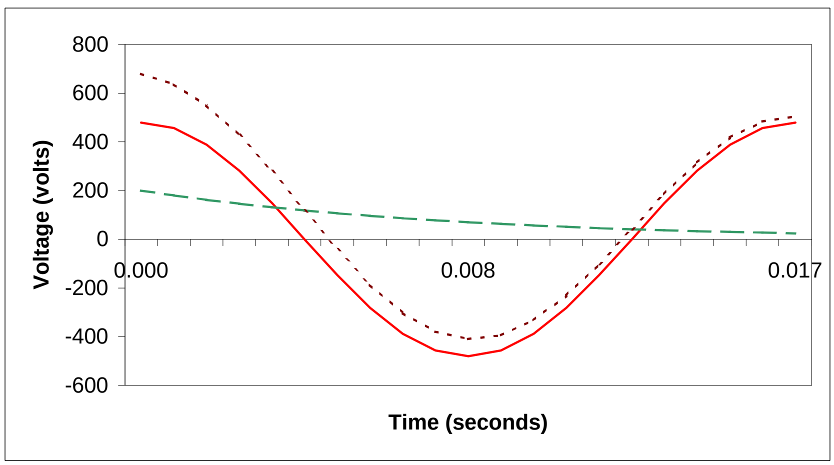


Figure 3. Sine wave (-------), decaying exponential (- - - - -), and their sum (·······).

Please note that the decaying exponential added to the sine wave causes the current to reach a much larger value than that of the sine wave alone. The waveform that equals the sum of the sine wave and the decaying exponential is called the asymmetrical current because the waveform does not have symmetry above and below the time axis. The sine wave alone is called the symmetrical current because it does have symmetry above and below the time axis.

The actual waveform of the asymmetrical fault current is hard to predict because it depends on what time in the voltage cycle waveform the fault occurs. However, the largest asymmetrical fault current occurs when a fault happens at a point when the voltage is zero. Then, the asymmetrical fault current depends only on the X/R ratio, or power factor, and the magnitude of the symmetrical fault current.

Figure 4 below shows how the ratio of the peak asymmetrical current to the RMS symmetrical current varies with the X/R ratio. (RMS symmetrical current equals the peak symmetrical current divided by the square root of 2.) What Figure 4 shows is that the peak asymmetrical current increases with the X/R ratio.

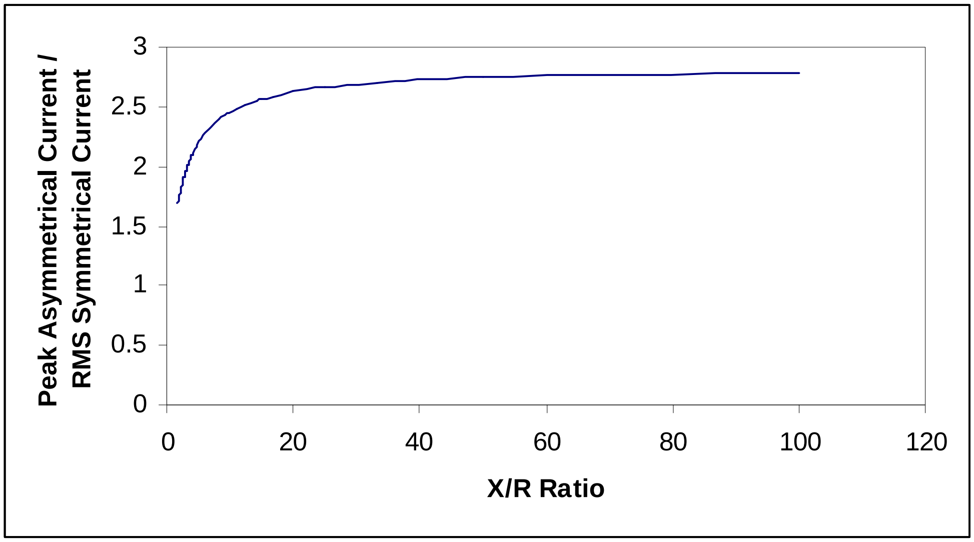


Figure 4. Peak asymmetrical current as a function of symmetrical RMS current. (Data taken from notes on the GE Electrical Distribution & Control Low-voltage Protector Application Seminar.)

Role of X/R Ratio when Comparing Short Circuit Ratings

Low voltage devices have one rating, as opposed to medium-voltage gear which have both a momentary and interrupting rating. This rating is reported in terms of symmetrical current. Therefore, the rating must be compared to the calculated symmetrical current.

But the story does not end here. All low voltage protective devices are tested at an X/R ratio. The X/R ratio at which a device is tested depends upon the device type. Table 1 below summarizes the device types and the X/R ratios at which they are tested.

Table 1. X/R ratios at which low voltage protective devices are tested.

Device Type	Test X/R Ratio	Test Power Factor
Low Voltage Power Circuit Breakers	6.6	0.15
Fuses, Fused Low Voltage Power Circuit Breakers, Insulated Case Circuit Breakers, Molded Case Circuit Breakers (rated >= 20kA)	4.9	0.20
Molded Case Circuit Breakers (rated > 10kA and < 20kA)	3.2	0.30
Molded Case Circuit Breakers (rated <= 10kA)	1.7	0.50

Although low voltage devices do not have asymmetrical ratings, if we know the symmetrical current rating and the test X/R ratio, Figure 4 gives us the maximum asymmetrical fault current. So, in a way, there is an asymmetrical fault current rating, but it is not explicit. Therefore, in any short circuit study, both the X/R ratio and the symmetrical fault current must be taken into account.

Remember that, for a calculated value of RMS symmetrical current, as X/R ratio increase, the maximum asymmetrical current (peak or RMS) also increases.

If the calculated symmetrical fault current is larger than the device short circuit rating, the device in underrated, regardless of X/R ratio. However, it is possible for the device to be underrated even if the short circuit rating exceeds the calculated symmetrical fault current. How is this possible? We will discuss this next.

Consider some equipment whose calculated symmetrical fault current is less than the short circuit rating of the equipment. Also, the calculated X/R ratio is less than or equal to the test X/R ratio. The maximum calculated asymmetrical fault current will be less than the maximum asymmetrical current that corresponds to the short circuit rating and the test X/R ratio. The device will be properly rated.

Now consider another possibility. What if the symmetrical fault current is the same as the equipment's rated current, but the actual X/R ratio is larger than the tested X/R ratio? Now, the maximum asymmetrical fault current will be larger than the maximum asymmetrical current corresponding to the short circuit rating and the test X/R ratio. Although the available symmetrical fault current is equal to the rating, the asymmetrical fault current is higher than that when the device was tested. The device is not rated properly.

The above two paragraphs motivate a de-rating factor, or multiplying factor (MF), that is defined by the following formula:

$$MF = \frac{I_{asym} @ X / R_{CALCULATED}}{I_{asym} @ X / R_{TESTED}}$$

If the calculated X/R ratio at a device is larger than the test X/R ratio of the device, then the calculated symmetrical fault current must be multiplied by the multiplying factor. Or, equivalently, the short circuit rating must be divided by the multiplying factor. The multiplying factor is equal to the ratio of the calculated asymmetrical fault current to the asymmetrical fault current at the test X/R ratio and the rated symmetrical current.

Here is an example of the process. After running a fault analysis, the symmetrical fault current at some low voltage switchgear is found to be 62kA during the first half-cycle. The switchgear contains power circuit breakers rated at 65kA. The asymmetrical peak fault current was found to be 149kA. The X/R ratio was calculated to be 11.1.

The test X/R ratio of low voltage power circuit breakers is 6.6. Although the symmetrical fault current is lower than the rating of the circuit breakers, the fact that the X/R ratio is higher than the test value means that we must use the multiplying factor.

$$MF = \frac{149}{139} = 1.07$$

Therefore, the effective symmetrical fault current is 1.07 X 62kA = 66kA. Because 66kA > 65kA, the switchgear is underrated. We can also de-rate the switchgear. Then, the effective rating of the gear is 65kA / 1.07 = 61kA. Now, because 62kA > 61kA, the switchgear is underrated.

<u>Summary</u>

When performing short circuit calculations, it is important to consider the X/R ratio. The higher the X/R ratio, the higher the asymmetrical peak fault current. Therefore, when verifying the ratings of electrical equipment, both the symmetrical short circuit rating and the X/R ratio must be taken into consideration.

If the calculated X/R ratio is larger than the test X/R ratio, then the equipment short circuit rating must be de-rated by a multiplying factor. This multiplying factor equals the ratio of the calculated peak asymmetrical fault current divided by the peak asymmetrical current corresponding to the rated symmetrical current and the test X/R ratio.

About the Author

John Merrell is an electrical engineer at Power Systems Engineering, P.S.. Mr. Merrell graduated from the University of Washington with a B.S.E.E. degree in 1999. Prior to graduating, Mr. Merrell worked at ALSTOM ESCA in Bellevue, WA. There he assisted in the development and testing of a graphical user interface for web based power software.

At Power Systems Engineering, he is responsible for performing short circuit, harmonic, load flow, and protection device coordination studies for industrial, commercial, and utility clients. Based outside of Seattle, Washington since 1986, Power Systems Engineering is an electrical engineering consulting firm specializing in power systems studies, power quality, and commissioning services. Customers include Boeing, Microsoft, University of Washington, General Electric, Siemens, Square D, Cutler-Hammer, and many others. Our web page address is www.powerstudies.com.