

AC SYSTEM IMPEDANCE TESTING

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ABSTRACT

Occasionally, a mining company extends its power system to the point where the calculated available trailing cable short-circuit current approaches the overcurrent protection setting of the system. Since theoretical calculations depend upon approximations of the power system components, a method to evaluate these calculations with empirical data is needed. This paper will discuss a test method to determine the impedance of an ac system. In addition to discussing this method, fault calculations and impedance measurements obtained from field testing will be compared with a theoretical analysis.

INTRODUCTION

Part of the mission of Technical Support's Mine Electrical Systems Division, of the Mine Safety and Health Administration is to provide engineering assistance to resolve safety problems related to the use of electricity in mines. This work has necessitated the development of unique testing procedures for diagnostic purposes. In this case, a test procedure was developed to determine system impedances and available fault currents.

One of the advantages of measuring the ac impedance of an electrical distribution system of a mine is that accurate calculations of fault currents can be made. The method presently used by mining companies to determine short-circuit currents is based on theoretical calculations. These calculations rely on information from the utility company that supplies power to the mine substation. Other data needed for the analysis are impedance values for each transformer in the system, as well as resistance and reactance values for all associated cables. The theoretical calculations for determining the system impedance use these values that are supplied by manufacturers and which can deviate from actual values. Therefore, errors can occur in the calculation for the amount of available fault current. Also, when the calculations result in values which indicate a small safety factor between settings on protective equipment and calculated short-circuit currents, in-mine testing may be needed to validate the theoretically calculated values.

The test procedure that will be discussed is simple to use and can be expected to be accurate within

10% for a system with a power factor of 0.90 or greater. This power factor is not the usual power factor that we normally relate to, but it is the power factor under a short-circuit condition at the end of the trailing cable, and does not include motor contributions. The test instrumentation and equipment used are not specialized and are normally available at most mines.

MINE POWER SYSTEM DISCUSSION

A test procedure was developed to measure the estimated power system impedance at the end of a trailing cable. To understand why the method works, certain information about the physical components of the system must be known. The one-line diagram in figure 1 shows a typical three-phase faulted power system.

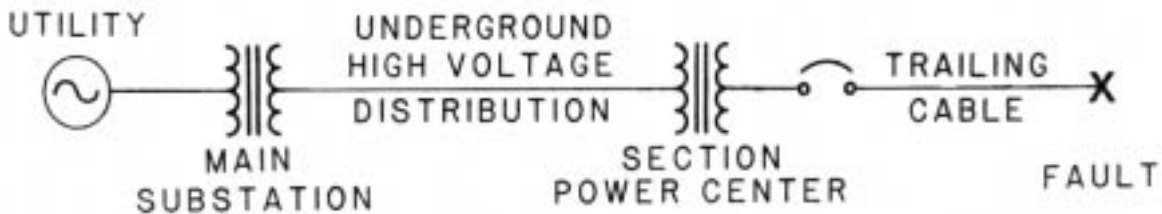


Figure 1. One-Line Diagram of a Three-Phase Faulted System

The impedance of each component in the power system is considered in determining the total system impedance, Z_{SYS} . To illustrate, typical impedance values of each of these components will be discussed. In this example, the power system source will have infinite buss (or be stiff).

The electric utility system delivering power to a mine is the source of short-circuit current. But the current contribution to a fault at a distant section of the mine will appear to be merely a small increase in the load current at the utility [1]. Since the utility current will essentially be unchanged, its impedance value, Z_U , will have very little influence on a section fault in by the power center secondary. Therefore, the utility impedance has limited effect on the system impedance and can be excluded from the calculations.

At a typical mine, the main substation transformer supplying power underground has a capacity of 3,000 kVA with a primary voltage of 69,000 volts, and a secondary distribution voltage of 7,200 volts [3]. This type of transformer will have approximately 7.0 percent impedance [2]. Since the resistance component of such a transformer is small, the impedance, Z_{sub} , is considered to be equal to the reactance [5].

High voltage (7,200 volts) underground distribution cables may extend up to 15,000 feet to the most distant mining section [4]. The typical size of power feeder cables used underground is #4/0 AWG. A resistance value of 0.9750 ohms, and a reactance value of 0.5100 ohms, are obtained for this size feeder cable [6] based on the maximum distance of 15,000 feet.

An average size section power center can have a transformer rated at 750 kVA, with a secondary utilization voltage of 480 volts [7]. The impedance of this type of transformer is 5.75% [2], and the values of resistance and reactance, will be 0.0035 ohms and 0.0174 ohms respectively [8].

Using the above information, the impedance of the source, Z_s , (power center and the electrical distribution system outby), can be found by combining the individual components together after they are converted to a common base. Since there are few voltage transformations, representation of system components in ohms-per-phase provides the most straightforward calculations [9]. For comparison, the resistance and reactance of the components just discussed are calculated using a base voltage of 480 volts, and are listed in table 1. The calculations produce a source impedance of $0.0263 \angle 73^\circ$ ohms.

Source Components		Impedance Values	
		R (ohm)	X (ohm)
Z_U	Utility	---	---
Z_{Sub}	Main Substation	0.0000	0.0054
Z_D	Distribution	0.0043	0.0023
Z_{PC}	Power Center	0.0035	0.0174
Z_s	Source (Total)	0.0078	0.0251
Table 1. Impedance Values for Components of the Source, Calculated Using a 480 Volt Base			

A number 4 AWG, 3-conductor trailing cable is used in this illustration. This size trailing cable is usually used on roof bolters and ac shuttle cars, and can have a maximum length of 600 feet. Therefore, it will have maximum resistance and reactance values of 0.2082 ohms and 0.0186 ohms respectively [6], and the impedance is $0.2090 \angle 5^\circ$ ohms.

When the impedance values of the source and trailing cable are compared, as in table 2, it becomes clear that the predominant component is the trailing cable. It can be further deduced that the trailing cable resistance is the dominant element in the power system impedance. This is because the trailing cable resistance comprises 96% of the total system's resistance and is about 5 times the system reactance. By combining the source impedance and the trailing cable impedance, the system impedance ($Z_{SYS} = 0.2204 \angle 11^\circ$ ohms) is found which, as can be seen, is essentially resistive.

Source Components		Impedance Values	
		R (ohm)	X (ohm)
Z_S	Source	0.0078	0.0251
Z_{TC}	Trailing Cable	0.2082	0.0186
Z_{SYS}	System	0.2160	0.0437

Table 2. Impedance Values for Components of the System,
Calculated Using a 480 Volt Base

Once the system impedance is known, the fault current can be calculated. The value obtained is only an estimate, however, because the impedances for the individual components from published reference materials are not exact. Also, the calculations are based on a symmetrical three-phase system, which will not necessarily be true since various mine loads may introduce factors which could slightly unbalance the phases.

MEASUREMENT TECHNIQUE

The most exact way to determine the short-circuit current is to place a bolted fault intentionally on the mine power system at the end of a trailing cable, but this is not a realistic method to determine fault currents. Also, equipment protective devices on the power center would interrupt the current in the trailing cable before measurements could be made. Prudent test procedures and safe engineering practice necessitate limiting the test fault currents. Therefore, a more realistic and practical method is to insert a low resistance power resistor in the circuit in place of the fault. The effects of this resistor are subtracted from the measurements when the system impedance is found. Using this test procedure the power system impedance at the end of a trailing cable can be measured, and hence the fault current can be determined.

As discussed previously, if the system impedance is predominately resistive, then a single point test method can be used to measure the system impedance. The per phase impedance of the power system is represented in figure 2 below, being energized by an ideal voltage source.

The test method for measuring the system impedance is performed in two steps. Initially, the no load voltage at the terminals of a section power center is measured as shown in figure 2. Then, as shown in figure 3, a resistive load is connected to the power center and the current and voltage are measured at the load resistor.

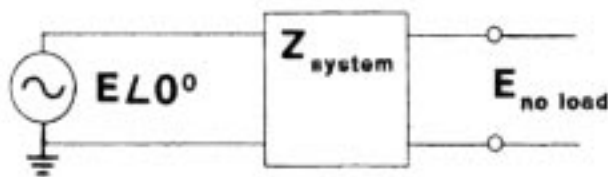


Figure 2. Single-Phase Equivalent Circuit for a Mine Power System, Under No Load Conditions

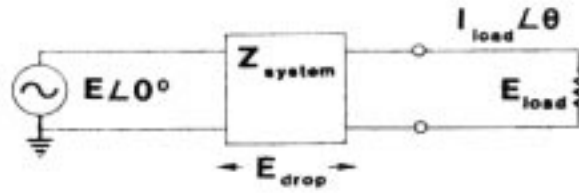


Figure 3. Single-Phase Equivalent Circuit for a Mine Power System, Under Load Conditions

Once the no load voltage, load voltage and current are measured, the system impedance can be calculated by dividing the voltage drop across the system impedance by the current passing through the system as expressed below.

$$\begin{aligned}
 Z'_{SYS} &= Z_t - R_l = \frac{E_{NL}}{I} - \frac{E_L}{I} \\
 &= \frac{E_{NL} - E_L}{I} = \frac{E_D}{I}
 \end{aligned}
 \tag{1}$$

- where:
- Z'_{SYS} = Calculated system impedance, in ohms per phase
 - Z_t = Total test impedance
 - R_L = Measured load resistor impedance
 - E_D = Voltage drop across the system impedance, in volts/φ
 - E_{NL} = No load voltage, phase to neutral, in volts/φ
 - E_L = Load voltage, phase to neutral, in volts/φ
 - I = Load current, in amperes

The phase angle, θ , can usually be ignored in these calculations because the resistance in the trailing cable, being much greater than the system reactance, will be the dominant factor. Having an impedance that is predominantly resistive will produce a phase angle near zero. This simplified analysis is valid for specific conditions and contains inherent limitations, which will be discussed in the following section.

Using the above measured data, the short-circuit current at a fault on the end of a trailing cable can now be calculated. The three-phase fault, calculated on a per-phase basis is the first one considered. This type of fault will result in the maximum short-circuit current [10]. In the equation below, the voltage, $E_{\phi\phi}$, is at the point where the system will be faulted. This value should be close to the maximum operating voltage under fully loaded system conditions.

Voltage per phase:

$$E_{\phi N} = \frac{E_{\phi\phi}}{\sqrt{3}} \quad (2)$$

A balanced three-phase bolted fault provides the maximum expected fault current.

Three-phase bolted fault current (to end of trailing cable).

$$I_{SC3} = \frac{E_{\phi N}}{Z_{SYS}} \quad (3)$$

The single phase-to-phase bolted fault current is used to determine the circuit breaker setting.

Single phase-to-phase bolted fault current (to end of trailing cable).

$$I_{SC1} = \left(\frac{\sqrt{3}}{2} \right) \frac{E_{\phi N}}{Z_{SYS}} \quad (4)$$

$$= 0.87 \times I_{SC3} \quad (5)$$

ERROR ANALYSIS

In an effort to simplify the test method and analysis, certain assumptions were made concerning the characteristics of the system impedance. These assumptions will be analyzed to reveal potential errors that may be introduced into the calculated system impedance.

The single point test measurement technique, as previously described, does not provide information related to the test system phase angle, ϕ , as shown in figure 4. Not knowing this phase angle, ϕ , prohibits complete quantification of the system impedance. To overcome this missing phase angle measurement, the test method assumes the power system impedance is primarily resistive. The power system is then analyzed without consideration of the phase shifting effects of the smaller reactive components, as shown in equation 1. This approach is justified since the trailing cable resistance was shown to be the predominant element of the power system impedance.

The system impedance calculations are simplified by subtracting the magnitude of the test load resistance directly from the total test impedance without regard to the phase angle. Since the power system is not purely resistive this analysis technique introduces an analytical error, ER, into the system impedance calculations, as illustrated in figure 4. This analytical error pertains only to the

procedure; it is not the error that would be associated with the measurement, as this error can make even more of a difference.

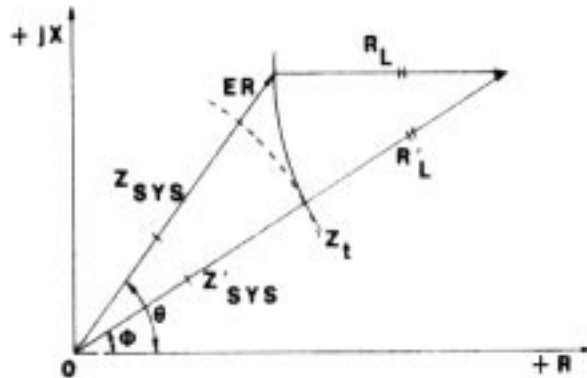


Figure 4. System Impedance Error Analysis Diagram

where:

\vec{Z}_{SYS}	=	True system impedance
\vec{Z}'_{SYS}	=	Calculated system impedance
\vec{Z}_t	=	Total test impedance
\vec{R}_L	=	Measured load resistor impedance (all resistive)
R'_L	=	Load resistor magnitude
θ	=	True system phase angle under bolted fault condition
ϕ	=	Total system phase angle under test condition
ER	=	Analytical error

The system impedance error analysis diagram was constructed by first plotting the true system impedance vector, \vec{Z}_{SYS} , at an exaggerated phase angle, θ , for illustrative purposes. The test load resistance, R_L , (shown as a smaller magnitude than used in actual practice) is then added vectorially to the system impedance. This vector summation yields the total test impedance, \vec{Z}_t , at an unknown phase angle, ϕ , as measured during testing. The magnitude of R_L (shown in the diagram as R'_L), is subtracted from the magnitude of \vec{Z}_t without regard to the unknown phase angle, ϕ , to calculate the system impedance, \vec{Z}'_{SYS} . The analytical error, ER , becomes evident when the calculated system impedance, \vec{Z}'_{SYS} is reflected onto the true system impedance, \vec{Z}_{SYS} , as illustrated by the dashed arc line.

With the aid of the system impedance error analysis diagram in figure 4, the analytical error can be derived from a mathematical relationship between the system impedance, load resistor, and phase angle, θ .

$$Z_{SYS} = Z_{SYS} \cos \theta + j Z_{SYS} \sin \theta \quad (6)$$

$$Z_t = R_L + Z_{SYS} \cos \theta + j Z_{SYS} \sin \theta \quad (7)$$

$$Z_t = \sqrt{(R_L + Z_{SYS} \cos \theta)^2 + (Z_{SYS} \sin \theta)^2} \quad (8)$$

$$= \sqrt{R_L^2 + 2R_L Z_{SYS} \cos \theta + Z_{SYS}^2} \quad (9)$$

% analytical error

$$= 100 \left[1 - \left(\frac{Z_t - R_L}{Z_{SYS}} \right) \right] \quad (10)$$

$$= 100 \left[1 - \left(\frac{\sqrt{R_L^2 + 2R_L Z_{SYS} \cos \theta + Z_{SYS}^2} - R_L}{Z_{SYS}} \right) \right] \quad (11)$$

Values were substituted for the variables shown in equation (11) to determine the range of percent analytical error that can be expected for a typical mine power system impedance test. The values used for the variables were: $Z_{SYS} = 0.2204 \angle 11.4^\circ$ ohms for the typical system impedance discussed earlier; $R_L = 1.32$ ohms for actual test that will be discussed later; and the $\cos \theta$ (power factor) ranging from 1.00 to 0.89 the maximum expected range at the end of a trailing cable. The sensitivity analysis graph generated by this substitution procedure shows the percent analytical error vs the system phase angle relationship in figure 5. The dashed lines indicate an analytical error of 1.7% that would be generated for a phase angle of 11.4° (power factor of 0.98) if the typical mine system was tested using this procedure.

The sensitivity graph demonstrates that the percent error is inversely proportional to the system power factor ($\cos \theta$). However, even with a faulted system power factor of 0.90 the analytical error is less than 10%.

