Improvement of Ground-Fault Relaying Selectivity through the Application of Directional Relays to High-Voltage Longwall Mining Systems

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ABSTRACT

The continuing trend toward larger longwall mining systems has resulted in the utilization of higher system voltages. The increase in system voltage levels has caused the industry to face complexities not experienced with the lower-voltage systems. One such complexity arises from the larger system capacitance that results from the outby configuration commonly used on 4,160-V longwall power systems. Simulations show that during a line-to-ground fault, the larger system capacitance can cause a situation where the ground current sensed by the ground-fault relays in unfaulted circuits is greater than the mandated ground-fault relay pick-up setting. Simulations show that ground-fault relaying selectivity is potentially lost as a result of this situation. Two alternatives were identified which could improve ground-fault relaying selectivity. They are: the application of a directional relaying scheme and increasing the ground-fault relay pick-up setting. It was determined that directional relays have an application to high-voltage longwall power systems as the ground current sensed by the relay in the unfaulted circuits is out of phase with the ground-fault current sensed by the relay in the faulted circuit. Furthermore, it was determined that raising the ground-fault relay pick-up setting by a factor of eight would also improve ground-fault relaying selectivity. A safety analysis considering the potential for electrocution and the power dissipated by the maximum fault resistance showed that increasing the pick-up setting by a factor of eight would have no detriment to safety. Therefore, either method would improve ground-fault relaying selectivity on high-voltage longwall mining systems, yet because of the escalating size of longwall systems, a directional relaying scheme is a longer term solution.

This thesis is dedicated to Judy Mullins.
Her exceptional kindness and support made an
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GLOSSARY OF ABBREVIATIONS, TERMS, AND UNITS OF MEASURE

A	ampere	mA	milli-ampere
AFC	armored face conveyor	µF	mirco-farad
AWG	american wire gauge	mH	milli-henry
C	capacitance [F]	ms	milli-second
CT	current transformer	NGR	neutral ground resistor
E_o	zero-sequence voltage [V]	^{o}	degree
ϕ	angle	P	power [kW or Hp]
η	efficiency	*pf*	power factor
F	farad	Q	reactive power [kVAR]
H	henry	R	resistance [Ω]
Hp	horsepower	s	second
Hz	hertz	S	apparent power [kVA]
I	current [A]	SHD	shielded
kcmil	kilo-circular mils	SHD-GC	shielded with ground check
kV	kilo-volt	V	volt [V]
kVA	kilo-volt ampere	VA	volt ampere
kVAR	kilo-volt ampere reactive	VT	voltage transformer
kΩ	kilo-ohm	Ω	ohm
kW	kilo-watt	Z	impedance [Ω]
L	inductance [H]	%	percentage

Chapter 1. Introduction

1.1 General

A notable increase in the voltage level supplied to longwall mining systems has occurred over the past two decades. Longwalls utilizing 1,000 V or less have been phased out during this period by systems utilizing 2,400 V or 4,160 V. Prior to 1986, the maximum voltage used on longwall mining systems in the United States was 1,000 V. Figure 1 shows the combined trends of the utilization voltages from 1986 to 2003.

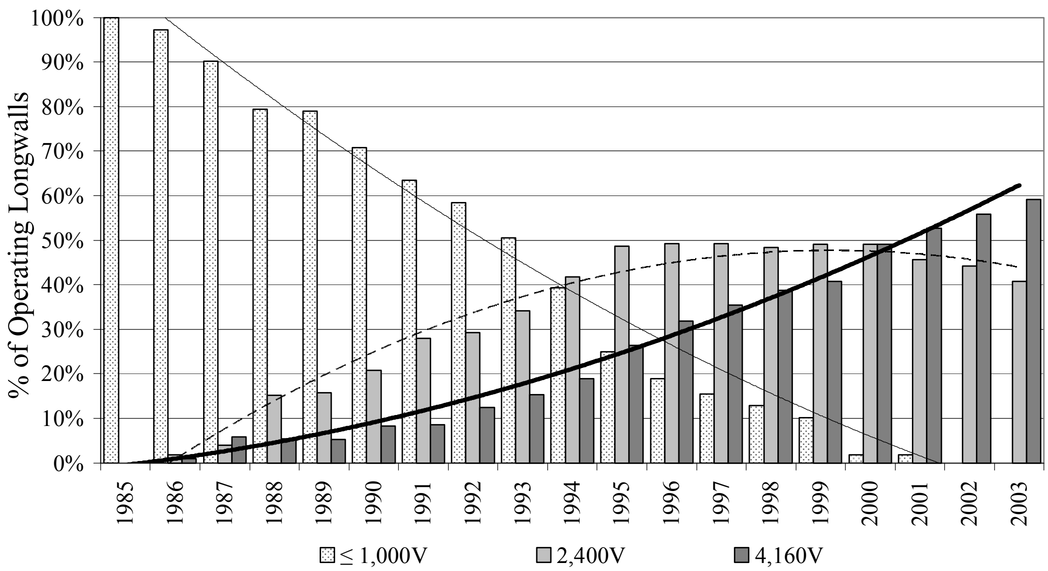

Fig. 1. Combined trends of utilization voltages.

The transition from the use of low-voltage (≤ 660 V) and medium-voltage (661 V – 1,000 V) to high-voltage (≥ 1,000 V) on longwall face equipment has been driven by the objective to achieve increased production levels from fewer operating units. To achieve this increased level of production, longwall panel width has substantially increased over the past two decades. The average longwall panel width has increased from 620 feet in 1986 to over 960 feet in 2004, which is equivalent to a 55% increase. The depth of the cutting web on the shearer has also increased. The average cutting depth has increased from 30 inches in 1986 to almost 38 inches in 2004, which is equivalent to a 26% increase. These sizeable changes have resulted in an increased power requirement for the face equipment. Low and medium-voltage became inadequate for powering the higher capacity motors that were being demanded by industry. The trend toward larger and more complex longwall systems has resulted in a corresponding increase in the size of longwall components as well as the standardization to high-voltage utilization (Basar and Novak, 2003).

The transition to the higher voltages followed a natural progression by taking incremental steps from low and medium-voltage levels to 2,400 V and ultimately 4,160 V. Initially, 2,400-V was utilized as the next logical step above the medium-voltage level (Novak et. al, 2003). The first experimental permit for purely high-voltage on-board switching was granted for a 2,400-V longwall system in July of 1985 (Boring and Porter, 1988). As 2,400-V systems proved their reliability, 4,160-V systems gained popularity. There were also a number of hybrid systems in operation (2,400 V or 4,160 V for the face conveyor motors and 995 V for all other equipment) during the transitional period from medium to high-voltage (Novak and Martin, 1996). An increasing trend of 4,160-V utilization began in the early 1990's and continues today. During the early part of this decade the percentage of longwall units operating at 2,400 V began to steadily decline, again in favor of the 4,160-V systems. In 2000, the 4,160-V system surpassed the 2,400-V system in total number of operating units.

The increase in voltage level has caused the industry to face complexities not experienced with the lower-voltage systems. In an effort to ensure safety, Federal Regulations have more stringent requirements for high-voltage systems. High-voltage systems are mandated to have lower neutral grounding resistor (NGR) current limits, lower ground-fault relay pick-up settings, and are, like the medium-voltage systems, required to use shielded cables (Electrical Protection, 30CFR§75.814). These requirements directly affect how the system responds during ground-fault events. As will be shown, this is especially the case with the outby[1] topology of the 4,160-V system.

1.2 Statement of the Problem

Initial research showed that the increased capacitance from the longer cable runs that result from the outby configuration commonly used on the 4,160-V longwall power systems can create a situation where the capacitive charging current that returns through the unfaulted circuits during ground-fault events is large enough to cause spurious tripping (Novak 2001-a, 2001-b, Novak et. al 2003, Novak et. al, 2004). When spurious tripping occurs, ground-fault relaying selectivity is lost. A loss of ground-fault relaying selectivity on a 4,160-V system may adversely affect both employee safety and longwall productivity.

The capacitance in the 4,160-V system results primarily from the shielded configuration of the power cable (Novak et. al 2004). Figure 2 shows the cross section of a typical shielded, SHD-GC, high-voltage mining cable. Figure 2 also shows the nature of the capacitance resulting from the shielded configuration of the cable. The total capacitance in the system varies linearly with cable length. The outby switching configuration that is most commonly used on 4,160-V systems dramatically increases the total system capacitance, as compared with the inby[2] configuration used on 2,400-V systems, as the total length of cable is increased over 100%. The outby configuration is preferred by industry since the motor-starting switchgear is kept more than 150 feet outby the

[1] The term outby is defined as away from the working face or toward the mine entrance.
[2] The term inby is defined as toward the working face, or interior, of the mine.

longwall face and therefore does not have to be housed in an explosion proof enclosure (Novak and Martin, 1996).

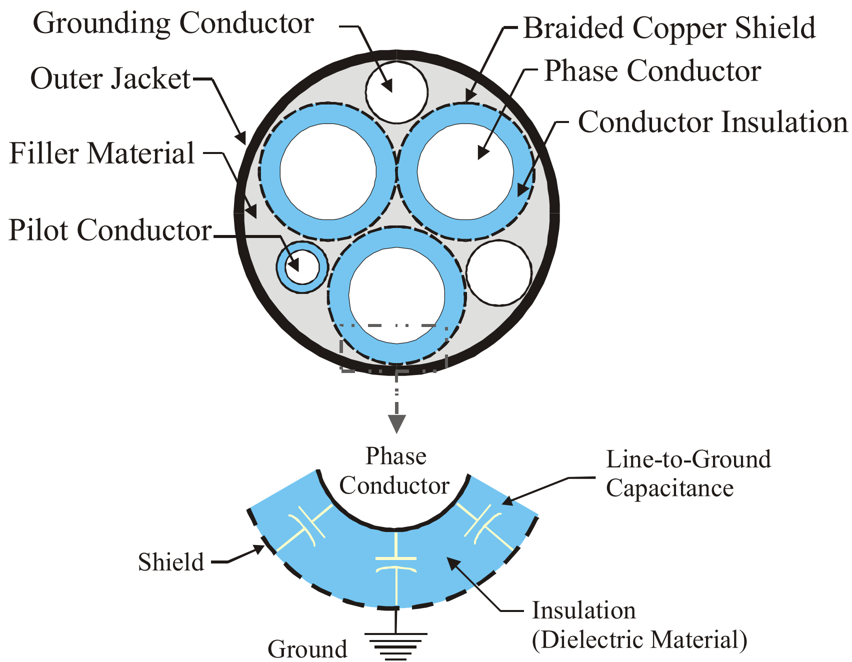

Fig. 2. Cross-section of an SHD-GC type cable.

A low ground-fault relay pick-up setting increases the potential for the capacitive charging current to cause spurious tripping of unfaulted circuits within the longwall power system. The ideal ground-fault relay pick-up setting should be low enough to protect against electrical hazards, mainly the risks associated with electrical shock, yet should be set at the highest non-hazardous level to help avoid spurious tripping of unfaulted circuits during ground-fault events. Therefore, the Federal Regulation that mandates the relay pick-up setting also directly affects relaying selectivity within the system. Subsequently, the mandated relay pick-up setting has been criticized as being unnecessarily low (Novak, 2001-b). As a result, a question has arisen as to the actual ramifications that the relay pick-up setting has on safety. Determining the effect that raising the relay pick-up setting has on safety is important in determining potential opportunities to improve relaying selectivity on high-voltage longwall power systems.

Problems with the ground-fault relay pick-up setting mandated by the Mine Safety and Health Administration (MSHA) have been corroborated by a major longwall operator. In conducting additional background research into relay pick-up settings, it was also found that MSHA has recently written a citation to a longwall operator for violating the relay pick-up setting. The company was citied for "…failing to set the circuit breakers to trip at the required amperage" (MSHA vs. Loadstar Energy, 2003). The fact that the relays were improperly set offers some evidence that problems do exist.

1.3 Scope of Research

The conducted research concentrated primarily on improving ground-fault relaying selectivity on 4,160-V longwall mining systems. For a three phase system, various types of faults are possible: a three-phase fault, phase-to-phase faults, phase-to-ground faults, and double phase-to-ground faults. The importance of ground-fault protection cannot be overemphasized as ground is involved in 75 - 85% of all fault events (Horowitz and Phadke, 1995). To perform an analysis of ground-fault relaying selectivity only line-to-ground faults need to be analyzed as a separate set of protective devices are employed to protect against multi-phase faults.

The research was performed by using a computer based model of an average size 4,160-V longwall power system to determine the systems behavior during ground-fault events. The original model was created from previous research performed on a similar topic (Novak 2001-a, 2001-b). Improvements were made to the model that focused on determining more accurate resistances for the ground conductors as well as a more accurate representation of the topology of the longwall power system. The size of the equipment components was determined from the annual Longwall Census published in Coal Age magazine (Fiscor, 2004).

Included in the research was an investigation into the effect that the ground-fault relay pick-up setting has on safety. The improved model was used to determine the touch potential that exits over a range of pick-up settings and values of body resistance. The results were then compared to the physiological response of humans to electrical shock to determine the risk hazard.

1.4 Thesis Structure

This thesis provides commentary on electrical safety and includes an explanation of high-resistance grounding and ground-fault protection schemes for 4,160-V longwall power systems. A detailed description of the model that was developed to simulate ground-fault scenarios on an outby 4,160-V system will be given, along with the methodology used to determine the component values in the model. The results of the simulations performed for the various ground-fault scenarios will then be presented.

Two potential methods to improve ground-fault relaying selectivity were identified and evaluated for their effectiveness. The two methods evaluated were the use of directional ground-fault relay protection, and raising the magnitude of the ground-fault relay pick-up setting. Based on the evaluations, recommendations will be made on how ground-fault relaying selectivity can be improved.

Chapter 2. Background and Literature Search

2.1 General

Safety is the primary concern when designing a power system. Unfortunately, the harsh environment of underground coal mining adds many variables that can cause short circuit conditions (Novak et. al, 2004). As a result, a power system's protection scheme must be robustly designed to prevent injury. It is dually important to ensure that the system's performance is not compromised. The remainder of this chapter is dedicated to providing background information on subjects ranging from electrical safety to the power system protection schemes currently being used on 4,160-V longwall mining systems.

2.2 Electrical Safety

Between 1990 and 1999, electrical accidents were the fourth leading cause of death in the mining industry (Cawley, 2003). During this period, the data showed that fatalities were *ten times more likely* to occur when the accident involved electricity. Electrical accidents tend to occur less frequently than other types of accidents, yet when they do occur they tend to be far more severe.

The most frequent type of electrical accident involves electrical shock. Injuries from electrical shock result from current flowing through the human body. The severity of the electric shock is dependent upon the exposure time as well as the magnitude and frequency of the current (Novak et. al, 1988). The estimated effects of 60 Hz currents which pass through the body are provided in Table 1.

Table 1. Physiological response to current.

Current Level	Physiological Response
1.1 mA	Barely perceptible
6.0 mA	Maximum Let-go current
50.0 mA	Ventricular Fibrillation
2.0 A	Cardiac Standstill

The table reports that a current of 1.1 mA is barely perceptible to the touch, while a current of 6.0 mA can cause involuntary contraction of flexor and extensor muscles in the forearm resulting in the inability for a victim to let go of any objects being held (DHHS, 1998). A current of 50 mA to approximately 2.0 A may cause ventricular fibrillation. Ventricular fibrillation can lead to a quick death from lack of oxygen to the brain.

Ventricular fibrillation poses the greatest risk of death from electrical shock. Extensive research has been conducted to determine the time-current characteristic which can cause ventricular fibrillation (Sottile and Novak, 2001). One method was developed by Daziel (Daziel and Lagan, 1941, Daziel, 1954, Daziel and Lee, 1969). Daziel's alternating current (ac) fibrillation prediction can be written to determine the maximum non-fibrillation current for the total circuit clearing time (Novak et. al, 1988). The equation is shown as follows,

$$\mathbf{I} = \frac{116}{\sqrt{t_1 + t_2}} \quad (8.3 \text{ ms} \leq t \leq 5.0 \text{ s})$$

where, I is the body current (mA),
t_1 is the relay operating time (s), and
t_2 is the circuit interrupter operating time (s).

To determine the ac fibrillation prediction for a protection system, the total clearing time must be estimated. A generally accepted standard for relay operating time is 1 - 3 electrical cycles (Horowitz and Phadke, 1995). For a 60 Hz system, one electrical cycle is completed every 0.0167 s. A vacuum type interrupter, which is the standard type used on high-voltage longwall circuits, requires 4.8 cycles to operate [Siemens]. Assuming the longest time of 3 cycles for the relay operation, the maximum tripping sequence is estimated to be 7.8 cycles. By applying the clearing time of 7.8 cycles to Daziel's ac fibrillation prediction, the maximum current that will not result in fibrillation is established to be 321 mA.

The level of current that will flow through the human body is directly related to the voltage across the body as well as the body's resistance. The presence of moisture from standing water, wet clothing, or perspiration increases the possibility of electrocution (DHHS, 1998, Sottile and Novak, 2001). All of these conditions are commonly found on longwall faces. The level of current that will flow through the body can be calculated using Ohm's law, which states:

$$\mathbf{I} = \frac{V}{R}$$

where, V is the voltage across the body, and
R is the body resistance.

Research indicates that body resistance can vary from 10 kΩ down to 1 kΩ, and may be as low as 200 Ω when the skin is broken. A value of 500 Ω is commonly used for performing safety analysis (Sottile and Novak, 2001).

The most common shock hazard occurs when a person comes into direct contact with an object that is at a significantly higher potential than earth (Sottile and Novak, 2001). If a person contacts the frame of a faulted piece of equipment, the current that will flow through the victim is dependent upon the fault current, the ground conductor impedance, and the victim's body resistance including contact resistance. Hazards that exist from the elevation of frame potentials can be reduced by providing a low impedance ground path and by controlling the maximum ground-fault current. This is accomplished by using a neutral grounding resistor (NGR), which is discussed in the next section.

2.3 High Resistance Grounding

Grounding is attained by providing an intentional connection between a phase or neutral conductor to earth. By providing a dedicated fault path for fault current to flow, protective schemes can be developed to monitor for undesirable operating conditions. These protective schemes can be designed to automatically respond and take corrective action if undesirable operating conditions are sensed.

The explosive atmosphere in underground coal mining demands that the energy dissipated by the fault resistance during ground-fault events be limited to reduce the possibility of an explosion. This is accomplished by using resistance grounding, which provides a practical method of controlling the amount of energy dissipated during a ground-fault by limiting the magnitude of the fault current.

In resistance grounding, the system's neutral is connected to ground through a resistor as shown in Figure 3.

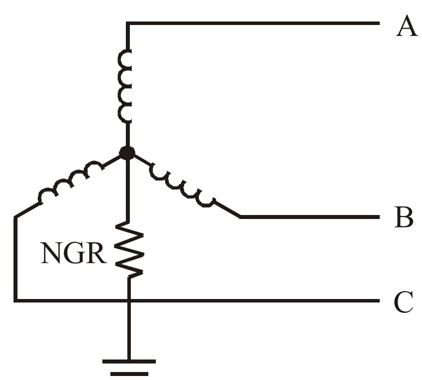

Fig. 3. Resistance grounding of wye system.

In underground coal mining, the system's neutral is commonly obtained from the wye connected secondary of the transformer. A wye system, as shown in Figure 3, is defined as a system in which one end of each phase winding of transformers or alternating current generators are connected together to form a neutral point, and the other ends of the windings are connected to the phase conductors.

There are two categories of resistance grounding, each defined by the magnitude of the current allowed to flow to ground. There is no defined standard for the level of ground-fault current which defines these two categories, but it is generally accepted that the ground-fault current level in high-resistance grounding is limited to a value less than 10 A while the ground-fault current level in low-resistance grounding is limited to at least 100 A (IEEE std. 142-1991).

2.4 Protective Relaying

Ground faults pose a potential safety risk to personnel. If undetected, ground-faults can cause serious damage to equipment, and if they are not isolated they can develop into more severe double line-to-ground faults (Wilks, 2003). Consequently, the function of a ground-fault protection system is to detect and remove ground-faults from the power system when they occur.

Ground-fault protection systems consist of three primary elements: transducers, relays, and circuit breakers. Transducers are also known as voltage and current transformers. The function of voltage and current transformers (VT and CT) is to transform the power system's voltages and currents to lower magnitudes and to provide signals to the relays which are faithful reproductions of the primary quantities (Horowitz and Phadke, 1995). For ground-fault detection, a single flux summing CT is used.

Current in each phase of a three-phase system can be mathematically described in terms of positive, negative, and zero-sequence components. This method of describing a three phase system is essential when dealing with asymmetrical faults. An example of an asymmetrical fault on a three-phase system is a line-to-ground fault, while conversely an example of a symmetrical fault would be a three-phase fault. The unbalanced phasors of a three-phase system during a line-to-ground fault can be resolved into three balanced systems of phasors, as shown in Figure 4. Resolving the unbalanced phasors of a faulted three-phase system into a system of balanced phasors simplifies the calculation of the fault current at the point of the fault. Once the fault current at the point of the fault is determined, the current and voltage at various points in the system to be found (Stevenson, 1975).

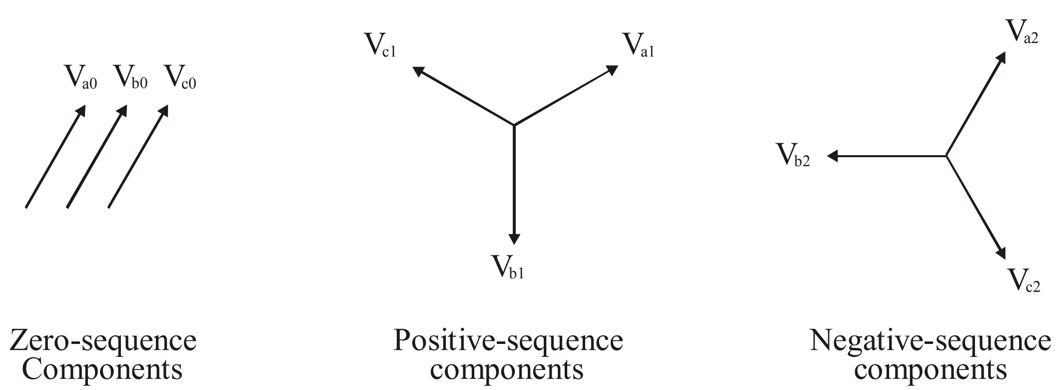

Fig. 4. Sequence components of phase voltages.

Under normal operations, or when a fault occurs that does not involve ground, there is no zero-sequence component and the sum of the phase currents I_a, I_b, and I_c is zero. When a ground-fault occurs, the sum of the phase currents I_a, I_b, and I_c will not be zero. In this case, the value resulting from the summation of the phase currents is known as the ground current.

The zero-sequence component only exists when the system experiences a fault involving neutral. Thus, it is possible to detect a ground-fault by monitoring the zero-sequence component. This is referred to as zero-sequence relaying. With zero-sequence relaying, the three individual phase conductors are passed through the window of a single toroidal CT while the grounding conductor is kept outside of the CT window (Novak et. al, 2003). This is shown in Figure 5.

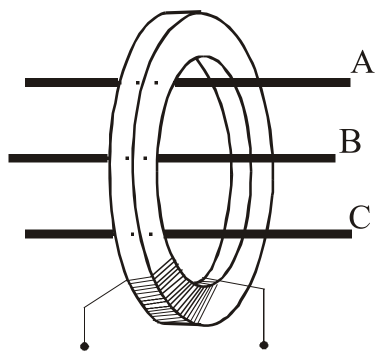

Fig. 5. Toroidal current transformer.

The arrangement in Figure 5 allows the CT to sum the flux produced by the three phase currents and allows the CT secondary to see the ground current if an imbalance in the phase currents exits. The ground current sensed by the CT secondary will be directly proportional to the current on CT primary by the CT turn’s ratio as long as the CT is not saturated.

Relays are the brains of the protection system. Relays process the data provided by the voltage and current transformers to determine the operating state of the power system (Horowitz and Phadke, 1995). If the power system is determined to be operating abnormally, relays use previously established parameters to take corrective action. A quick response to abnormal conditions is essential. Federal Regulations require that high-voltage longwall mining systems use instantaneous relays inby the power center that operate as soon as a decision is made, with no intentional time delay to slow down the relay’s response.

Relays can be classified into different categories based upon the input parameters to which they respond. Some of the different categories of relays are level detection, magnitude comparison, differential comparison, phase angle comparison, pilot relaying, and frequency sensing relaying (Horowitz and Phadke, 1995). Relays used in underground coal mining exclusively use level detection as their operating parameter.

Level detection is the simplest principle of relay operation. Relays that use level detection as their operating parameter to monitor current are also known as overcurrent relays. When a predetermined level on an overcurrent relay is exceeded, the relay initiates a trip sequence. This predetermined level is known as the relay's pick-up setting. There are many different types of relays, some of which are electromechanical relays (which include induction disk and plunger-type), solid state relays, and microprocessor based relays. High-voltage longwall power systems almost exclusively use solid state relays.

2.5 Ground-Fault Protection

High-voltage longwall power systems have zero-sequence ground-fault overcurrent protection located in the motor starting unit and power center. Figure 6 shows the configuration of an outby 4,160-V longwall power system (Novak and Martin, 1996). All outgoing circuits in the motor starting unit have instantaneous overcurrent ground-fault protection. The protection in the power center is allowed to have a time delay of up to 0.25 s in order to provide coordination with the protection located in the motor starting unit (Novak et. al, 2004). As will be discussed in greater detail later in this chapter, Federal Regulations limit the maximum current through the NGR to 3.75 A for 4,160-V longwall system systems. The maximum ground-fault relay pick-up setting at the power center is limited to 40% of the NGR current limit or 1.5 A for a 4,160-V system. The maximum pick-up setting for the instantaneous ground-fault relays in the motor-starting unit is 0.125 A.

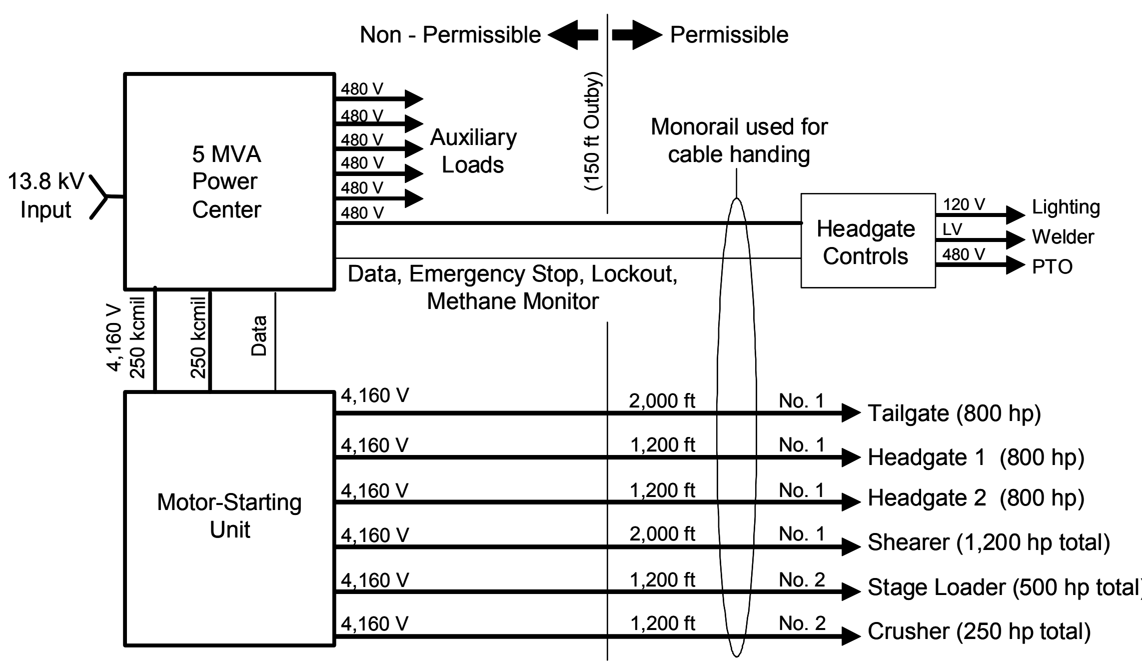

Fig. 6. Configuration of an outby 4,160-V longwall.

2.6 Ground-Fault Relaying selectivity

There are three general terms which define the success of a relay operation - reliability, dependability, and security (Horowitz and Phadke, 1995). The term reliability refers to the degree of certainty that a relay will perform as intended. There are two possible ways that a relay can be unreliable: a relay can fail to operate when it should, or it can unwontedly operate when it should not. The reliability of relays can be described by the terms dependability and security. The term dependability is defined as the measure of certainty that a fault will be cleared. The term security is defined as the measure of certainty that only the correct relay will operate to clear the fault. Power systems in underground coal mining tend to be biased towards dependability at the expense of security, as it is imperative that faults be cleared as soon as possible to limit the total amount of energy dissipated during the fault event.

The property of security is defined topologically within a power system by regions. These regions are known as zones of protection. A secure relay will only operate for a fault within its assigned zone (Horowitz and Phake, 1995). The standard for designing power system protection is to have overlapping zones of protection. This ensures that all regions of the power system are protected and that a backup is provided in the event of protection equipment failure. An example of the relaying scheme for a 4,160-V longwall power system is shown in Figure 7.

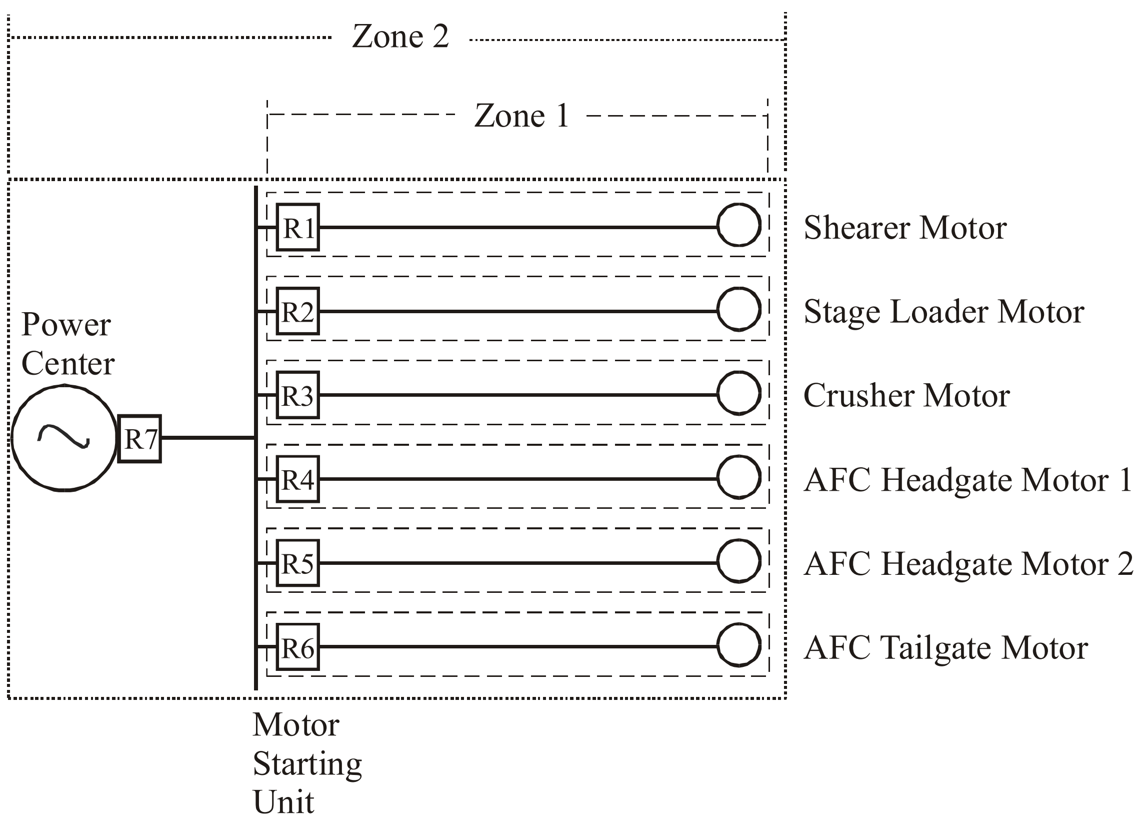

Fig. 7. Relay protection scheme.

When a ground-fault occurs within the shearer circuit, the instantaneous relay shown in Figure 7 as R1 should operate, effectively removing the faulted circuit. If R1 fails to operate, R7 should operate after the specified time delay of up to 0.25 s. In this case, R7 is considered a backup to R1, and the 0.25 s time delay is allowed for coordination. When R1 operates properly, the system is selective. If R1 fails to operate and the relays R2 – R6 operate, relay selectivity is lost. Selective relaying is the process of detecting abnormal conditions and providing quick isolation of the abnormality while limiting the amount of disruption to the entire power system. It is imperative that a ground-fault be cleared as soon as possible, and that the protection system is selective when clearing the fault. When multiple relays spuriously trip on an unselective system, power is often turned back on in an effort to locate the fault. After the power has been turned back on, the relays will trip again, but only after more power has been re-applied at the point of fault (K-TEC, 1991). Selective relaying is essential in power system protection as it reduces the troubleshooting necessary to locate a fault, thus reducing the time that miners are exposed to the faulted system. Equipment downtime is also reduced.

2.7 Federal Regulations

Federal Regulations pursuant to the use of high-voltage longwall mining systems were enacted into law in March 2002 (Basar and Novak, 2003). These regulations can be found in the updated 30 CFR Parts 18 and 75 (Title 30CFR). The purpose of these regulations is to ensure miner safety by reducing the likelihood of fire, explosion, and shock hazards by citing requirements for electrical enclosures, circuit protection, and personal protective equipment (USBM, 1997). From the inception of high-voltage longwalls in 1986 until the time that the new Federal Regulations were enacted into law, operators of high-voltage longwalls were required to file for a Petition for Modifications on a case-by-case basis. Filing Petition for Modifications is a means for operators to request a modification of a mandatory safety standard with the stipulation that the modification provides the same level of safety as is provided by the existing standard.

When the first Petition for Modifications was proposed for a 4,160-V longwall mining system in 1986, the current allowed to flow through the NGR was limited to 3.75 A and the ground-fault relay pick-up setting was mandated at 0.125 A (Novak and Martin, 1996). During the early stages of high-voltage utilization, however, a NGR current limit of 0.5 A and a ground-fault relay pick-up setting of 0.100 A became the generally accepted standard for 4,160-V systems (Novak et. al, 2003). These values were initially proposed by industry to help gain approval for the required Petition for Modifications. In March 2002, the updated 30 CFR Parts 18 and 75 reversed the stance on NGR current limits and ground-fault relay pick-up settings, and returned them to the original values that were suggested for the first high-voltage longwalls in 1986.

2.8 Summary

The information presented in this chapter was intended to provide a general background on the ground-fault protection system currently used on 4,160-V systems. Federal Regulations require that 4,160-V systems use high-resistance grounding with a NGR current limit of 3.75 A. High-resistance grounding is a practical method to limit the frame potential to earth when a ground-fault occurs. When a ground-fault does occur, the protective system must be designed to recognize the abnormality and promptly remove the affected circuit from the system. Federal Regulations require that ground-fault relays inby the power center operate when the ground current is ≥ 0.125 A. Ground-fault relays inby the power center are required to operate instantaneously in order to limit the amount of energy dissipated during ground-fault events and to reduce the duration of frame elevations. It is imperative that relays operate selectively when removing a fault as selective relaying reduces the troubleshooting necessary to locate the fault.

Chapter 3. Model Development

3.1 General

A typical outby 4,160-V longwall power system is modeled in this chapter. The sizes of the equipment components in the model are chosen to represent an average size system. The following sections describe various aspects of the model, including the computer program used to simulate the system and the premises used to determine the values assigned to the equipment components.

3.2 PSpice

PSpice is a member of the SPICE family of circuit simulators. The acronym SPICE stands for Simulation Program with Integrated Circuit Emphasis. PSpice was the first SPICE-based simulator available for personal computers, and has been continually updated since its release in 1984. The circuit simulation program PSpice® Version 8 was used to simulate the system. PSpice has the capability of performing transient analysis of a complex circuit while providing voltage and current waveforms at nodes and branches throughout the given circuit.

3.3 Analysis Using PSpice Program

PSpice allows for a circuit to be drawn using graphic symbols that are stored in the program's internal symbol library. The attributes of the symbols can then be assigned values. Once the circuit is drawn on a schematic page, a text file (".cir") is automatically created for the circuit. This text file is also known as a netlist. A netlist is a list of components and the nodes to which the components are connected. When a simulation is initiated, PSpice reads from the netlist and then performs the requested analysis. The result of the simulation is then stored in a text output (".out.") and a binary date file. The result of the simulation can then be viewed graphically using an internal graphic viewer which has the ability to plot voltage and current waveforms at locations throughout the circuit (eCircuit Center).

3.4 Model Description

The circuit model shown in Figure 8 was developed for the computer analysis. The basis of this circuit model was developed by Novak (2001-a, 2001-b). Novak's model has been altered to improve the topological representation of a longwall power system.

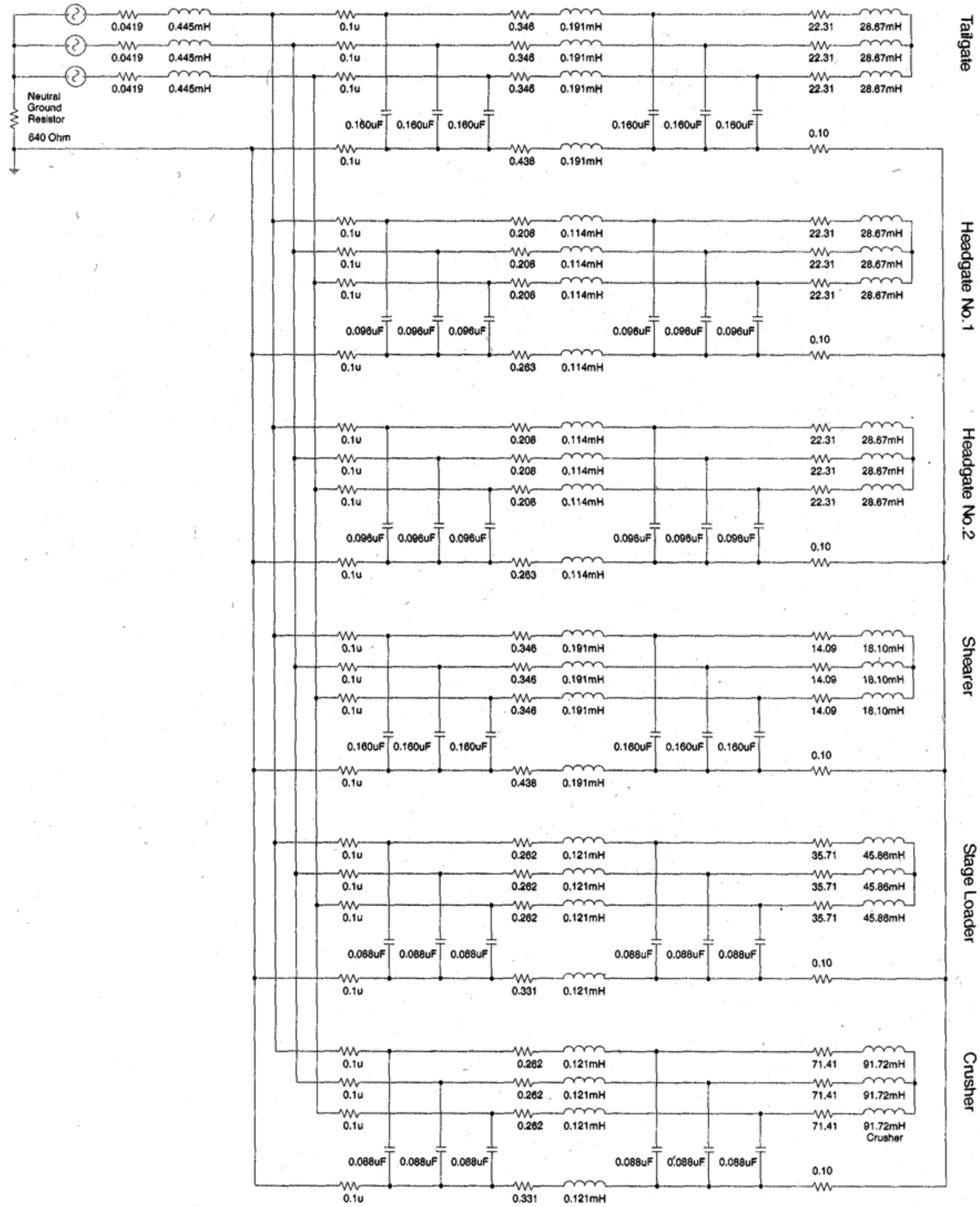

Fig. 8. Model of an outby 4,160-V longwall power system
(adj. after Novak, 2001-a and 2001-b)

Most notably, a circuit path was added to the grounding scheme of the model to represent the path that results from the individual component frames being in contact with each other through the panline. This alteration is necessary to ensure the directionality of the ground current as it returns to the neutral of the transformer during ground-fault events. Determining the correct direction of the ground current is necessary for evaluating the applicability of a directional relaying scheme. Also, the resistances of the ground conductors were altered to represent their actual value. Novak's model used the same value of resistance for both the phase and ground conductors. The improved representation of the ground conductors is necessary to ensure the accuracy of the safety investigation involving touch potential. Also included in the model is a 0.1 μΩ resistor located between the motor starting unit and the first value of cable capacitance. This resistor is insignificant to the calculations but is necessary as PSpice requires a node to measure current values. The zero-sequence voltages and currents are measured at this location.

3.5 Component Modeling

This section borrows heavily upon research performed by Novak and Sottile (2002). The premise behind the component modeling is acceptable for performing the transient analysis (Glover and Sarma, 2002). The following subsections provide the detailed calculations of the values for the various components.

3.5.a Transformer

The secondary of the power center transformer is modeled as three voltage sources with series impedances connected in a wye configuration. The three voltage sources are modeled as $2{,}400\angle 0^\circ$ V, $2{,}400\angle -120^\circ$ V, and $2{,}400\angle 120^\circ$ V. The series impedance of the transformer is based upon a transformer impedance of 5% with an X/R ratio of 4. The resistance and inductance of the transformer are calculated as follows:

The phase angle for the impedance is calculated by

$$\phi = Tan^{-1}\frac{X}{R} = Tan^{-1}\frac{4}{1} = 75.96^\circ$$

The per-unit impedance of the transformer can now be expressed as

$$\mathbf{Z_{pu}} = 0.05\angle 75.96^\circ = 0.0121 + j0.0485\,\text{pu}$$

The base impedance at the transformer's secondary is given by

$$\mathbf{Z_{Base}} = \frac{\text{kV}_{\text{Base}}^2}{\text{MVA}_{\text{Base}}} = \frac{(4.16)^2}{5} = 3.46\,\Omega$$

and the impedance for the transformer, referred to the secondary, can be obtained from

$$\mathbf{Z} = Z_{pu} \times Z_{Base} = (0.0121 + j0.0485) \times 3.46 = 0.0419 + j0.1678\,\Omega$$

PSpice requires that impedance be input in terms of its resistance and inductance or capacitance. The transformer inductance is calculated by

$$\mathbf{L} = \frac{X_L}{\omega} = \frac{0.1678}{2\pi 60} = \mathbf{0.445\ mH}$$

and the transformer's resistance is $\mathbf{R} = \mathbf{0.0419\ \Omega}$

3.5.b Neutral Grounding Resistor

The neutral grounding resistor (NGR) in the model is connected between the neutral of the transformer and ground. The size of the NGR is determined by the maximum ground-fault current allowed by Federal Regulation which is 3.75 A for 4,160-V systems. The resistive value of the NGR required to limit the ground-fault current to this value is calculated by:

$$\mathbf{R}_{\mathbf{NGR}} = \frac{V_{1\phi}}{I_{gf(max)}} = \frac{\frac{4{,}160}{\sqrt{3}}}{3.75} = \mathbf{640\ \Omega}$$

3.5.c Motors

The motors are modeled as three fixed wye-connected impedances. This method of modeling provides sufficient accuracy for transient analysis of the system during fault events. The impedances of the motors are calculated with the assumption that the motors are operating at rated capacities with typical power factors and efficiencies. The calculations for the equivalent impedances of the various motors follow:

3.5.c.i Headgate and Tailgate Motors

Around 83% of 4,160-V longwall mining systems in operation use three motors to drive the armored face conveyor (AFC); the other 17% use two motors (Fiscor, 2004). The model is developed to represent an average size 4,160-V system. Therefore, three motors are modeled. Two of the three motors are located at the headgate while the other is located at the tailgate. Because of the large horsepower ratings, each of the three motors is supplied by a separate power cable. All motors have identical ratings, as shown in Table 2:

Table 2. AFC motor ratings.

Parameter	Symbol	Value
Output Power	Po	800 hp
Rated Voltage	V	4,160 V
Rated Power Factor	*pf*	0.90
Rated Efficiency	η	0.95%

The three phase input power to each motor is given by

$$\mathbf{P_i} = \frac{P_e}{\eta} = \frac{800\,\text{hp}}{0.95} \times \frac{0.746\,\text{kW}}{\text{hp}} = 628.2\,\text{kW}$$

and the phase angle can be calculated as follows:

$$\phi = \text{Cos}^{-1}\,0.9 = 25.84°$$

The three-phase reactive power of the motor can be found by

$$\mathbf{Q_i} = P_i \tan\phi = 628.2 \times \tan 25.84° = 304.2\,\text{kVAR}$$

and the per-phase apparent power is given by

$$\mathbf{S_\phi} = \frac{P_i + jQ_i}{3} = \frac{628.2 + j304.2}{3} = 209.4 + j101.4 = 232.7\angle 25.84°\,\text{kVA}$$

The per-phase impedance can now be found by

$$\mathbf{Z} = \frac{V_\phi^2}{S^*} = \frac{\left(\frac{4{,}160}{\sqrt{3}}\right)^2}{232{,}700\angle -25.84°} = 24.79\angle 25.84° = 22.31 + j10.81\Omega$$

and the equivalent resistance and inductance for the motor is given by

$$\mathbf{R} = \underline{\underline{\mathbf{22.31\,\Omega}}}$$

$$\mathbf{L} = \frac{X_L}{\omega} = \frac{10.81}{2\pi 60} = \underline{\underline{\mathbf{28.7\,mH}}}$$

3.5.c.ii Shearer

A shearer uses numerous motors to provide power for its various functions. To simplify the model, the multiple motors are lumped and modeled as a single equivalent motor that represents the total combined power requirement of the shearer. A single power cable is used to supply power to the shearer motors. The total power requirement of the shearer is shown in Table 3:

Table 3. Shearer motor rating.

Parameter	Symbol	Value
Output Power	Po	1,200 hp
Rated Voltage	V	4,160 V
Rated Power Factor	*pf*	0.90
Rated Efficiency	η	0.95%

The equivalent per-phase impedance for the shearer is calculated by:

$$\mathbf{P_i} = \frac{P_e}{\eta} = \frac{1{,}200\,\text{hp}}{0.95} \times \frac{0.746\,\text{kW}}{\text{hp}} = 994.7\,\text{kW}$$

$$\phi = \text{Cos}^{-1}\,0.9 = 25.84°$$

$$\mathbf{Q_i} = P_i \tan\phi = 994.7 \times \tan 25.84° = 481.7\,\text{kVAR}$$

$$\mathbf{S_\phi} = \frac{P_i + jQ_i}{3} = \frac{994.7 + j481.7}{3} = 331.6 + j160.6 = 368.4\angle 25.84°\,\text{kVA}$$

$$\mathbf{Z} = \frac{V_\phi^2}{S^*} = \frac{\left(\frac{4{,}160}{\sqrt{3}}\right)^2}{368{,}400\angle -25.84°} = 15.66\angle 25.84° = 14.09 + j6.825\,\Omega$$

$$\mathbf{R} = \underline{\underline{\mathbf{14.09\,\Omega}}}$$

$$\mathbf{L} = \frac{X_L}{\omega} = \frac{6.825}{2\pi 60} = \underline{\underline{\mathbf{18.1\,mH}}}$$

3.5.c.iii Stage Loader

It is common to have two motors power the stage loader. Similar to the shearer circuit, the two motors are lumped and represented as a single motor. Also, like the shearer circuit, a single power cable is used to supply power to the stage loader motors. The total power requirement of the stage loader is shown in Table 4:

Table 4. Stage loader motor rating.

Parameter	Symbol	Value
Output Power	Po	500 hp
Rated Voltage	V	4,160 V
Rated Power Factor	*pf*	0.90
Rated Efficiency	η	0.95%

The equivalent per-phase impedance for the stage loader is summarized as follows:

$$\mathbf{P_i} = \frac{P_e}{\eta} = \frac{500\,\text{hp}}{0.95} \times \frac{0.746\,\text{kW}}{\text{hp}} = 392.6\,\text{kW}$$

$$\phi = \text{Cos}^{-1}\,0.9 = 25.84°$$

$$\mathbf{Q_i} = P_i \tan\phi = 392.6 \times \tan 25.84° = 190.1\,\text{kVAR}$$

$$\mathbf{S_\phi} = \frac{P_i + jQ_i}{3} = \frac{392.6 + j190.1}{3} = 130.9 + j63.38 = 145.4\angle 25.84°\,\text{kVA}$$

$$\mathbf{Z} = \frac{V_\phi^2}{S^*} = \frac{\left(\frac{4{,}160}{\sqrt{3}}\right)^2}{145{,}400\angle -25.84°} = 39.67\angle 25.84° = 35.71 + j17.29\,\Omega$$

$$\mathbf{R} = \underline{\underline{\mathbf{35.71\,\Omega}}}$$

$$\mathbf{L} = \frac{X_L}{\omega} = \frac{17.29}{2\pi 60} = \underline{\underline{\mathbf{45.86\,mH}}}$$

3.5.c.iv Crusher

The crusher is powered by a single motor fed by a single power cable. The total power requirement of the crusher is shown in Table 5:

Table 5. Crusher motor rating.

Parameter	Symbol	Value
Output Power	Po	250 hp
Rated Voltage	V	4,160 V
Rated Power Factor	*pf*	0.90
Rated Efficiency	η	0.95%

The equivalent per-phase impedance for the crusher is summarized as follows:

$$\mathbf{P_i} = \frac{P_e}{\eta} = \frac{250\,\text{hp}}{0.95} \times \frac{0.746\,\text{kW}}{\text{hp}} = 196.3\,\text{kW}$$

$$\phi = \text{Cos}^{-1}\,0.9 = 25.84°$$

$$\mathbf{Q_i} = P_i \tan\phi = 196.3 \times \tan 25.84° = 95.07\,\text{kVAR}$$

$$\mathbf{S_\phi} = \frac{P_i + jQ_i}{3} = \frac{163.3 + j95.07}{3} = 65.43 + j31.69 = 72.70\angle 25.84°\,\text{kVA}$$

$$\mathbf{Z} = \frac{V_\phi^2}{S^*} = \frac{\left(\frac{4{,}160}{\sqrt{3}}\right)^2}{72{,}700\angle -25.84°} = 79.34\angle 25.84° = 71.41 + j34.58\,\Omega$$

$$\mathbf{R} = \underline{\underline{\mathbf{71.41\,\Omega}}}$$

$$\mathbf{L} = \frac{X_L}{\omega} = \frac{34.58}{2\pi 60} = \underline{\underline{\mathbf{91.7\,mH}}}$$

The values of motor resistance and impedance are summarized in Table 6.

Table 6. Summarized motor values.

	Motor Data				
Equipment	Rated Power [hp]	Power Factor *pf*	Motor Efficiency %	Equivalent Resistance [Ω]	Equivalent Inductance [mH]
Shearer	1,200 Total	0.90	95	14.09	18.10
Stage Loader	500 Total	0.90	95	35.71	45.86
Crusher	250	0.90	95	71.41	91.72
AFC Headgate 1	800	0.90	95	22.31	28.67
AFC Headgate 2	800	0.90	95	22.31	28.67
AFC Tailgate	800	0.90	95	22.31	28.67

3.5.d Cables

The impedance values assigned to the cables in the model were determined from data provided in a mining cable handbook (Anaconda, 1977). The resistance, inductance, and capacitance of the cables are included in the model. A typical 5-kV SHD-GC cable is show in Figure 9 (General Cable, 2004).

Fig. 9. Picture of a 5-kV SHD-GC cable.

The capacitance in the model is solely from the cables - the capacitance from the transformer and motor windings is ignored. In reality, the cable capacitance is distributed along the entire length of the cable, but for simplicity the capacitance is shown in the model as a lumped value that is halved and connected from phase-to-ground at both ends of the cable. This is referred to as a π configuration and is considered to be standard procedure for modeling cable capacitance (Chapman, 2002). Capacitance values for the typical 5-kV SHD-GC cables used in the model are shown in the following Table 7 (Novak, et. al, 2004).

Table 7. Cable capacitance values.

Conductor Size	Capacitance (per 1000 ft.)
#2	0.147 μF
#1	0.160 μF

The values of resistance and inductance for a cable are a function of the cable's size and length. The values of resistance and inductance are inserted into the model as lumped impedances connected in a π configuration. The values of resistance, reactance, and inductance for the cables used in the model are summarized in Table 8.

Table 8. Cable resistance, reactance, inductance.

	Impedance of Cables (per 1,000 feet)		
Cable Size	Resistance	Reactance	Inductance
#6 AWG	0.552 Ω	0.043 Ω	0.114 mH
#5 AWG	0.438 Ω	0.042 Ω	0.111 mH
#2 AWG	0.218 Ω	0.038 Ω	0.101 mH
#1 AWG	0.173 Ω	0.036 Ω	0.0955 mH

The nomenclature assigned to cables is governed by the size of the cable's phase conductors. For example, a three-phase #1 AWG (American Wire Gauge) cable has three #1 AWG power conductors. To improve the accuracy of the model, the ground conductors were assigned resistive values based upon their AWG size. As shown in the picture labeled Figure 9, 5-kV SHD-GC cable has two ground conductors. The two ground conductors in a #1 AWG cable are #5 AWG while the two ground conductors in a #2 AWG cable are #6 AWG (PD Wire & Cable, 2004). An equivalent single ground conductor is shown in the model by combining the parallel ground conductors. Determining a more accurate value for the inductance of the ground conductors is unnecessary as the cable is primarily resistive. Therefore, for the simulations the ground conductor's inductance is given the same value as the phase conductor's inductance. A sensitivity analysis was performed to determine the effect of varying the value of ground conductor inductance. The result of this analysis is provided in the forthcoming section regarding sensitivity analyses. The values for the cables are shown in Table 9.

Table 9. Summarized cable values.

	Cable Data				
Equipment	Cable Size [AWG]	Cable Length [ft]	Phase Conductor Impedance [Ω]	Ground Conductor Resistance [Ω]	Shunt Capacitance [μF]
Shearer	# 1	2,000	0.346 + j0.072	0.438	0.320
Stage Loader	# 2	1,200	0.262 + j0.046	0.331	0.176
Crusher	# 2	1,200	0.262 + j0.046	0.331	0.176
AFC Headgate 1	# 1	1,200	0.208 + j0.043	0.263	0.192
AFC Headgate 2	# 1	1,200	0.208 + j0.043	0.263	0.192
AFC Tailgate	# 1	2,000	0.346 + j0.072	0.438	0.320

Chapter 4. Computer Modeling

4.1 Model Scenario

Simulations were performed using the model in Figure 8 to determine the systems response during line-to-ground fault events. The results of the simulations are shown in Table 10. The system model employed to obtain the values reported in Table 10 used a frame contact resistance of 0.10 Ω, a grounding conductor resistance value equivalent to the ground conductor size, and the standard inductance value determined by the phase conductors. The phasor quantities are referenced to the system's zero-sequence voltage. A sensitivity analysis was performed on the model and is presented in the next section.

Table 10. Current sensed by ground-fault relays.

Current [A] Sensed by Ground-Fault Relays for Faults at Various Locations							
		Fault Location					
		Shearer	AFC Headgate 1	AFC Headgate 2	AFC Tailgate	Stage Loader	Crusher
Ground-Fault Relay Locatoin	Shearer	**4.50 ∠ 143°**	0.84 ∠ -91°	0.84 ∠ -91°	0.84 ∠ -91°	0.84 ∠ -89°	0.85 ∠ -91°
	AFC Headgate 1	0.50 ∠ -89°	**4.78 ∠ 138°**	0.51 ∠ -91°	0.50 ∠ -91°	0.51 ∠ -89°	0.51 ∠ -91°
	AFC Headgate 2	0.50 ∠ -89°	0.51 ∠ -91°	**4.78 ∠ 138°**	0.50 ∠ -91°	0.51 ∠ -89°	0.51 ∠ -91°
	AFC Tailgate	0.83 ∠ -89°	0.84 ∠ -91°	0.84 ∠ -91°	**4.54 ∠ 143°**	0.84 ∠ -89°	0.85 ∠ -91°
	Stage Loader	0.46 ∠ -89°	0.46 ∠ -91°	0.46 ∠ -91°	0.46 ∠ -91°	**4.81 ∠ 138°**	0.47 ∠ -91°
	Crusher	0.46 ∠ -89°	0.46 ∠ -91°	0.46 ∠ -91°	0.46 ∠ -91°	0.46 ∠ -89°	**4.83 ∠ 138°**

As determined from the simulations, the minimum rms ground-fault current sensed by a relay in a faulted circuit is 4.50 A. The maximum rms ground current sensed by a relay in a non-faulted circuit is 0.85 A. It was also determined from the simulations that the ground-fault current sensed by a relay in a faulted circuit lags the system's zero-sequence voltage in every case by 138^o to 143^o. The ground current sensed by a relay in the unfaulted circuits, as would be expected, leads the system's zero-sequence voltage by approximately 90^o. Figure 10 shows the waveforms of the ground-fault current sensed by the relay in the shearer circuit for a fault at the shearer, the system's zero-sequence voltage, and the ground current sensed by the relay in the tailgate circuit. Only the waveform for the tailgate circuit is shown as the ground current sensed by the relay in the unfaulted circuits are all in phase with each other.

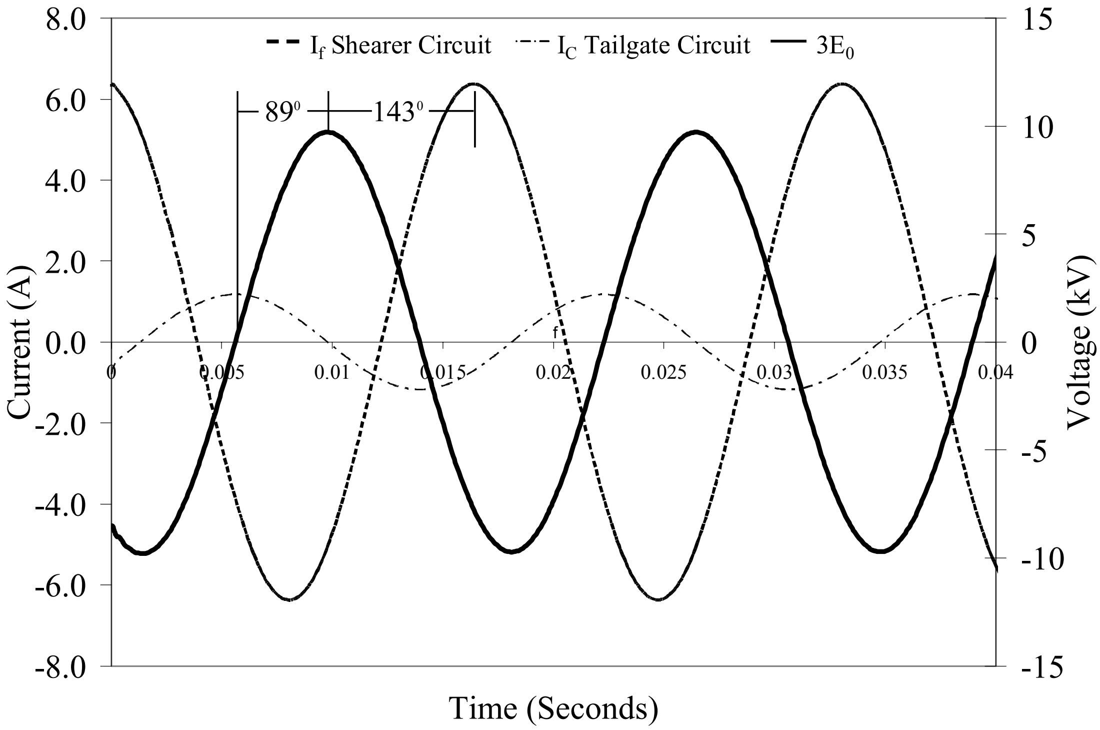

Fig. 10. Time trace of fault currents for a line-to-ground fault at the shearer.

Figure 10 shows that the ground-fault current sensed by the relay in the shearer circuit lags the zero-sequence voltage while the ground current sensed by the relay in the tailgate circuit leads the zero-sequence voltage.

4.2 Sensitivity analysis

A sensitivity analysis was performed on the model. The following parameters were analyzed: (1) effect of frame contact resistance, (2) effect of ground conductor inductance, and (3) effect of varying the faulted phase. The results of the analysis are presented in the following three sub-sections.

Sensitivity Analysis 1. Effect of Frame Contact Resistance

An analysis was performed to determine the effect that varying the frame contact resistance has on the simulation results. Figure 11 shows where the frame contact resistance was varied for the sensitivity analysis. For simplicity only the tailgate circuit is shown in the figure.

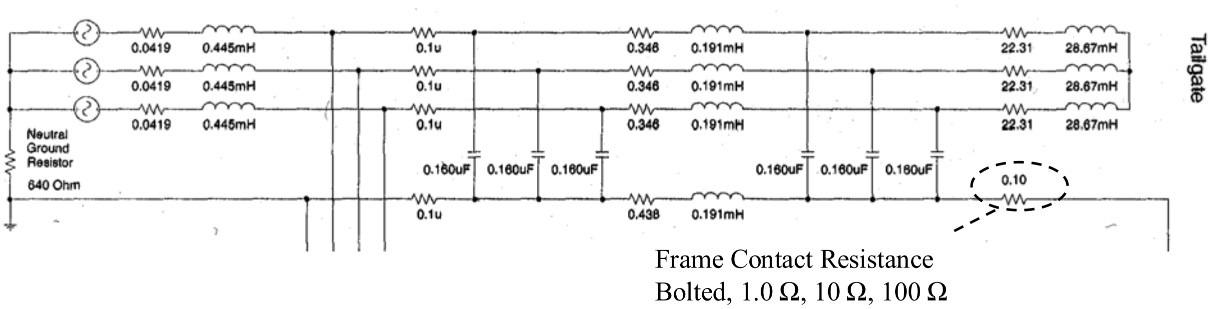

Fig. 11. Sensitivity analysis for frame contact resistance.

A value of 0.10 Ω is chosen as the most realistic value for frame contact resistance. Although the frames of the equipment are bolted together to form a single conductor, there will always be some contact resistance from attributes such as paint and rust. To determine the effect of varying the contact resistance the following values were also simulated: no resistance, 1.0 Ω, 10.0 Ω, and 100 Ω. The tests were performed for a PhaseC-to-ground fault in the shearer circuit. The results are shown in Table 11.

Table 11. Sensitivity analysis for frame contact resistance.

Current [A] Sensed by Ground-Fault Relays Over Various Contact Resistances						
		Fault at the Shearer				
	Contact Resistance ⟶	Bolted	0.10 Ω	1.0 Ω	10.0 Ω	100 Ω
Ground-Fault Relay Locatoin	Shearer	**4.51 ∠143°**	**4.50 ∠143°**	**4.50 ∠143°**	**4.50 ∠143°**	**4.50 ∠143°**
	AFC Headgate 1	0.50 ∠ -89°	0.50 ∠ -89°	0.50 ∠ -89°	0.50 ∠ -91°	0.50 ∠ -93°
	AFC Headgate 2	0.50 ∠ -89°	0.50 ∠ -89°	0.50 ∠ -89°	0.50 ∠ -91°	0.50 ∠ -93°
	AFC Tailgate	0.83 ∠ -89°	0.83 ∠ -89°	0.83 ∠ -89°	0.83 ∠ -91°	0.83 ∠ -93°
	Stage Loader	0.46 ∠ -89°	0.46 ∠ -89°	0.46 ∠ -89°	0.46 ∠ -91°	0.46 ∠ -93°
	Crusher	0.46 ∠ -89°	0.46 ∠ -89°	0.46 ∠ -89°	0.46 ∠ -91°	0.46 ∠ -93°

The result of the sensitivity analysis shows that the frame contact resistance has little effect on the ground-fault current sensed by the relay in the faulted circuit. The phasor of the ground current sensed by the relay in the unfaulted circuits responded as expected as when the resistance increased, the phase angle correspondingly increased.

Sensitivity Analysis 2. Effect of Ground Conductor Inductance

An analysis was also performed to determine the effect that varying the ground conductor inductance has on the simulation results. Figure 12 shows where the ground conductor inductance was varied for the sensitivity analysis. For simplicity only the tailgate circuit in shown in the figure.

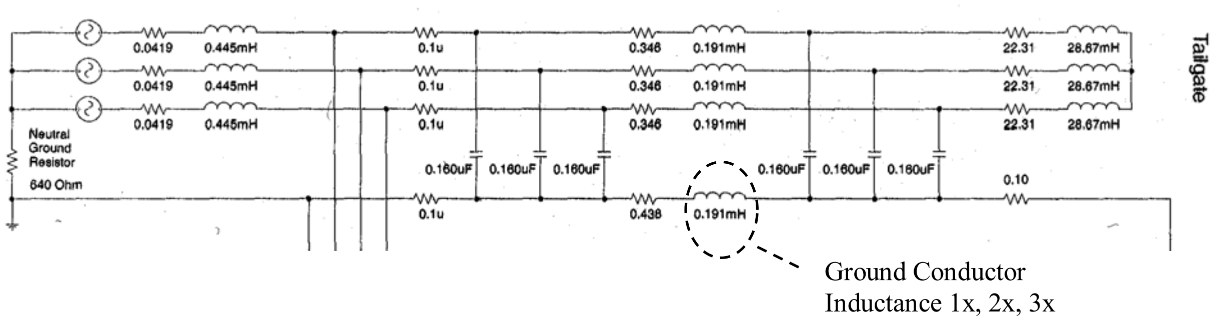

Fig. 12. Sensitivity analysis for ground conductor inductance.

The values of ground conductor inductance were arbitrarily doubled and tripled. The simulations were performed for a PhaseC-to-ground fault in the shearer circuit. The results of the simulations are shown in Table 12.

Table 12. Sensitivity analysis for ground conductor inductance.

Current [A] Sensed by Ground-Fault Relays Over Various Ground Conductor Inductance Values				
		Fault at the Shearer		
	Varied Inductance →	0.191mH [1 x]	0.392 mH [2 x]	0.573mH [3 x]
Ground-Fault Relay Locatoin	Shearer	**4.50 ∠ 143°**	**4.51 ∠ 143°**	**4.51 ∠ 143°**
	AFC Headgate 1	0.50 ∠ -89°	0.50 ∠ -86°	0.50 ∠ -91°
	AFC Headgate 2	0.50 ∠ -89°	0.50 ∠ -86°	0.50 ∠ -91°
	AFC Tailgate	0.83 ∠ -89°	0.83 ∠ -86°	0.83 ∠ -91°
	Stage Loader	0.46 ∠ -89°	0.46 ∠ -86°	0.46 ∠ -91°
	Crusher	0.46 ∠ -89°	0.46 ∠ -86°	0.46 ∠ -91°

The result of this sensitivity analysis shows that the ground conductor inductance over a reasonably defined range has little effect on the fault currents.

Sensitivity Analysis 3. Effect of Varying Faulted Phase

Finally, an analysis was performed to determine the effect that varying the faulted phase has on the simulation results. Figure 13 shows the location of the phase-to-ground fault that was varied in the sensitivity analysis.

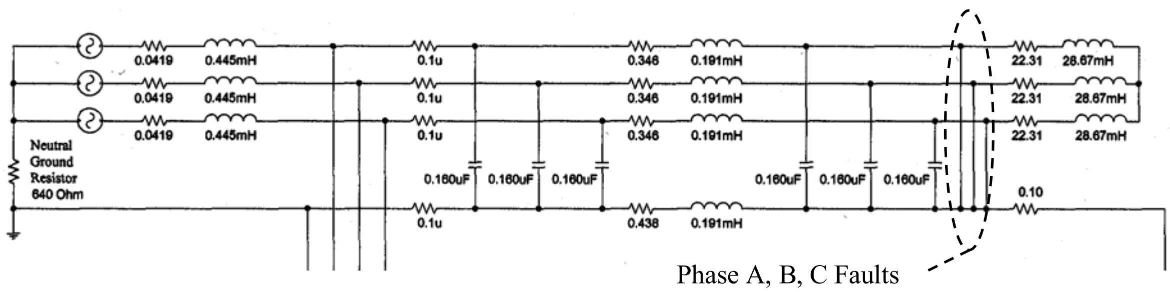

Fig. 13. Sensitivity analysis for varying faulted phase.

For the sake of simplicity, the simulations were primarily performed with a PhaseC-to-ground fault. To ensure the response of the model, PhaseA-to-ground and PhaseB-to-ground faults were also tested. The sensitivity analysis was performed for a fault in the shearer circuit. The results of the simulations are shown in Table 13.

Table 13. Sensitivity analysis for varying faulted phase.

Currents [A] Sensed by Ground-Fault Relays for Phase A, B, & C Faults				
		Fault at the Shearer		
		A - ϕ	B - ϕ	C - ϕ
Ground-Fault Relay Locatoin	Shearer	**4.51 ∠ 143°**	**4.50 ∠ 143°**	**4.50 ∠ 143°**
	AFC Headgate 1	0.50 ∠ -90°	0.50 ∠ -91°	0.50 ∠ -89°
	AFC Headgate 2	0.50 ∠ -90°	0.50 ∠ -91°	0.50 ∠ -89°
	AFC Tailgate	0.83 ∠ -90°	0.83 ∠ -91°	0.83 ∠ -89°
	Stage Loader	0.46 ∠ -90°	0.46 ∠ -91°	0.46 ∠ -89°
	Crusher	0.46 ∠ -90°	0.46 ∠ -91°	0.46 ∠ -89°

These results show that the phase in which the fault occurs has no significant effect on the magnitude or phase angle of either the ground-fault current sensed by the relay in the faulted circuit or the ground current sensed by relay in the unfaulted circuits.

4.3 Directional Relaying

As determined from the simulations, when a ground-fault occurs on a 4,160-V longwall power system, both the magnitude and phase angle of the fault currents are affected. The simulations show that the ground-fault current sensed by the relay in the faulted circuit and the ground current sensed by the relay in the unfaulted circuits are out of phase with respect to each other. A group of protective relays exist that can identify changes in phasor quantities. Directional relays, also known as phase comparison relays, compare the relative phase angles between two ac quantities and use this information as a trip parameter (Horwitz and Phadke, 1995). Directional relays require two inputs, the phase angle of the current phasor, which varies with the direction of the fault, and a reference, or polarizing quantity, that is independent of the fault location. For ground-fault relays, the polarizing quantity is almost always the zero-sequence voltage (Andrichak and Patel). The zero-sequence voltage can be used as the polarizing quantity as it is always in the same direction regardless of the fault location. The zero-sequence voltage can be obtained across the open corner of a wye-grounded, broken delta voltage transformer. The sum of the three line-to-neutral voltages E_a, E_b, and E_c is zero for balanced conditions and for faults that do not involve ground (Horowitz and Phadke, 1995).

The simulations show that the capacitive charging current returning in the unfaulted circuits has a phase angle that leads the zero-sequence voltage by almost 90°, while the ground-fault current in the faulted circuit lags the zero-sequence voltage by around 140°. A simplified one-line diagram of a ground-fault scenario showing the returning capacitive charging current is shown in Figure 14. The ground-fault relay in the unfaulted circuit will sense a ground current equal to the capacitive charging current.

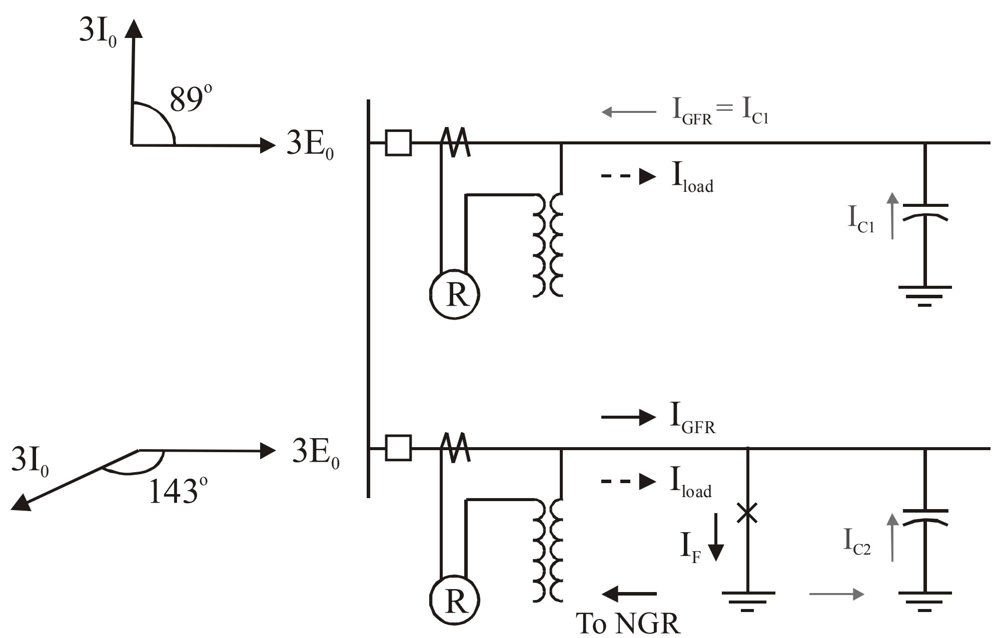

Fig. 14. Phase angle comparison.

The scenario shown in Figure 14 is repeated in every simulated ground-fault event. As determined by the sensitivity analyses, the phase angles of the fault currents polarized against the system's zero-sequence voltage are irrespective of frame contact resistance, ground-conductor inductance, and the phase that goes to ground.

4.4 Effect of Neutral Grounding Resistor Value

An analysis was performed to determine the effect that the value of the neutral grounding resistor (NGR) has on the phase angle of the fault currents. For the analysis, the value of the NGR was varied from having zero to infinite resistance. In other terms, the system was modeled over the range of being solidly grounded to ungrounded. Figure 15 shows the phase angle of the ground-fault current polarized against the system's zero-sequence voltage over a range of NGR values. The phase angle of the ground-fault current and the corresponding NGR value is shown in increments of 10^o.

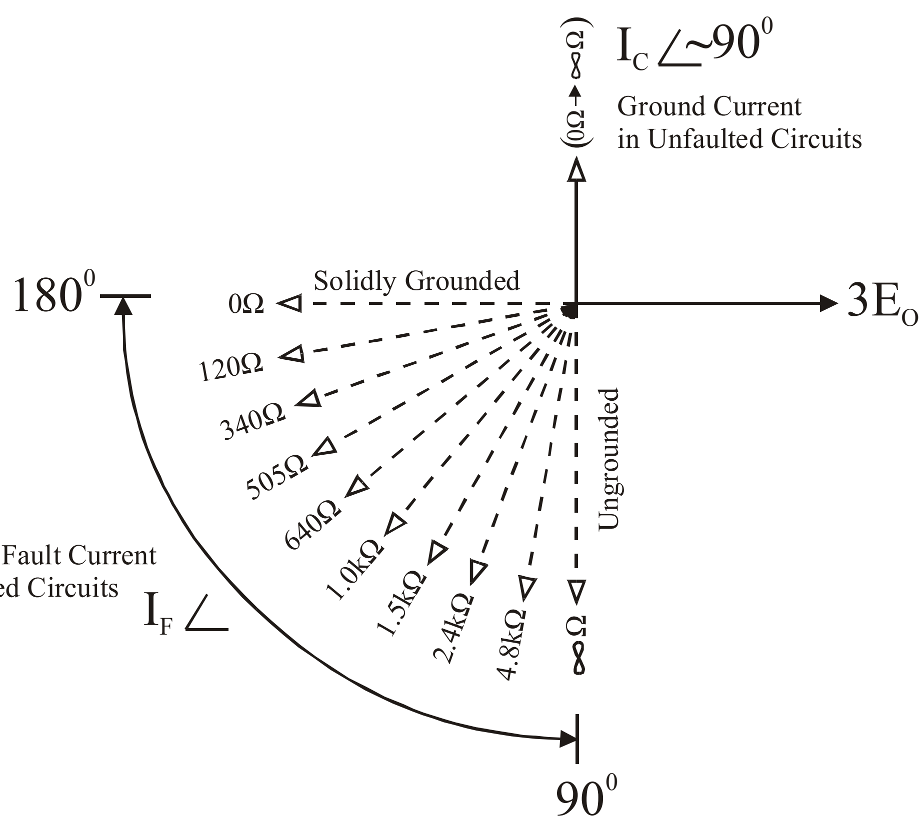

Fig. 15. Effect of NGR on the phase angle of the fault current.

It was discovered that over the NGR range of zero resistance to infinite resistance, the ground-fault current sensed by the relay in a faulted circuit always lags the system's zero-sequence voltage by 90^o to 180^o. When the system is ungrounded (NGR = ∞ Ω), the ground-fault current lags the zero-sequence voltage by 90^o. When the system is solidly grounded (NGR = 0 Ω), the ground-fault current is 180^o out of phase with the zero-sequence voltage. Figure 15 shows that the ground-fault current sensed by the relay in the faulted circuit is always in the same quadrant, while the ground current sensed by the relay in the unfaulted circuits always leads the system's zero-sequence voltage by approximately 90^o.

4.4.a Directional Relay Availability

Directional ground-fault relays are available in electromechanical, solid state, and digital designs. There are two approaches to providing directionality to an overcurrent relay: directional control and directional overcurrent (Horowitz and Phadke, 1995). The design of a directional control relay is such that the overcurrent element will not operate until after the directional element operates. Although this method is the most secure, it is not satisfactory in underground coal mining applications because the operating time will add in series resulting in an additional delay. The other approach is the directional overcurrent method. Directional overcurrent relays have independent contacts connected in series with the circuit breaker trip coil. This allows for both relays to begin operation simultaneously. A benefit of directional overcurrent relay scheme is the operating time of the directional unit is so small that it can be neglected (Horowitz and Phadke, 1995, GE, 2002).

4.5 Raising the Pick-up Setting

The results of the simulations as reported in Table 10 provide evidence that ground-fault relaying selectivity could easily be improved while maintaining the use of overcurrent relays if the pick-up setting for these relays is raised to a value less than the minimum ground-fault current sensed by a relay in a faulted circuit but greater than the maximum ground current sensed by a relay in the unfaulted circuits. The simulations show that there is an ample range available to select a pick-up setting that is between these two values for all ground-fault events.

Simulations to determine the touch potential from raised frame potentials were performed at various levels of body resistance. A resistor was inserted in parallel with the ground conductor to represent a person's body resistance. A line-to-ground fault was then inserted. The simulations were performed to determine the amount of current that would flow through the resistor. Figure 16 shows the location of the resistor that was inserted. For simplicity only the tailgate circuit is shown in the figure.

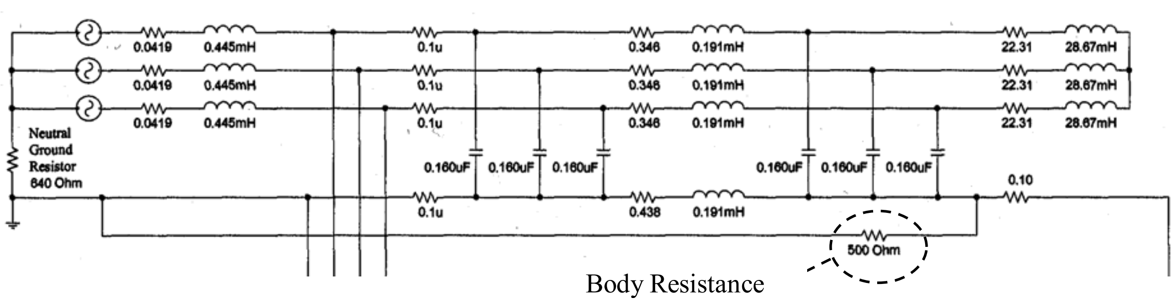

Fig. 16. Simulation of safety analysis.

During a ground fault, the frame of the equipment is elevated for the duration of the clearing time required by the protection system (Sottile and Novak, 2001). The current that flows through the resistor is equivalent to the current that would flow through the body of a victim if the victim were touching the frame and standing at ground potential. Table 14 summarizes the simulations. The body current was recorded for every ground-fault scenario. A body resistance of 500 Ω was used as this is the standard value used for performing safety analysis (Sottile and Novak, 2001).

Table 14. Current through a 500 Ω body resistance.

Current [mA] through 500 Ω resistance parallel to ground conductor							
		Fault Location					
		Shearer	Headgate 1	Headgate 2	Tailgate	Stage Loader	Crusher
Touch Location	Shearer	1.17	0.31	0.31	0.36	0.34	0.34
	Headgate 1	0.32	1.03	0.29	0.33	0.31	0.31
	Headgate 2	0.33	0.29	1.03	0.33	0.31	0.31
	Tailgate	0.36	0.31	0.31	1.18	0.34	0.34
	Stage Loader	0.35	0.31	0.31	0.39	1.11	0.33
	Crusher	0.35	0.31	0.31	0.35	0.33	1.12

By comparing the results of the simulations shown in Table 14 to the value calculated with Daziel's fibrillation equation, it is determined that as long as the protection system operates as designed, no risk of shock is posed from elevated frame potentials. The maximum currents determined from the simulations would only be barely perceptible to the touch. The simulations were also run using body resistances of 1.0 kΩ and 2.0 kΩ. The values that resulted from these simulations were reduced by an equivalent percentage compared with the values shown in Table 14. The simulations show that as far as touch potentials are concerned, the ground-fault relay pick-up setting can be increased to a reasonable level without compromising the safety of personnel.

An argument made in the defense of the low ground-fault relay pick-up setting on 4,160-V longwall power systems is that the low pick-up setting reduces the magnitude of low-level faults that can potentially persist in the system. A low-level fault is defined in this thesis as a fault whose magnitude is below the relay's pick-up setting. If the relay's pick-up setting is not exceeded, a low-level fault can remain in the system and continually dissipate power as a function of the fault current and the fault resistance. This will continue until the fault either clears itself or causes further degradation of the system components and eventually exceeds the relay pick-up setting. Low-level faults can occur during the initial breakdown of motor insulation, from cable splices that begin to fail, and from the tracking of leakage current through a conductive material.

The remainder of this section compares the power dissipated through a fault resistance whose value is selected to limit the ground-fault current to just below the ground-fault relay's pick-up setting. For simplicity, this current will be set at the relay's pick-up current. This scenario can occur as relay tolerances can change with age and use (Horowitz and Phadke, 1995).

Figure 17 is a simplified diagram of a line-to-ground fault in a 4,160-V longwall power system utilizing a 640 Ω NGR and a 0.125 A relay pick-up setting. The sum of the system's capacitance is inserted in parallel with the NGR. The fault resistance for this scenario is solved using PSpice. It is determined that the fault resistance for this configuration must be below 18.9 kΩ for a ground-fault current of ≥ 0.125 A to occur.

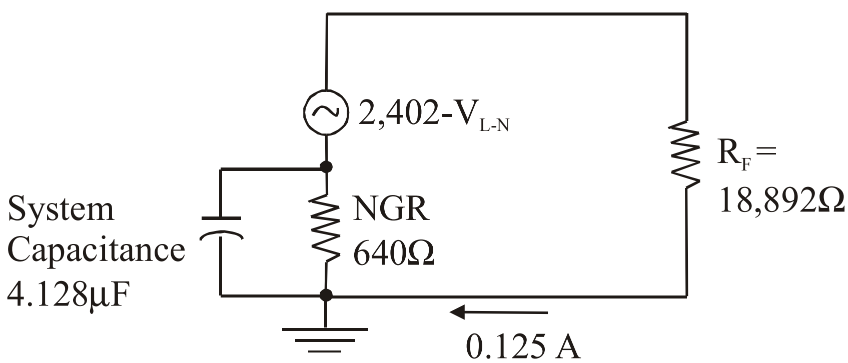

Fig. 17. Fault diagram with system capacitance included.

A calculation was performed to determine the amount of power dissipated through the fault resistance in this low-level ground-fault scenario. The calculation is as follows:

Parameter	Value
Rated Voltage	4,160 V
NGR Limit	3.75 A
Low-level Ground-fault	0.125 A

$$\mathbf{R}_{\mathbf{NGR}} = \frac{V\phi}{I_{gf(max)}} = \frac{\frac{4{,}160}{\sqrt{3}}}{3.75} = 640\Omega$$

$$\mathbf{R}_{\mathbf{f}} = \frac{2{,}402\angle 0\,\mathrm{V}}{0.125\,\mathrm{A}} - \left(640\Omega \| 4.128\,\mu\mathrm{F}\right) = 18{,}895\Omega$$

$$\mathbf{P} = I^2R = 0.125^2\ \mathrm{A} \times 18{,}895\,\Omega = \underline{\underline{\mathbf{0.295kW}}}$$

The calculations establish that 0.295 kW of power could dissipate through the fault resistance of a low-level ground-fault in a 4,160-V longwall mining system with a 0.125 A pick-up setting. The same series of calculations were performed for a 995-V power system using a single-line diagram similar to Figure 17. Figure 18 shows the results of various system configurations, including a calculation performed for a 995-V system with a NGR current limit of 15 A and a 6.0 A pick-up setting. A 6.0 A low-level ground-fault was used for this 995-V system.

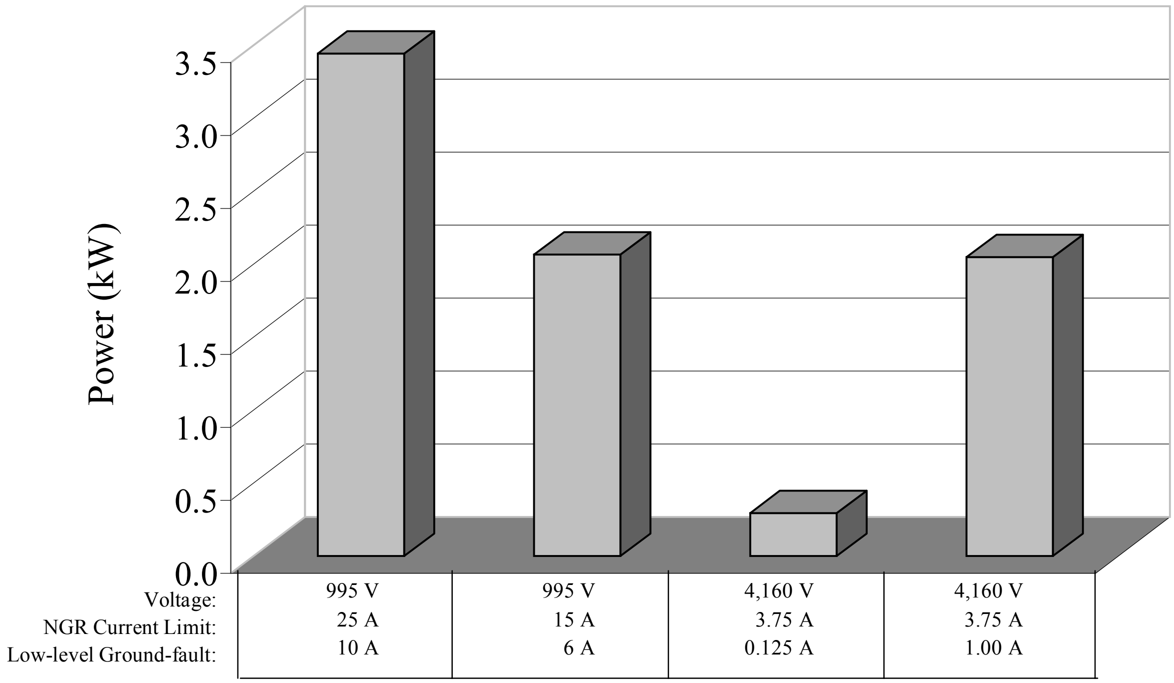

Fig. 18. Power dissipated by the fault resistance during a ground-fault.

Figure 18 shows that more power can potentially dissipate through the fault resistance of a low-level ground-fault in a 995-V system with a 6.0 A pick-up setting than could potentially dissipate through the fault resistance of a low-level ground-fault in a 4,160-V system with a 0.125 A pick-up setting. The calculations show the same amount of power would dissipate through the fault resistance of a low-level ground-fault in a 4,160-V system with a 1.0 A pick-up setting as would dissipate through the fault resistance of a low-level ground-fault in a 995-V system with a 6.0 A pick-up setting.

Figure 19 shows the beneficial ramification of raising the ground-fault relay pick-up setting to 1.0 A on a 4,160-V system. The graph shows the fault currents sensed by the current transformers (CT) in the six separate fault scenarios. The elevated bars shown in the graph are the ground-fault currents sensed by the CT's in the faulted circuits, while the lower bars are the ground current sensed by the CT's in the unfaulted circuits.

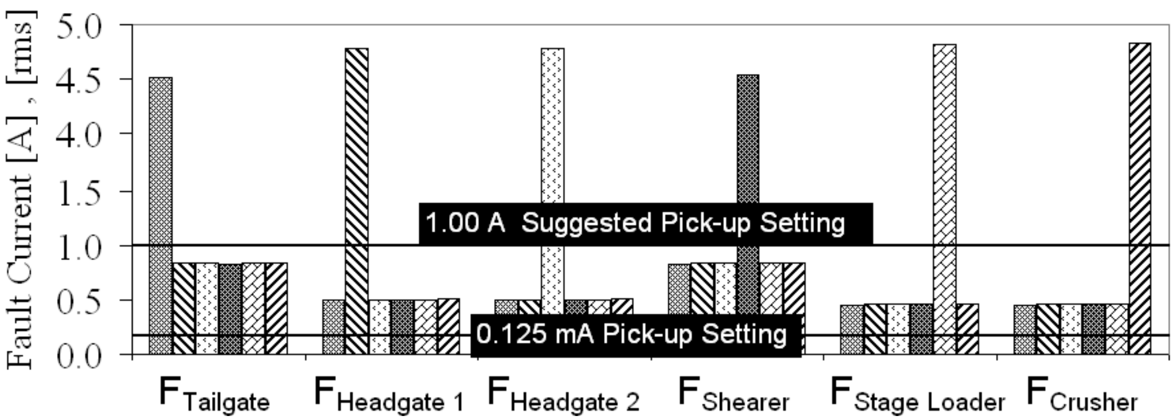

Fig. 19. Suggested pick-up setting for a 4,160- V longwall mining system.

Figure 19 shows that if the ground-fault relay pick-up setting was raised to 1.0 A, only the relay in the faulted circuit would sense a ground-fault current great enough to cause a trip sequence, thereby improving the system's selectivity.

4.6 Summary

A model of a 4,160-V longwall power system was developed in PSpice and its response was analyzed for line-to-ground fault events. The results of the analysis show that the protective relaying scheme currently employed on 4,160-V systems may not be selective. The simulations show that selectivity may be defeated during ground-fault events as the capacitive charging current returning through the unfaulted circuits exceeds the Federally Regulated ground-fault relay pick-up setting of 0.125 A. A sensitivity analysis was performed on the model to determine the effect of varying the frame contact resistance, ground conductor impedance, and for the phase which goes to ground. The sensitivity analysis showed that these attributes do not significantly affect the results.

Two potential changes were identified that could improve ground-fault relaying selectivity. These two methods were the application of a directional relaying scheme and raising the ground-fault relay pick-up setting. Directional relays were found to be applicable as the ground-fault current sensed by the relay in the faulted circuit lags the system's zero-sequence voltage while the ground current sensed by the relay in the unfaulted circuits leads the system's zero-sequence voltage. It was also determined that relay selectivity could be improved by simply raising the relay pick-up setting on the overcurrent relays to a value between the minimum ground-fault current sensed by the relay in the faulted circuit and the maximum ground current sensed by the relay in the unfaulted circuits. A safety analysis showed that raising the relay pick-up setting does not increase the risk of shock from touch potential hazards.

Chapter 5. Conclusions

The continuing trend toward larger and more complex longwall mining systems has resulted in a corresponding increase in the size of longwall components as well as the standardization to high-voltage utilization. The increase in voltage over previous levels has caused the industry to face complexities not experienced with the lower-voltage systems.

In an effort to ensure safety, Federal Regulations have more stringent requirements for high-voltage systems. Federal Regulations require that 4,160-V longwall power systems use instantaneous overcurrent ground-fault relays inby the power center that operate when the ground current is ≥ 0.125 A. This low ground-fault relay pick-up setting increases the potential for the capacitive charging current that returns through the unfaulted circuits during ground-fault events to cause spurious tripping. It is imperative that spurious tripping be avoided and that a protection system be selective when clearing faults. Selective relaying is essential in power system protection as it reduces the troubleshooting necessary to locate a fault.

A typical outby 4,160-V longwall power system was modeled to test for selectivity. The sizes of the components were chosen to represent an average size 4,160-V system. The motors in the system were modeled as three wye-connected impedances. This method of modeling provided sufficient accuracy for analysis of the system during ground-fault events. The impedances of the motors were calculated with the assumption that the motors are operating at rated capacities with typical power factors and efficiencies.

The simulations showed that ground-fault relaying selectivity is potentially lost during ground-fault events as the capacitive charging current returning though the system in the unfaulted circuits exceeds the Federal Regulation for ground-fault relay pick-up setting. As determined from the simulations, the minimum rms ground-fault current sensed a relay in a faulted circuit was 4.50 A while the maximum rms ground current sensed by a relay in an unfaulted circuit was 0.85 A. It was also determined from the simulations that the ground-fault current sensed by the relay in the faulted circuit always lags the system's zero-sequence voltage by 138° to 143°. The ground current sensed by the relay in the unfaulted circuits always leads the system's zero-sequence voltage by approximately 90°.

Two potential methods to improve ground-fault relaying selectivity were identified and evaluated for their effectiveness. The two methods evaluated were the use of directional ground-fault relay protection and raising the magnitude of the ground-fault relay pick-up setting.

It was determined that directional relays have application to 4,160-V systems as when a ground-fault occurs, the ground-fault sensed by the relay in the faulted circuit lags the system's zero-sequence voltage while the ground current sensed by the relay in the unfaulted circuits leads the system's zero-sequence voltage. The system's zero-sequence voltage can be used as the polarizing quantity for a directional relaying scheme as the phasor value of the system's zero-sequence voltage is irrespective of fault location.

It was also determined that ground-fault relaying selectivity could be improved by simply raising the pick-up setting on the overcurrent ground-fault relays to a value between the minimum ground-fault current sensed by the relay in the faulted circuit and the maximum ground current sensed by a relay in the unfaulted circuits. A safety analysis showed that increasing the ground-fault relay pick-up setting to a reasonable level would not significantly increase the risk of shock from elevated frame potentials.

Calculations were also performed to determine the amount of power that is potentially dissipated through the fault resistance of a low-level line-to-ground fault. During a low-level ground-fault, a 4,160-V system with a 3.75 A NGR current limit and a 1.0 A pick-up setting could dissipate 2.05 kW of power through the fault's resistance. During an equivalent low-level ground-fault, the currently permitted 995-V system with a 15 A NGR current limit and a 6.0 A pick-up setting could dissipate 2.07 kW of power through the fault's resistance. Therefore, raising the ground-fault relay pick-up setting to 1.0 A on a 4,160-V system would not cause any more power to dissipate during a low-level ground-fault event than could potentially dissipate on a permitted 995-V system.

It was determined from the simulations that raising the ground-fault relay pick-up setting to 1.0 A would improve ground-fault relaying selectivity on an average sized outby 4,160 V system. Raising the pick-up setting to 1.0 A is not an indefinite solution though, as the continuing trend towards larger longwall mining systems will only exacerbate the issues with ground-fault relaying selectivity. It was recently published that by March of 2005, a longwall operator in the United States plans to increase its face width to 1,450 feet (Hookham, 2004). The operator plans to use three 1,450 hp motors to power the armored face conveyor. A system with similar component values was modeled, and it was determined that the minimum rms ground-fault current sensed by a relay in a faulted circuit would be 4.56 A and the maximum rms ground current sensed by a relay in an unfaulted circuit would be 1.04 A. Therefore, the ground-fault relay pick-up setting for this system would have to be raised above 1.0 A to improve relaying selectivity. As the increase in longwall component size and panel dimensions will inevitably outpace the rate at which the Federal Regulations governing the use of high-voltage longwalls is updated, a directional relaying scheme should be considered as it is a practical long term solution to improving ground-fault relaying selectivity that is irrespective of longwall component size and panel dimension.

Suggested future research in this area would focus on confirming the accuracy of the computer model that was used to determine a 4,160-V longwall mining system's response during a line-to-ground fault event. To verify the model's response during a line-to-ground fault event, field testing of an operating 4,160-V system would be required. If properly recorded, the value of the ground-fault currents that occur during a line-to-ground fault event on an operating 4,160-V system could be used to verify the computer model. The ground-fault currents could be monitored at the system's current transformers using standard equipment. There are two possible methods to gather the required data. The recording equipment could either be applied at the current transformers and a line-to-ground fault could be *safely* inserted in the system, or the recording equipment could be applied and remain attached to the current transformers until a line-to-ground fault naturally occurred in the system. The second option is more realistic, and would be plausible as line-to-ground faults are not infrequent events.

REFERENCES

Anaconda Wire and Cable Company. 1977. *Mining Cable Engineering Handbook*.

Andrichak, J.G. and S.C. Patel. Polarizing Sources for Directional Ground Relays. General Electric. (File GER-3182A).

Basar, J. and T. Novak. 2003. The Evolution of Utilization Voltages on Longwall Faces in the United States and Its Effects on Productivity. presented at the 25th International Mining Convention and Exhibit, Acapulco.

Boring, C.M. and K. J. Porter. 1988. Criteria for Approval of Mining Equipment Incorporating On Board Switching of High-Voltage Circuits. *Proceedings of the Ninth WVU International Mining Electrotechnology Conference*. July: 267-274.

Cawley, J.C. 2003. Electrical Accidents in the Mining Industry, 1990-1999. *IEEE Transactions on Industry Applications*. Vol. 39, No. 6, Nov/Dec: 1570-1577.

Chapman, S. 2002. Electric Machinery and Power System Fundamentals. International Edition. New York: McGraw Hill

Dalziel, C.F. and J.B. Lagen. 1941. Effects of Electric Current on Man. *Electrical Engineering*.

Dalziel, C.F. 1954. Threshold of Perception Currents. *Electrical Engineering*.

Dalziel, C.F. and W.R. Lee. 1969. Lethal Electric Currents," *IEEE Spectrum*. Feb.

Dunki-Jacobs, Jr., J.R. 1977. The Reality of High-Resistance Grounding. *IEEE Transactions on Industry Applications*. Vol. 13, No. 5, Sept/Oct: 469-475.

eCircuit Center. 13 Mar 2004. <http://www.ecircuitcenter.com/AboutSPICE.htm>

Electrical Protection. Title 30, *Code of Federal Regulation* (CFR) § 75.814, (a)(1-6) available at the website: <http://www.msha.gov/regdata>

Fiscor, S. 2004. Longwall Census '04. *Coal Age*, Feb: 26-31.

General Cable. 10 Mar 2004. Available online at: <http://www.mining-technology.com/contractors/cables/general_cable/>

General Electric Corporation (GE). 2002. M Family Digital Ground Protection Relay. Available online at: <http://www.geindustrial.com/products/brochures/min.pdf>

Glover, J.D. and Sarma, M.S. 2002. Power System Analysis and Design. 3rd ed. Pacific Grove, California: Brooks/Cole.

Hookham, M. 2004. Emerald Sets Sights Wide. *International Longwall News*. 26 March 2004. Published in *Australia's Longwalls*. Aspermont Limited, West Leederville WA.

Horowitz, S.H., and A.G. Phadke. 1995. Power System Relaying. 2nd ed. Hertfordshire, England: Research Studies Press Ltd.

IEEE Std. 142-1991, IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems, pp. 3-8.

K-TEC Corporation. 1991. Protection Prediction Monitoring & Electrical Safety.

Novak, T., J. Basar, J. Sottile and J.L. Kohler. 2004. Selectivity of Ground-Fault Relaying in Longwall Power Systems. presented at the 2004 Annual Society of Mining and Minerals Engineering Conference, Denver.

Novak, T., J. Basar, J. Sottile and J.L. Kohler. 2003. The Effects of Cable Capacitance on Longwall Power Systems. presented at the 2003 IEEE/IAS Annual Meeting, Salt Lake City.

Novak, T., and J. Sottile. Quarterly Report – 10/01/02-12/31/02 *Reduction of Mining Electrical Hazards Through Improved Engineering Controls.* Prepared for NIOSH.

Novak, T. 2001-a. The Effects of Very-High Resistance Grounding on the Selectivity of Ground-Fault Relaying in High Voltage Longwall Power Systems. *IEEE Transactions on Industry Applications*. Vol. 37, No. 2, Mar/Apr: 398-406.

Novak, T. 2001-b. Analysis of Very-High Resistance Grounding in High-Voltage Longwall Power Systems. *IEEE Transactions on Industry Applications*. Vol. 37, No. 1, Jan/Feb: 104-111.

Novak, T. and J. K. Martin. 1996. The Application of 4160 V to Longwall Face Equipment. *IEEE Transactions on Industry Applications*. Vol. 32, No. 2, Mar/Apr: 471-479.

Novak, T. L.A. Morley, and F.C. Trutt. 1988. Sensitive Ground Fault Relaying. *IEEE Transactions on Industry Applications*. Vol. 24, No. 5, Sept/Oct: 853-861.

PD Wire & Cable. *Power Cables – Industrial and Mining*. Ref. No. PC-00041. Available online at: <http://www.pdwc.com/pdfs/Power/Industrial/SHDGC_PC-00041.pdf>

Secretary of Labor, Mine Safety Health Administration (MSHA) vs. LodeStar Energy. Federal Mine Safety and Health Review Commission. Docket Nos. KENT 2002-184, -238 July 3, 2003

Siemens Power Engineering Guide. Transmission and Distribution. 4th ed. Available online at: siemens.com

Sottile, J. and T. Novak. 2001. Electrical Safety. In *Mine Health and Safety Management*, ed. Michael Karmis. Colorado: Society of Mining, Metallurgy, and Exploration, Inc.

Stevenson, Jr., William. 1975. Elements of Power System Analysis. 3rd ed. Tokyo, Japan: Tosho Printing Co.

Title 30, Code of Federal Regulations (CFR) available at the website: < http://www.msha.gov/REGDATA/MSHA/0.0.HTM >

U.S. Bureau of Mines. (USBM) 1997. Distinguishing Motor Starts From Short Circuits Through Phase-Angle Measurements. (Report of Investigations 9638).

U.S. Department of Health and Human Services. (DHHS) 1998. Worker Deaths by Electrocution: A summary of NIOSH Surveillance and Investigative Findings. (NIOSH Publication No. 98-131). Cincinnati, OH.

Wilks, J. 2003. Electrical Protection: Limits to Reliable Operation. presented at the Mining Electrical & Mining Mechanical Engineers Society 2003 meeting, Port Stephens NSW.