MINING

Mine electrical distribution and utilization circuits have evolved into complex systems that must conform to numerous regulations, mandated by government agencies. The power systems in most industries are located in stationary, permanent facilities and are not subjected to harsh operating conditions. This is not the case with the mining industry. Mining equipment is usually mobile and self-propelled, powered by portable cables. With the extraction of the mineral or rock, the electrically driven machines must advance, followed by their source of power. Each move stresses both equipment and cables by their being dragged over rough surfaces and impacted. Also, the noncontinuous mining process subjects electrical components to rigorous duty cycles, with a high degree of shock loading. Environmental conditions of the mine, such as dirt, dust, and water, detrimentally affect the insulating properties of equipment and increase the possibility of electrical faults. Because of these circumstances, the safe and reliable operation of a mine power system requires elaborate grounding and ground-fault protection systems.

Another critical factor that affects the design and fabrication of mine electrical systems is the ever-present potential for explosion, particularly in underground coal mines. Coal and other carbonaceous rock formations can store large amounts of methane, which are subsequently liberated during the mining process. Methane can also be found in some noncoal mines, most notably in trona mines and in some potash, limestone, oil shale, and salt mines (1). A methane–air mixture in the proper proportions will explode if an ignition source is present. Thus, in some areas of coal and other gassy mines, electrical equipment must be built with explosion-proof enclosures. For some very-low-power applications, such as monitoring, control, and some types of lighting, intrinsically safe circuits are used. These circuits limit the amount of energy to a level below that required to ignite an explosive methane-air mixture.

A final factor, physical size of the mine openings, places constraints on electrical equipment. Low seam heights in underground mines, sometimes less than 1 m, cause severe limitations on the physical size of electrical equipment. The design of low-profile equipment, which can fit and be maintained within these confined spaces, is very challenging.

Given the unique set of operating conditions in the mining industry, the design, fabrication, installation, and maintenance of the electrical equipment are both fascinating and demanding.

HISTORY OF MINE ELECTRICAL SYSTEMS

Electricity was first introduced into mines shortly before the beginning of the twentieth century in the form of direct current for rail haulage, with batteries serving as the first power source (2). Even though constrained by rails, battery-powered vehicles were very mobile. Soon thereafter, 250 V or 550 V trolley wires were installed in mines. The first electrically driven mining machine, the coal cutter, was introduced in the early 1920s and was soon followed by the loading machine. (For a general description of the mining machines discussed in this article, see Ref. 3.) Direct current powered these machines, since the dc trolley was readily available. The battery-powered shuttle car, which hauls coal from the working face to the primary haulage system, was invented in 1937. The addition of an automatic cable-spooling device soon occurred, which overcame deficiencies associated with batteries. Continuous mining machines became popular in the late 1940s and were initially powered from the dc trolley line. As the horsepower requirements of the continuous miner grew, the dc trolley quickly became inadequate for the power distribution system. The use of three-phase alternating current for distribution and utilization proliferated during the 1950s and 1960s. Initially, 2300 V or 4160 V was used for the distribution voltage, but these levels later increased to 7200 V. The distribution systems for modern underground mines typically operate at 12.47 kV, 13.2 kV, or 13.8 kV.

With the introduction of alternating current into mines, 440 V became the popular utilization voltage. However, the power requirements of mining machines continued to increase, which resulted in increased trailing cable sizes until the cable's weight was almost more than personnel could handle. To compensate, the utilization voltage was first increased to 550 V. More recently, manufacturers have produced machines with 950 V, 2300 V, and 4160 V motors to overcome trailing-cable problems. The two higher voltages have recently gained popularity with high-capacity longwall mining systems. Title 30, Code of Federal Regulations (CFR), classifies voltage levels for mines in the United States as follows: low voltage—0 V to 660 V, medium voltage—661 V to 1000 V, and high voltage—greater than 1000 V. Equipment operating at the different voltage levels is subjected to different safety regulations as defined by the CFR.

MINE POWER SYSTEMS

Although numerous power-distribution arrangements exist, the radial system is by far the most popular configuration in mining. Figure 1 shows a one-line representation of the underground portion of a longwall coal mine. A large variety of power-system practices and equipment exist; however, Fig. 1 is a relatively good representation of the equipment that can be found in this type of mine. It should be noted that Fig. 1 only shows the underground portion of the power system; surface loads, such as the preparation plant, mine-ventilation fans, and belt conveyors, may constitute a combined power requirement larger than that of the underground loads. To illustrate current practices in the mining industry, a modern longwall power system will be discussed in this article. This type is more sophisticated and complex than most other mine power systems. Some mines utilize dc trolley systems for the

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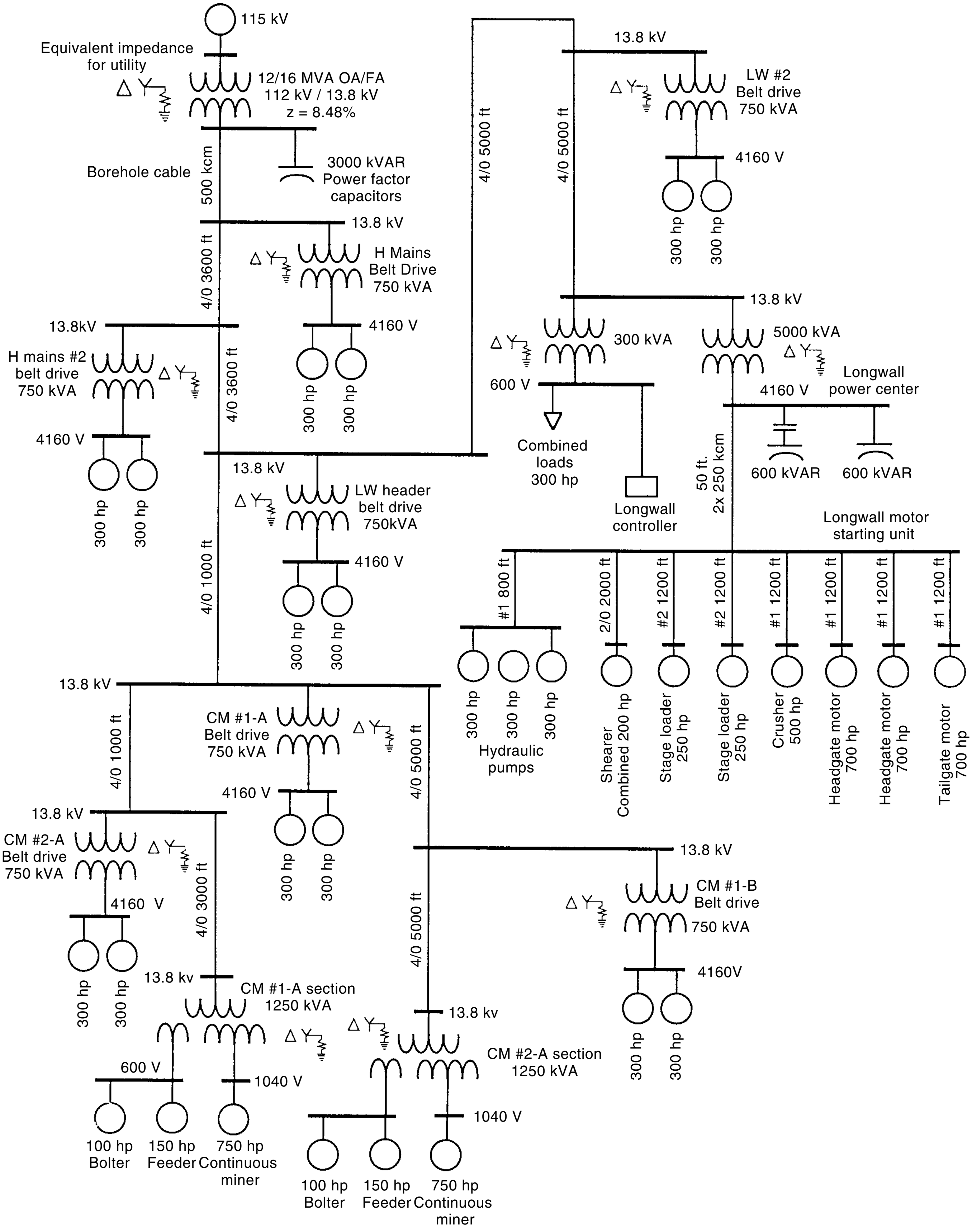


Figure 1. One-line diagram of a longwall power system illustrating a radial arrangement commonly used in the mining industry.

transportation of workers and supplies. The mine associated with the power system of Fig. 1 uses diesel or battery-powered equipment for these purposes, since the one-line diagram does not include trolley rectifiers.

Mining companies typically purchase electric power from a utility company; however, in very remote locations, electric power may have to be generated on site. Figure 1 shows a utility connection at 115 kV. For the system in Fig. 1, a 12/16 MVA OA/FA (oil air/forced air) power transformer in the surface substation steps down the utility's transmission voltage of 115 kV to the mine's underground distribution voltage of 13.8 kV. The mine operator or the utility company may own the power transformer—both methods are common. (The surface substation will be discussed in more detail in a subsequent section of this article.) The power system enters the mine by means of a borehole, which is a steel-cased hole drilled from the surface to the mine. The depth of this hole typically varies from 100 m to 700 m for coal mines. At the bottom of the borehole, the power system begins its radial branching to supply various equipment at numerous locations throughout the mine. Although not shown in Fig. 1, single- or double-breaker switchhouses, which are portable metal-enclosed equipment, allow branching of the radial system and provide protective relaying.

In Fig. 1, the distribution voltage throughout the mine is 13.8 kV, although 12.47 kV and 13.2 kV are common. The primary loads for this example include belt drives, continuous-miner equipment, and longwall equipment. Figure 1 shows the various utilization voltages that are used for different applications. The belt drives in this example use 4160 V, but 480 V and 600 V are also commonly used, depending on motor sizes. Soft-start or variable-frequency drives are typically used with the lower voltages of 480 V and 600 V; whereas with 4160 V, across-the-line starting is commonly used in conjunction with fluid couplers or controlled start transmissions (CSTs). Direct-coupled wound-rotor motors still find use in some applications, and modern dc drives have gained popularity. Reference 4 presents a thorough description of the various types of conveyor drives used in the mining industry.

In addition to mining coal, the major function of continuous-miner sections is to develop mine openings for the longwall operation. The primary equipment associated with a continuous-miner section includes the continuous mining machine, a roof bolting machine, shuttle cars or ram cars, and a feeder/breaker. Other ancillary equipment may include scoop tractors and their battery-charging stations, rock dusters, and pumps. Figure 1 shows a 1250 kVA power center supplying each of the two continuous-miner sections. These power centers essentially consist of input and output plug/receptacles, a high-voltage disconnect switch, a three-winding power transformer with fused primary and surge protection, a neutral-grounding resistor, molded-case circuit breakers for each outgoing circuit, and the associated protective relaying. Continuous miners usually operate at 995 V, which is at the maximum extreme of the medium voltage classification. Federal regulations in the United States permit only low or medium voltage to be used at the working face (the area of the mine where coal extraction actually occurs), without the approval of a petition for modification by the Mine Safety and Health Administration (MSHA). Generally, the remaining electrical equipment on the continuous-miner section typically operates at low voltage (600 V or 480 V).

Longwall mining provides the most productive method of mining coal in deep underground mines. In the United States, this type of mining, shown in Fig. 2, generally consists of driving two to four parallel gate entries (tunnels) with continuous miners. These gate entries are located on both sides of a large block of coal. One set of gate entries is referred to as the headgate; the other is known as the tailgate. Sets of entries at the extreme ends of the coal block connect the headgate and tailgate. A shearing machine extracts coal bidirectionally, along the width of the block between the headgate and tailgate entries. The width of the block typically ranges from 250 m to 350 m, and the block's length frequently exceeds 3000 m. The equipment for a longwall system basically consists of a shearer, a coal haulage system, and a self-advancing roof-support system. The shearer mines laterally across the block as it propels itself along an armored face conveyor, which transports the newly cut coal to the belt conveyor at the headgate. Self-advancing hydraulic roof supports protect the workers, shearer, and armored face conveyor from the caving roof along the entire width of the block. The caved area behind the roof supports is referred to as the *gob*. Shearer-initiated roof-support advancement is a rapidly developing technology. Sensors detect the shearer's location, and a processor automatically controls the advancement of the roof supports. Also, automatic control of the cutting height of the shearer (auto-steering) is under development (5).

The longwall power equipment consists of a power center, motor-starting unit, and controller, as shown in Fig. 1. Each of these components will be discussed in detail, later.

SURFACE SUBSTATION

Figure 3 shows a one-line diagram of a surface substation. As stated in the previous section, the power transformer may be owned by the utility company or the mining company. If the utility owns the transformer, it generally maintains its own substation adjacent to the mine's substation, and the utility is responsible for the maintenance and repair of the transformer. If the mining company owns the transformer, the company maintains it. With this arrangement, the mining company receives a discounted rate structure, since the mine is fed directly from a transmission voltage. Both types of ownership are common in the mining industry.

The CFR requires high-resistance grounding for all circuits that feed portable equipment. Thus, most coal mining applications utilize delta-wye connected transformers, since the wye-connected secondary provides a neutral point that can be connected to ground through a resistor, as shown in Fig. 3. For distribution applications, the neutral grounding resistor typically limits maximum ground-fault current to 25 A. If the transformer has a delta-connected secondary, a neutral point for the system must be derived by a zig-zag or grounding transformer.

Substation transformers are almost always liquid (oil) immersed. The standard ratings for substation transformers are based on an allowable average winding temperature rise of 65°C. The transformer capacity always has a self-cooled OA rating and may also have an FA and forced-air-and-oil (FOA) rating. The transformer shown in Fig. 3 has an OA rating of

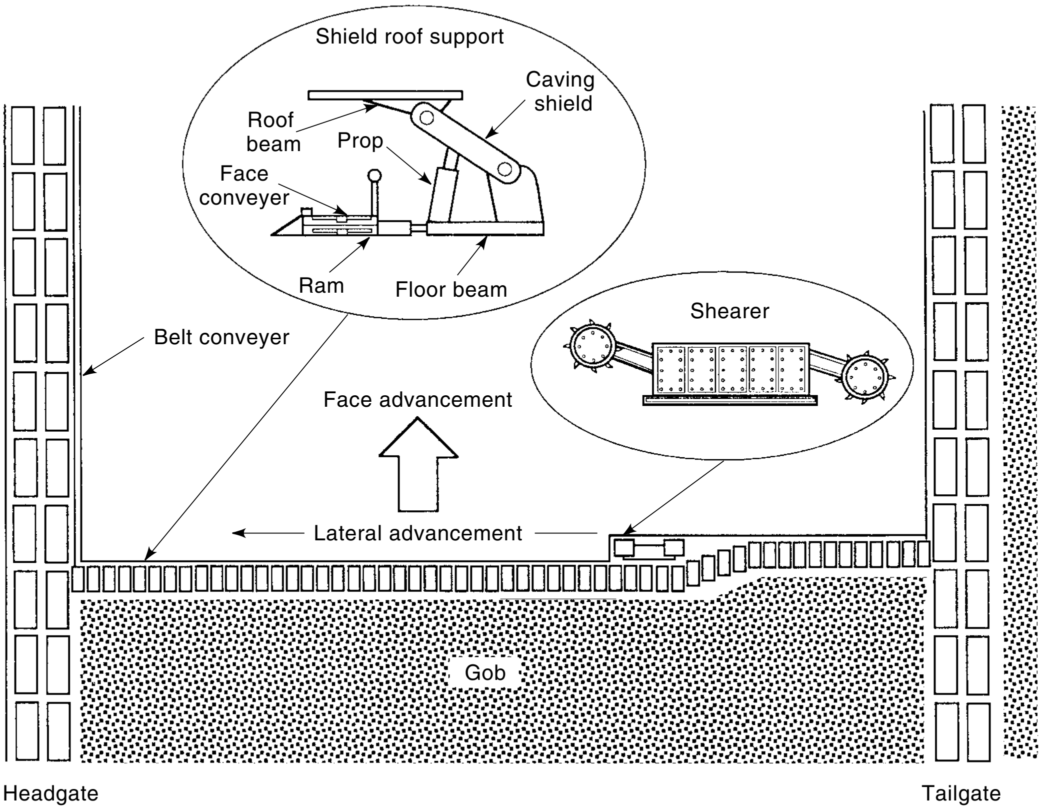


Figure 2. A plan view of the general layout of a longwall face shows the shearer extracting coal, laterally across the face, while the roof support system advances. An armored face conveyor transports the coal to a belt conveyor, and the roof caves behind the shields.

12 MVA and an FA rating of 16 MVA. Voltage taps are provided in the primary winding—two $2\frac{1}{2}\%$ above and two $2\frac{1}{2}\%$ below the nominal voltage. In some instances, voltage regulators, which utilize automatic tap changing under load, are used.

Figure 3 shows two gang-operated disconnect switches, one mounted on a pole with the other located in the power house. For safety purposes, US regulations require a visible disconnect, which can be locked out in the open position, when performing maintenance on downstream equipment or circuits. A key interlock system can provide an interlock for the main disconnect switch, so that access to the outgoing circuits cannot be gained unless the main disconnect is open. The main disconnect switch is usually interlocked with the circuit breakers to prevent opening the disconnect switch under load; in other words, the breakers will trip prior to contact separation of the disconnect switch.

Figure 3 shows two separate ground fields, a station ground and a safety ground. Federal regulations in the United States require these two ground beds, and they must be separated by a minimum distance of 8 m. The safety ground generally consists of a driven-rod ground bed, which has a resistance of 4 Ω or less, when measured by the fall-of-potential method (6). Only the frames and ground connections of the equipment in the mine are permitted to be connected to this bed. Since mining equipment frequently changes location, the safety ground bed is established at a fixed location near the surface substation. The low-resistance safety ground bed prevents dangerous potentials from being developed on mining equipment frames if an electrical fault occurs. Reference 7 presents a methodology for designing a low-resistance driven-rod ground bed. A ground-mesh, located under the entire substation area, generally provides the station ground field (8). The frames of all the equipment enclosed in the substation area, along with the surge arresters and fence, are connected to the station ground, as shown in Fig. 3.

Station-class surge arresters, which are usually installed on both the primary and secondary sides of the substation transformer, provide transient overvoltage protection. The arrester ratings are coordinated with the transformer BIL ratings and, as previously discussed, the arresters must be connected to the station ground.

A preassembled weatherproof structure protects the switchgear and the service aisle. The indoor switchgear typically consists of a lineup of vertical sections that are mounted side by side, and grounded metal barriers isolate the main compartments of each circuit. An electrically operated 15 kV vacuum circuit breaker (VCB) usually protects each circuit in the power house. The breaker may be a horizontal or vertical drawout type, equipped with a shunt trip, undervoltage release, operation counter, and position-indicating lights. A fail-safe capacitor trip device can be provided that trips the VCB if the capacitor looses its charge. A three-phase solid-state relay, supplied by three multiratio relaying-class current transformers, generally provides instantaneous and overload protection.

Zero-sequence relaying provides primary ground-fault protection for each circuit. A solid-state definite-time relay, with

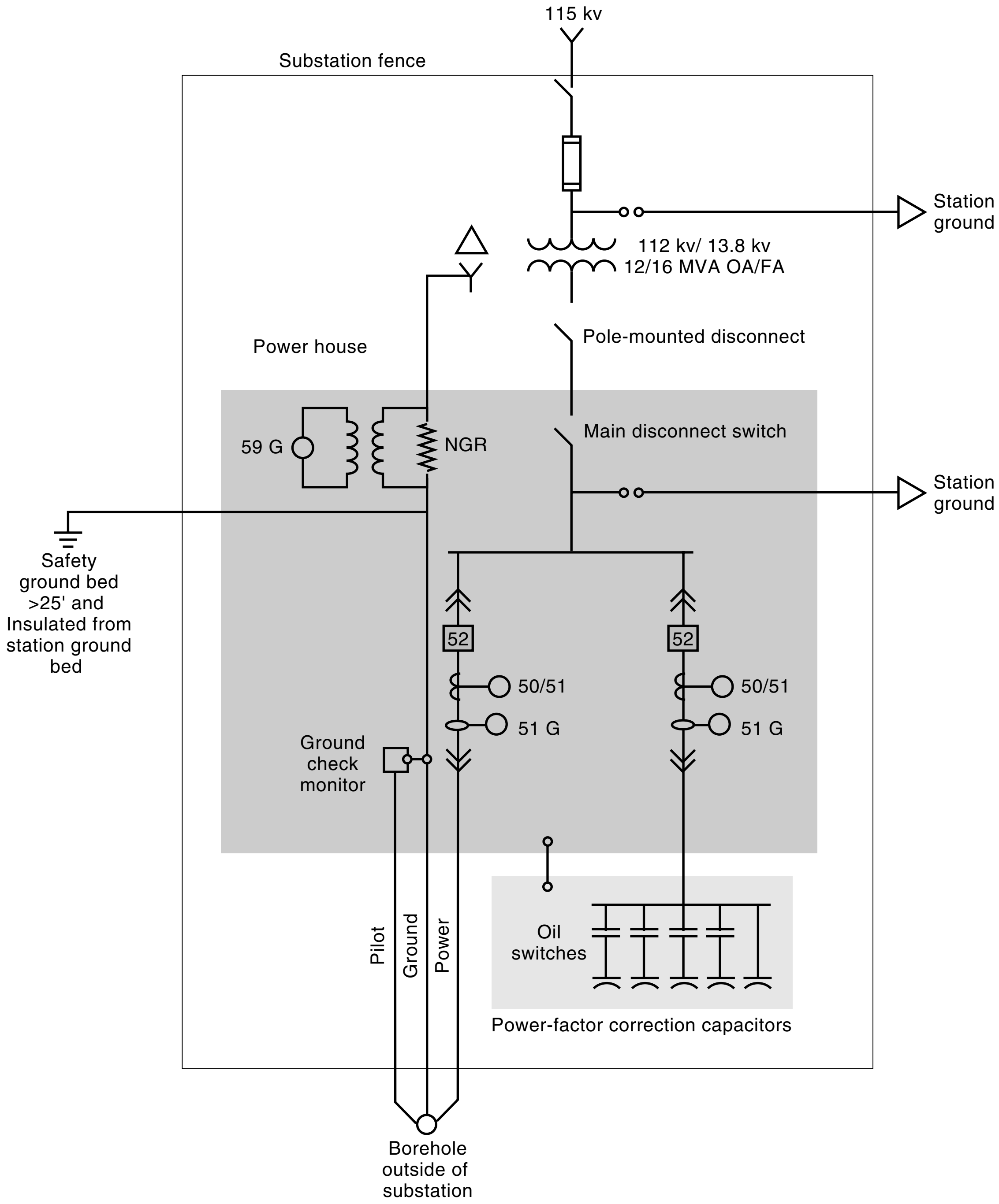


Figure 3. One-line diagram of a surface substation showing a resistance-grounded system, the protective-relaying schemes, and the two separate ground beds required by federal regulations in the United States.

appropriate pickup and time-delay ranges for coordination with other ground-fault relays in the system, is typically used. An unfused potential transformer, connected across the neutral grounding resistor, provides backup ground-fault protection, as shown in Fig. 3. The secondary of this transformer supplies a definite-time solid-state overvoltage relay with adequate tap settings and time-delay range to ensure proper relay coordination with the primary ground-fault protection. Potential relaying detects a ground-fault even if the neutral grounding resistor is open, which provides an added degree of protection.

The CFR requires all circuits feeding mobile equipment to have a fail-safe circuit to monitor continuously the continuity of the grounding conductor. Impedance-type monitors are commonly used for high-voltage distribution systems. These types of monitors require the monitored cable to have a pilot conductor, as shown in Fig. 3. The monitor is calibrated to the impedance of the loop formed by the pilot and grounding conductors, and the device then monitors the change of impedance from the initial calibration. If the impedance of the loop increases beyond a preset value, the monitor trips the associated circuit breaker.

Figure 3 shows a bank of capacitors with a total rating of 3000 kVAR located outside the switchgear enclosure for power-factor correction. The bank is arranged with one 600 kVAR fixed bank and four 600 kVAR switched banks. Factory-wired fuses (with blown-fuse indicators) and bleeder resistors are provided with each capacitor. Reactors are connected in series with the switched capacitors, and capacitor switching is designed to occur with sufficient time delays to prevent excessive switching with power-factor variations of short duration.

Metering and transducer modules are available to display detailed information about the system, such as line currents, line voltages, kW, kVAR, MWh/MVARh, maximum MW demand, MVAR demand, kVA demand, current demand, current unbalance, voltage unbalance, power factor, neutral current, frequency, and total harmonic distortion. A programmable logic controller (PLC), connected to a minewide data highway, may be used in some applications (9). The panelview display of the PLC can display information about the power house, such as the position of the main disconnect switch, the status of each circuit breaker, cause for tripping, and time of tripping. The PLC can also provide remote tripping and closing of circuit breakers with the appropriate level of password protection, single-phase protection, an appropriate fault signal for each outgoing circuit, VAR sensing at the main bus, and capacitor switching for the power-factor correction circuit.

LONGWALL POWER EQUIPMENT

The power requirements of high-capacity longwall systems have significantly increased in recent years, such that the combined horsepower for the face conveyor, shearer, stage loader, crusher, and hydraulic pumps can easily exceed 5000 hp (10). The standard practice of using 995 V as the utilization voltage is inadequate for these high-capacity applications for the following reasons: (1) The available fault currents from high-capacity power-center transformers with 995 V secondaries can exceed the interrupting capabilities of existing 1000 V molded-case circuit breakers; (2) the maximum practical limit on the size of cables can be exceeded because of the high-current requirements at 995 V; (3) excessive voltage drop, which is a function of cable size and line currents, significantly reduces motor torque; and (4) the maximum instantaneous trip settings allowed by MSHA may be exceeded when starting large motors rated at 995 V. The last two concerns, reduced torque and maximum inrush current, are criti-

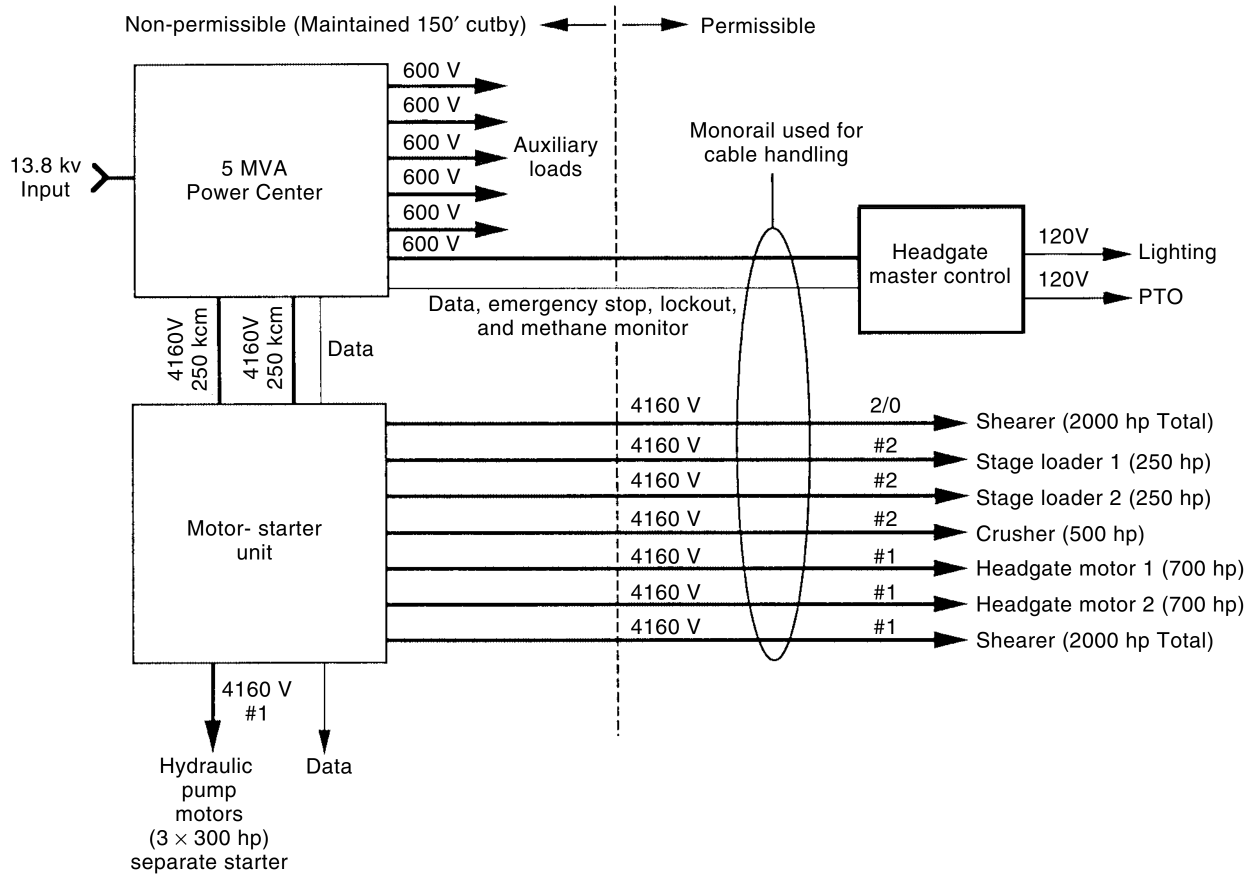


Figure 4. One-line diagram showing the general arrangement for a typical 4160-V longwall electrical system. All equipment beyond the dashed line toward the coal face must be permissible (explosion-proof).

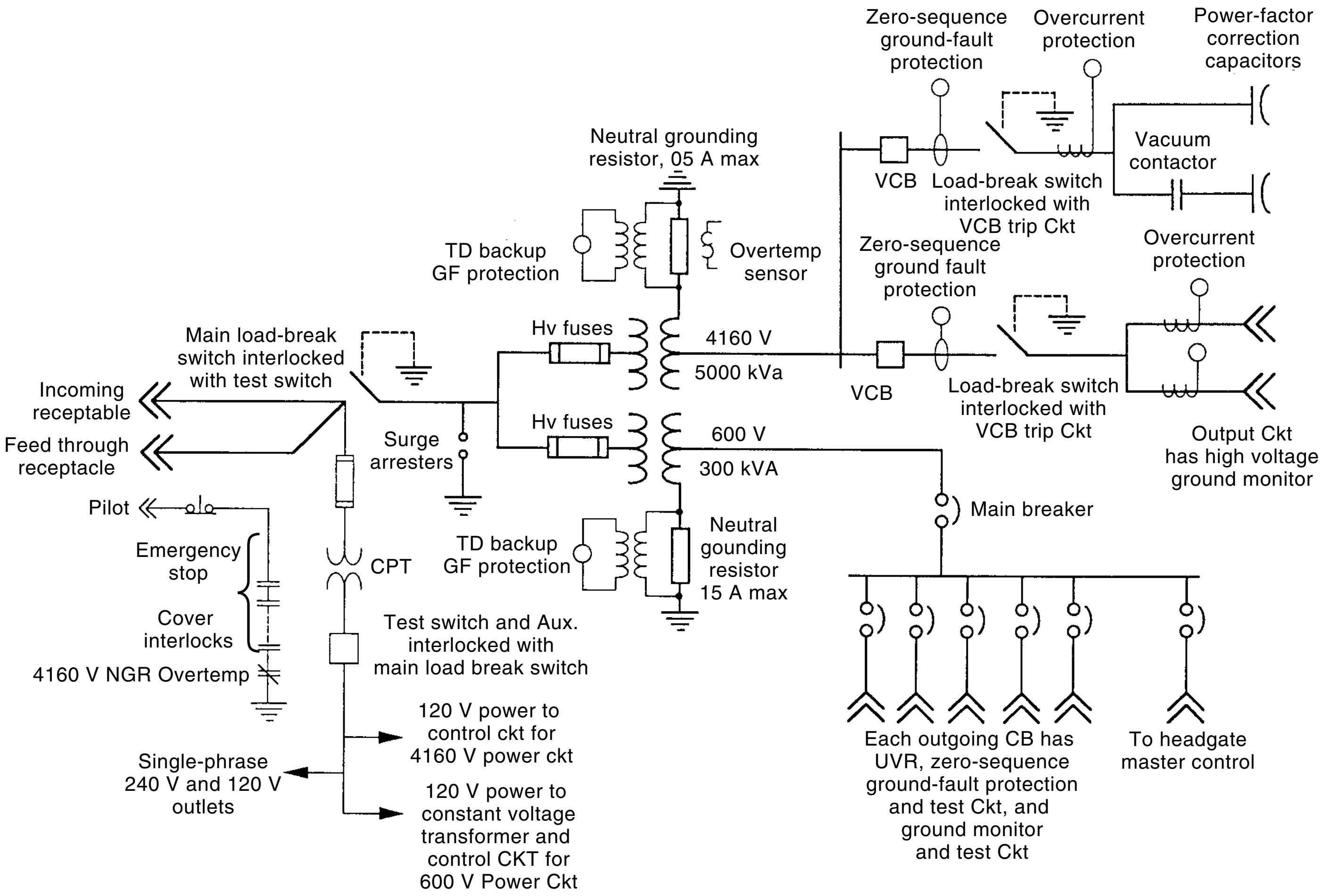
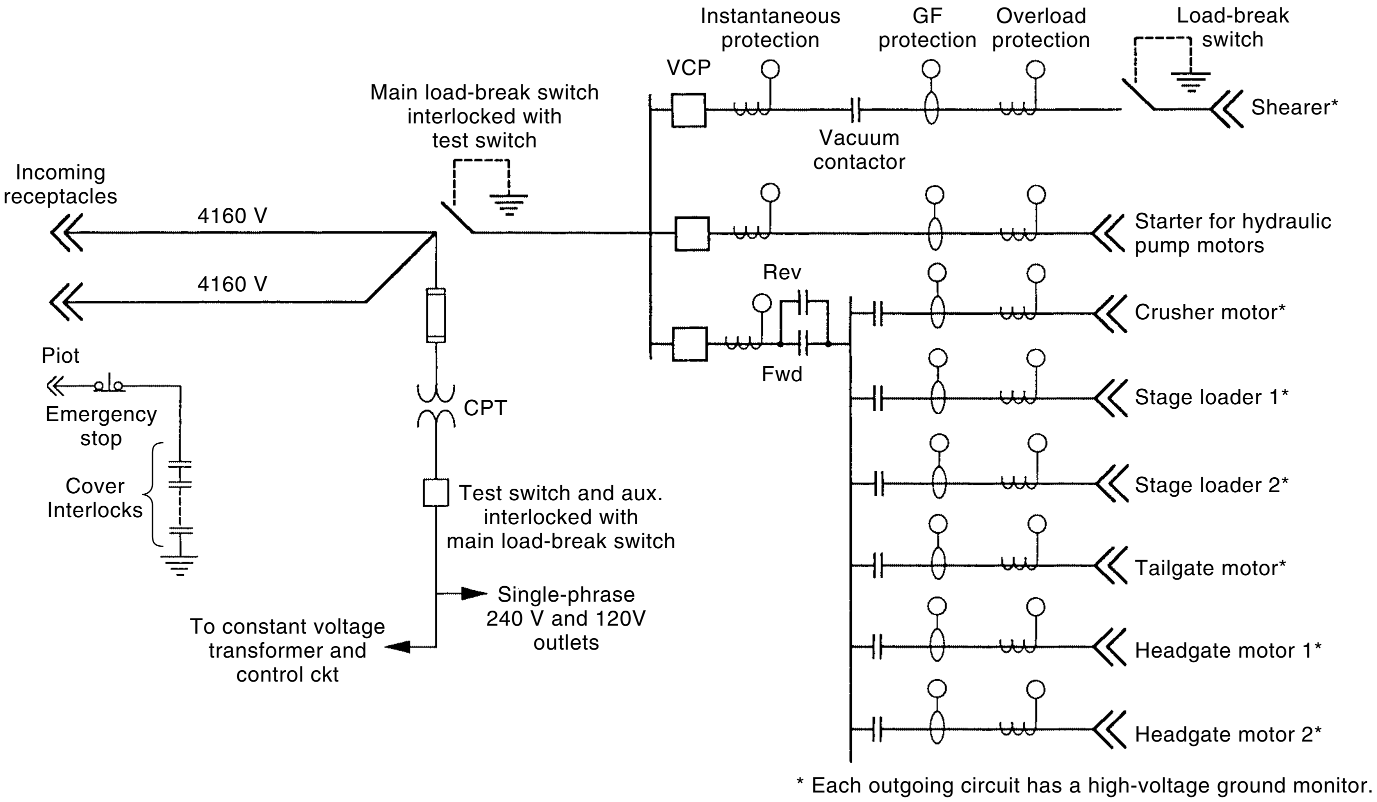


Figure 5. One-line representation illustrating the components, and their arrangement, in a longwall power center. Many of the safety features, such as high resistance grounding, sensitive ground-fault protection (zero-sequence and potential), and an overtemperature sensor for the neutral grounding resistor, are shown.

cal to the operation of the face conveyor. With reduced torque due to excessive voltage drops, it may be difficult, if not impossible, to start and run a loaded conveyor. Also, the first-cycle inrush currents of large motors may exceed MSHA-mandated maximum instantaneous trip settings for associated cables.

Higher utilization voltages minimize, if not eliminate, the aforementioned concerns. However, the use of high voltage (greater than 1000 V) to power face equipment requires approval from MSHA. To obtain approval, the mine operator must show that a proposed alternative method will at all times guarantee no less than the same measure of protection afforded by the existing standards (11). Figure 4 shows the general arrangement of a typical 4160 V system. With this type of system, the motor-starting switchgear is located near the power center more than 50 m *outby* the longwall face; therefore, the switchgear does not have to be housed in an explosion-proof enclosure. A monorail cable-handling system supports the 4160 V cables.

Figure 5 shows a one-line diagram for a typical 4160 V power center. The power center has two power transformers—one for the 4160 V longwall circuit and the other for the 600 V auxiliary equipment. Each transformer has a delta primary and wye secondary with its neutral point tied to ground through a neutral grounding resistor. The CFR requires that the maximum ground-fault current be limited to 25 A for low- and medium-voltage circuits, but the 15 A limit shown for the 600 V circuit in Fig. 5 is standard practice. For 4160 V systems, MSHA requires a maximum ground-fault current limit of 3.75 A; however, more stringent ground-fault current limits from 0.5 A to 1.0 A have been successfully used with a ground-fault relay pickup of less than 100 mA. This sensitive ground-fault protection system also has a “look-ahead” circuit to prevent the circuit breaker from closing into a line-to-ground fault. Monitoring the impedance between the phase conductors and ground accomplishes this look-ahead function. Figure 5 also shows backup ground fault protection (potential relaying) that will de-energize the power circuit if a ground-fault occurs even with the neutral grounding resistor open. MSHA requires this backup protection for all high-voltage systems. MSHA also requires overtemperature protection of the neutral grounding resistor. As shown in Fig. 5, this type of protection typically opens the ground-check pilot circuit of the incoming distribution cable supplying the power center, if a sustained fault causes heating of the grounding resistor. Special consideration must be given to the design



* Each outgoing circuit has a high-voltage ground monitor.

Figure 6. One-line diagram describing a typical motor starting unit for a 4160-V system. Vacuum contactors control the starting and stopping of the motors, while vacuum circuit breakers provide the interrupting capacity for fault protection.

and location of this device because of the relatively low level of heat produced by the grounding resistor compared with that of the nearby power transformer.

Instantaneous and overload relaying in conjunction with a vacuum circuit breaker protects the 4160 V outgoing and power-factor correction circuits, while molded-case circuit breakers, with instantaneous overcurrent protection, are used on the outgoing 600 V circuits. Figure 5 shows a normal/test switch interlocked with the main load-break switch to allow the 120 V control circuit to be energized in the test position, while the load-break switch is locked in the open position. Under normal circumstances, the control circuit is de-energized when the load-break switch is in the open position. A separate load-break switch provides a visible disconnect for

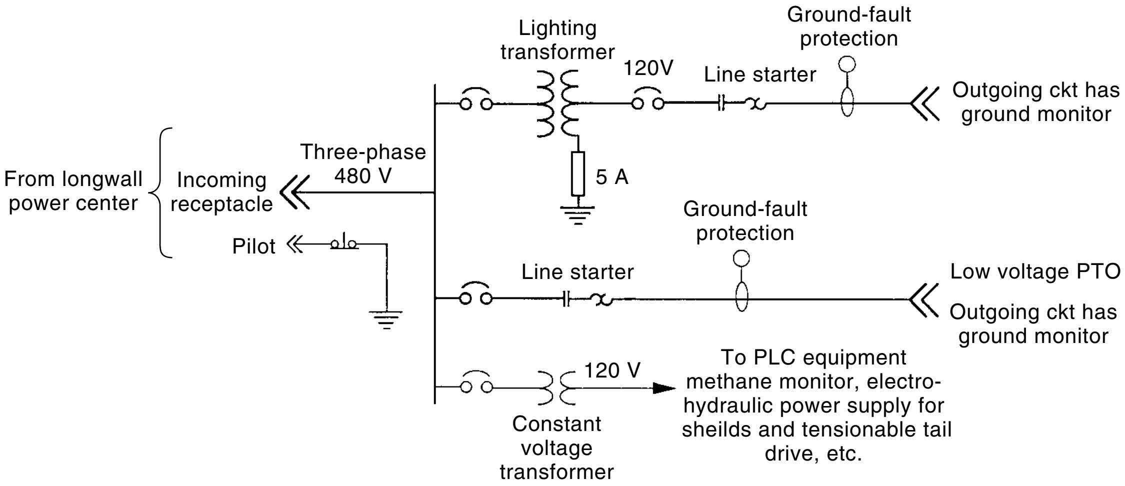


Figure 7. One-line diagram showing equipment housed within an explosion-proof enclosure of a headgate controller. The entire operation of the longwall system is controlled from a panel located on the controller.

the 4160 V output circuit and power-factor correction circuit. It should be noted that the load-break switches are grounded in the open position.

Figure 6 shows a one-line diagram for the motor-starting unit of a typical 4160 V system. A vacuum circuit breaker provides protection for each of the three branch circuits—shearer, hydraulic pumps, and conveyor system. Motor starting and stopping is controlled by vacuum contactors, and a reversing contactor is located at the bus feeding the motors associated with the face conveyor system. Instantaneous, overload, and sensitive ground-fault relaying provides protection for each outgoing circuit. As with the power center, a normal/test switch is interlocked with the main load-break switch to allow the 120 V control circuit to be energized in the test position while the load-break switch is locked in the open position. Under normal circumstances, the control circuit is deenergized when the load-break switch is in the open position. A separate load-break switch provides a visible disconnect for the shearer circuit. Again, both load-break switches are grounded in the open position.

Although not shown in Fig. 6, a PLC is usually located in the motor-starting unit. The PLC communicates with the motor-starting unit, the master controller, and the hydraulic pumping station via data-highway cables. The PLC controls all relay logic associated with the system. The PLC also monitors the operating status of major components in the system and displays relevant operational and fault-diagnostic information at the master controller.

A one-line diagram for the headgate master controller of a typical 4160 V system is shown in Fig. 7. The control box houses the lighting transformer, associated controls, and protection for longwall face illumination, a power take-off, control circuitry, and PLC rack and display panel for the face equipment. Since the controller is located at the headgate, it must be housed in an explosion-proof enclosure; however, the maximum voltage is 600 V and therefore does not need to meet MSHA's approval criteria for high-voltage equipment.

SUMMARY

A standard mine power system does not exist. Each mine has a unique set of operating conditions. Thus, most mine power equipment is custom built to meet the particular needs of a given mine. The information presented in this article is intended to provide some insight into the current practices of the mining industry.

BIBLIOGRAPHY

1. E. J. Miller and R. W. Dalzell, Mine gases, in Hartmann, Mutmansky, and Wang (eds.), *Mine Ventilation and Air Conditioning,* 2nd ed., New York: Wiley, 1982.
2. L. A. Morley, *Mine Power Systems,* U.S. Bureau of Mines Information Circular IC9258, p. 3, 1990.
3. R. Stefanko, *Coal Mining Technology Theory and Practice,* C. J. Bise (ed.), Society of Mining Engineers, Littleton, CO, 1983.
4. M. L. Nave, A comparison of soft start mechanisms for mining belt conveyors, in M. P. Evans (ed.), *Conveyor Belt Engineering for the Coal and Mineral Mining Industries,* Society for Mining, Metallurgy, and Exploration, Littleton, CO, 1993.
5. J. J. Sammarco et al., Safety issues and the use of software-controlled equipment in the mining industry, *Conf. Record 1997 IEEE Ind. Appl. Soc.,* 1997.
6. Anonymous, *IEEE Recommended Practice for Electric Power Distribution for Industrial Plants,* IEEE Standard 141–1993, pp. 385–389.
7. R. L. King et al., *Guide for the Construction of Driven-Rod Ground Beds,* U.S. Bureau of Mining Information Circular IC8767, 1978.
8. W. L. Cooley and R. L. King, *Guide to Substation Grounding and Bonding for Mine Power Systems,* U.S. Bureau of Mining Information Circular IC8835, 1980.
9. T. Novak and J. L. Kohler, Technological innovations in deep coal mine power systems, *Conf. Record 1995 IEEE Ind. Appl. Soc.,* pp. 2008–2016, 1995.
10. T. Novak and J. K. Martin, The application of 4160 V to longwall face equipment, *IEEE Trans. Ind. Appl.,* **32**: 471–479, 1996.
11. C. M. Boring and K. J. Porter, Criteria for approval of mining equipment incorporating on-board switching of high-voltage circuits, *Proc. 9th WVU Int. Mining Electrotechnol. Conf.,* pp. 267–274, July 1988.

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MINING DATA. See DATA WAREHOUSING.