The Application of 4160 V to Longwall Face Equipment

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Abstract— Since the introduction of longwall mining in the United States, continuous developments and improvements of face equipment have occurred. These developments have caused a trend toward high-capacity longwalls with face widths of 1000 ft. This evolution of longwall equipment has resulted in significant increases in power requirements such that the combined horse-power for the face conveyor, shearer, stage loader, crusher, and hydraulic pumps can now exceed 5000 hp. With increased power requirements, the traditional utilization voltage of 995 V became inadequate for many applications, resulting in an initial trend toward 2400 V. But power requirements have continued to grow, and the present trend is toward the use of 4160 V as a longwall utilization voltage. This paper discusses the design of a 4160-V system and compares some of its operational characteristics with those of a similar 2400-V.

I. INTRODUCTION

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 exceed 5000 hp. 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.

4) The maximum instantaneous trip settings allowed by Mine Safety and Health Administration (MSHA) may be exceeded when starting large motors rated at 995 V.

The last two concerns, reduced torque and maximum inrush current, are critical 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

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MSHA-mandated maximum instantaneous trip settings for associated cables.

The above-mentioned concerns have been minimized, if not eliminated, by using higher utilization voltages. Paragraph 18.47 (d) (3) of Title 30, *Code of Federal Regulations,* permits alternating-current machines to have nameplate ratings up to 4160 V if all high-voltage switchgear are remotely located and operated by remote control. Also, the Mine Safety and Health Administration (MSHA) has developed approval criteria for high-voltage equipment to supplement existing regulations. However, the use of high voltage (greater than 1000 V) to power face equipment still requires approval from MSHA to modify the application of Paragraph 75.1002 of Title 30, *Code of Federal Regulations,* which states that "Trolley wires and trolley feeder wires, high-voltage cables and transformers shall not be located inby the last open crosscut and shall be kept at least 150 ft from pillar workings."

To obtain approval from MSHA, 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.

The first MSHA experimental permit for high-voltage on-board switching was granted for a 2400-V longwall system on July 7, 1985. Within three years, ten other 2400-V longwall systems received permits enabling operation of on-board switching [1]. Thus, the trend toward high voltage was launched. MSHA's present practice is to grant approvals for systems rather than experimental permits for individual installations, and a 1993 survey shows that 26 of the 90 operating longwalls in the U.S. coal industry use 2400 V [2]. Some mining companies have used a hybrid system (4160 V for the face-conveyor motors and 995 V for all other equipment) to ease into the use of high voltage. But when 4160-V shearers became available a few years ago, the use of 4160 V for the entire longwall face became attractive. The 1993 survey shows that there are eight 4160-V longwall faces in operation. The authors are also aware of two 4160-V systems that will be installed in 1994. This paper discusses the design of a 4160-V system and compares some of its operational characteristics with those of a similar 2400-V system.

II. SYSTEM DESIGN

For the purpose of discussion, a 5 MVA power center will be assumed with face-equipment motor sizes given in Table I. Table I also shows the rated current for each motor which is based on a power factor and efficiency of 0.87 and 0.93,
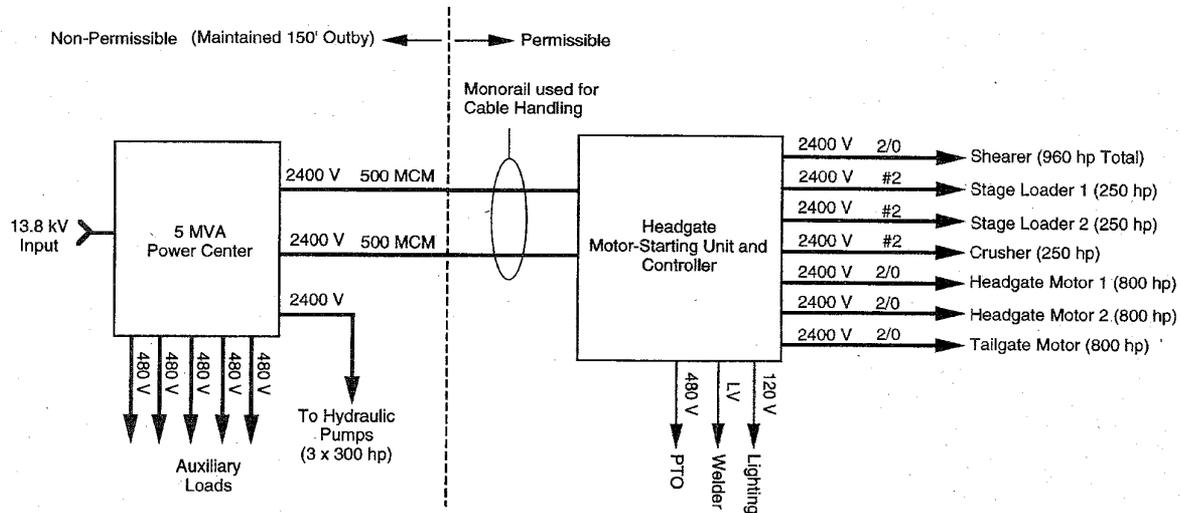
Fig. 1.   General arrangement diagram for a typical "inby" 2400-V system.

TABLE I
MOTOR SIZES FOR LONGWALL FACE EQUIPMENT

Equipment	Power [hp]	Rated Current [A] 2400 V[a]	4160 V[b]
Shearer	960 tot.	222	123
Headgate Motor	2 x 800	185 ea.	102 ea.
Tailgate Motor	800	185	102
Stage Loader	2 x 250	58 ea.	32 ea.
Crusher	250	58	32
Hydraulic Pumps	3 x 300	208 tot.	115 tot.

[a] Assumes a terminal voltage of 2300 V, a power factor of 0.87,
and an efficiency of 0.93

[b] Assumes a terminal voltage of 4160 V, a power factor of 0.87,
and an efficiency of 0.93

respectively. The values used in Table I are actual motor sizes
for a recently installed longwall.

A typical arrangement for a 2400-V longwall power system
is shown in Fig. 1. The layout of this system is essentially
the same as a standard 995-V system; however, there are
many different design criteria and safety enhancements to
accommodate the use of high voltage. These design criteria
and safety enhancements are discussed in detail in [1] and
[3], and for the sake of brevity will not be presented here.
This type of system is termed "inby" since the motor-starting
switchgear is located at the headgate of the longwall, within
150 ft of the face. Because of this location, the switchgear
and its associated controls are required to be mounted in
an MSHA approved permissible (explosion-proof) enclosure.
Fig. 1 shows a 5 MVA power center supplied from a 13.8-
kV distribution system. (With some high-capacity longwalls,
the use of 7200 V as a distribution voltage has even become
questionable). As with most longwalls, the power center has

two distribution voltages—2400 V for the face equipment
and hydraulic pumps, and 480 V for auxiliary loads, such
as battery chargers, sump pumps, etc. The 5 MVA power
center requires two 500 MCM cables for supplying the motor-
starting controller, which is typically located around 800 ft
inby the power center. With medium-voltage (995-V) systems,
these trailing cables are permitted to lie on the ground, and
a winch is often used to move the cables as the longwall
system advances. However, with high voltage, MSHA requires
a cable handling system, thus the use of a monorail support
systems is standard practice. Fig. 1 shows the type of loads
and typical cable sizes for a high-capacity system. Minimum
cable sizes are based on rated motor currents (Table I), but
cables are frequently oversized to reduce voltage drop and for
standardization purposes.

In contrast to the "inby" 2400-V system, an "outby" system
is typically used with 4160 V, and its general arrangement is
shown in Fig. 2. (The authors are aware of one 4160-V inby
system recently built for a trona mine.) The major difference
between the two systems is that the motor-starting switchgear
of the outby system is located near the power center more than
150 ft outby the longwall face; therefore, the switchgear does
not have to be housed in an explosion-proof enclosure. Similar
to the 2400-V system, the 4160-V cables are supported by a
monorail cable-handling system. However, the seven cables
that supply the 4160-V face equipment, the one 480-V power
cable to the master controller, and the data-highway cable
are supported by the monorail (Fig. 2). With the inby 2400-V
system, only the two large feeder cables need to be supported
by the monorail, as shown in Fig. 1. One should note the
reduction in cable sizes of the 4160-V system, as compared
with the 2400-V system.

A one-line diagram for a typical 4160-V power center is
presented in Fig. 3. The arrangement for a 2400-V power
center would be very similar except a 480-V output circuit for
the headgate controller would not be necessary and a separate
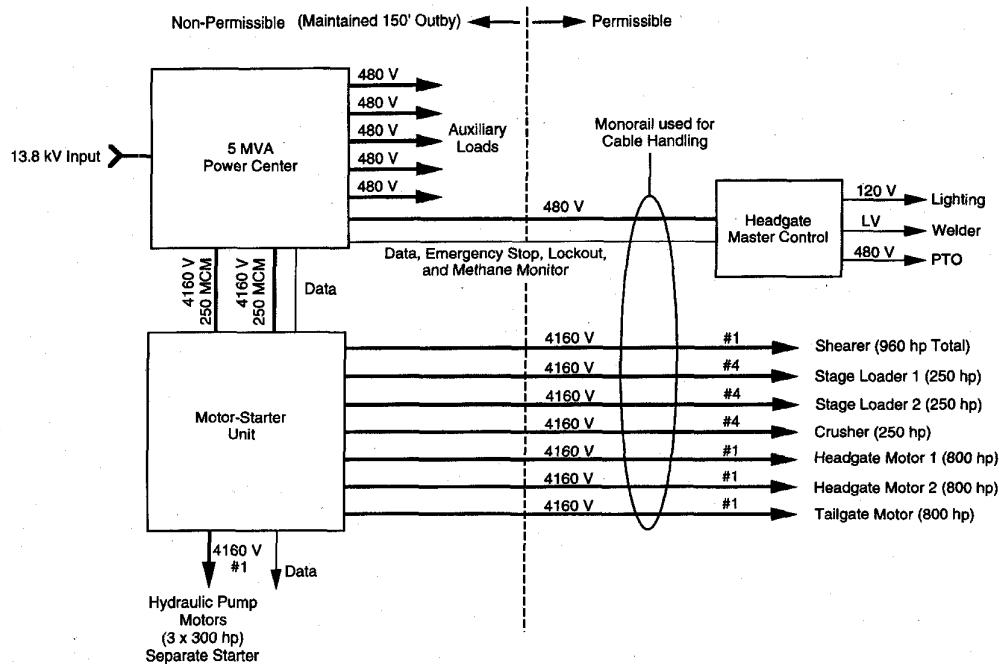vacuum breaker would be used to supply the hydraulic pump

Fig. 2. General arrangement diagram for a typical "outby" 4160-V system.

motors. The power center has two power transformers—one for the 4160-V longwall circuit and the other for the 480-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 480-V circuit in Fig. 3 is standard practice. For 4160-V systems, MSHA requires a maximum ground-fault current limit of 3.75 A (6.5 A for 2400 V). Fig. 3 shows a more stringent ground-fault current limit of 0.5 A, which has 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. This function is accomplished by monitoring the impedance between the phase conductors and ground. Fig. 3 also shows backup ground-fault protection (potential relaying) that will de-energize the power circuit if a ground-fault occurs 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. 3, 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 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 overcurrent relaying in conjunction with a vacuum circuit breaker protects the outgoing 4160-V circuit, while molded-case circuit breakers, with instantaneous over-

current protection, are used on the outgoing 480-V circuits. Fig. 3 shows a single vacuum breaker supplying two parallel cables. In some instances, a separate interlocked breaker for each cable may be necessary (particularly at the lower 2400 V) because of the continuous current rating of the breakers and the maximum instantaneous trip setting required by MSHA. As also shown in Fig. 3, 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 de-energized when the load-break switch is in the open position. A separate load-break switch provides a visible disconnect for the 4160-V output circuit. It should be noted that both load-break switches are grounded in the open position.

Fig. 4 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, overcurrent, and sensitive ground-fault protection is provided for each outgoing circuit. Power-factor-correction capacitors are connected at the load side of the vacuum contactors so that they are on-line only when the loads are energized. 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 de-energized when the load-break is in the open position. A separate load-break switch provides a visible disconnect for the
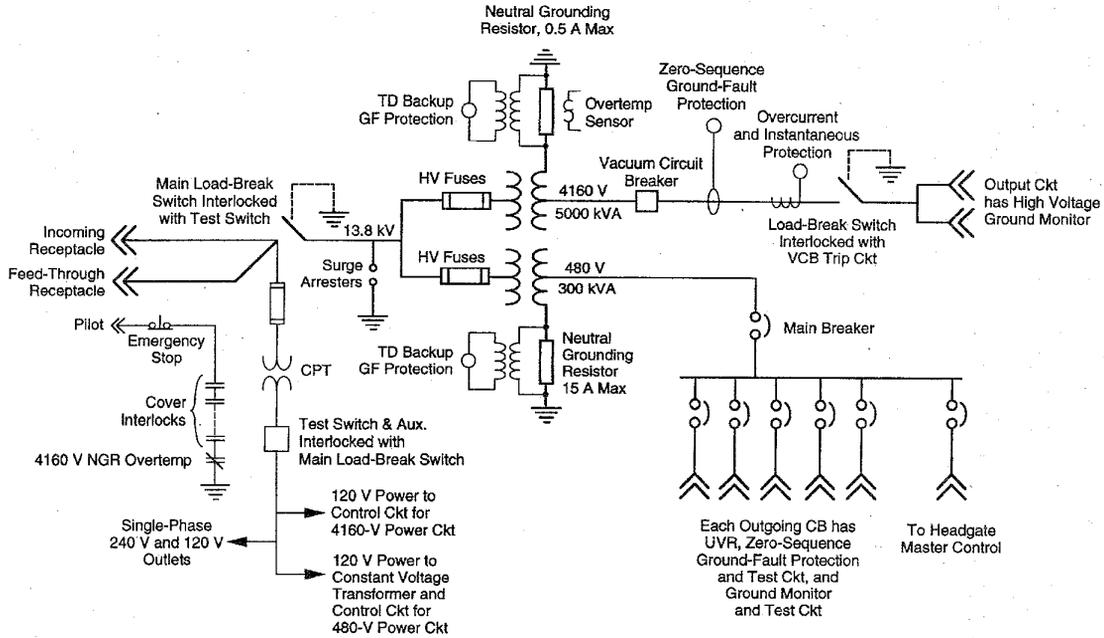
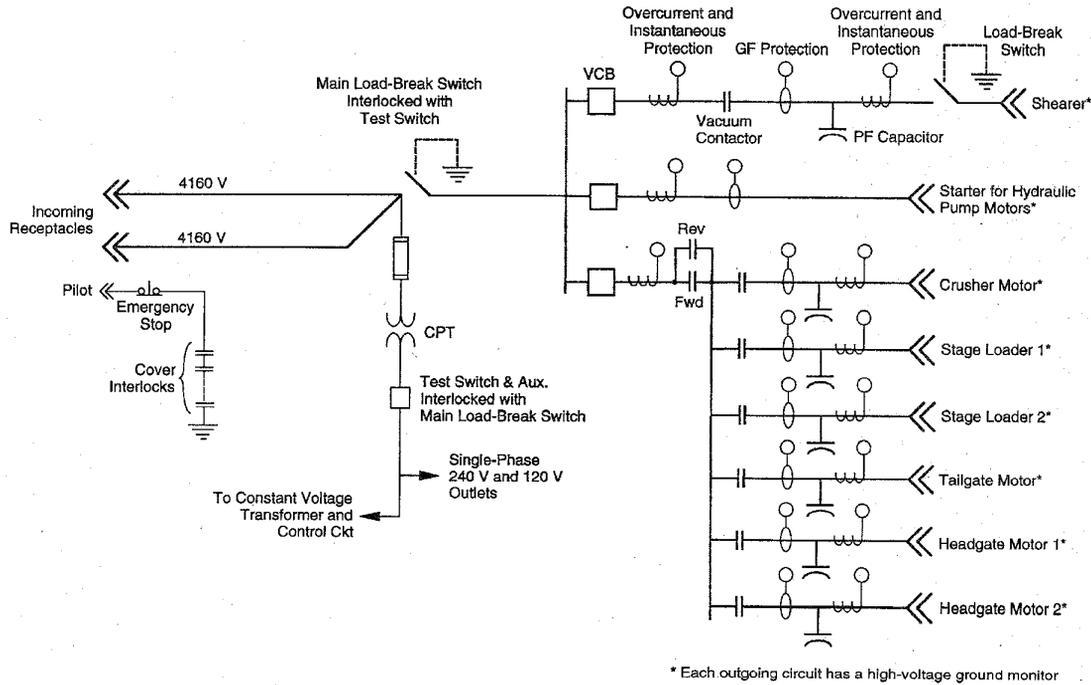Fig. 3. One-line diagram for a typical 4160-V power center.

Fig. 4. One-line diagram of a typical "outby" 4160-V motor-starting unit.

shearer circuit. Again, both load-break switches are grounded in the open position.

Although not shown in Fig. 4, a programmable logic controller (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. All relay logic associated with the system is controlled by the PLC. 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. 5. The control box houses the lighting transformer, associated controls and protection for longwall face illumination, a welder, a power take-off, control circuitry, and PLC rack and display panel
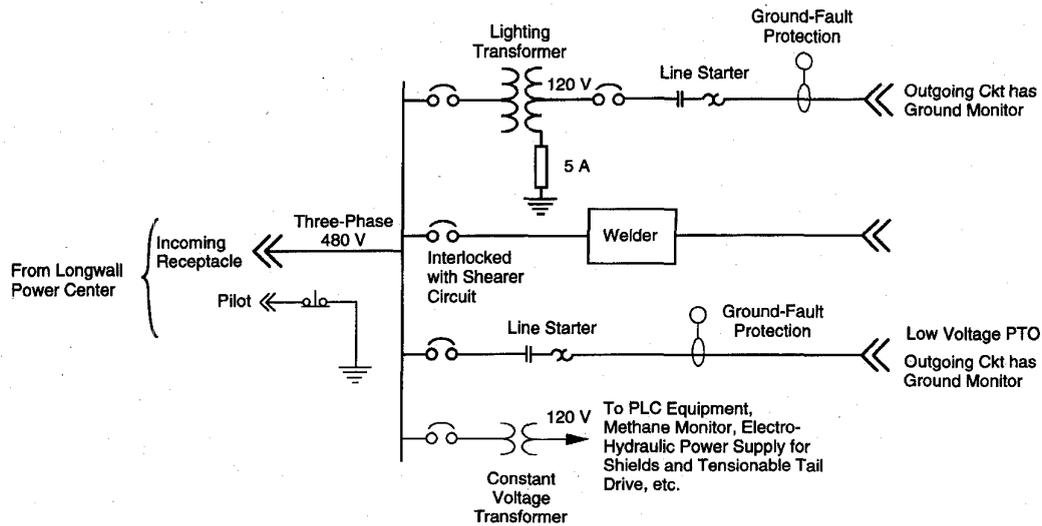
Fig. 5. Typical headgate controller for an "outby" 4160-V longwall system.

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 480 V and therefore does not need to meet MSHA's approval criteria for high-voltage equipment.

III. OPERATIONAL CHARACTERISTICS

The operational characteristics of a 4160-V system will be compared with those of a similar 2400-V system. To perform a realistic comparison, each method is included as part of a total mine power system, as shown in Figs. 6 and 7. (The system layout is based on an actual power system at an operating coal mine.) The two figures are identical up to the primary of the longwall power center. Beyond that point, the differences in configurations of the 4160-V outby and 2400-V inby systems are reflected in Figs. 6 and 7, respectively. In both figures, the equivalent impedance at the primary of the substation transformer is based on a short-circuit capacity of 210 MVA with an X/R ratio of 5.13. In both figures, a 10 MVA oil-filled transformer is used at the surface substation, and a 2000 kVA bank of power-factor correction capacitors is connected at the secondary of the transformer. A maximum length of 15 000 ft of 4/0 distribution cable extends from the bottom of the borehole to the longwall power center in each figure. A 1000-kVA power center for a dual 500-hp belt drive is located at one-half the distribution distance (7500 ft from the borehole). The cable lengths and sizes for both systems are shown in Figs. 6 and 7. For simplicity, the power-factor correction capacitors in Fig. 6 are modeled as a single capacitor connected to the 4160-V bus of the motor starting unit. To provide for a fair comparison, a similarly-sized bank of capacitors are connected to the 2400-V at the power center in Fig. 7. Impedances for cables are obtained from reference [4].

A. Fault Currents

A short circuit analysis of the longwall power system is performed to calculate minimum and maximum fault currents. The maximum fault currents can determine the adequacy

of interrupting capacities for circuit breakers, and minimum fault currents can be used to establish maximum instantaneous trip settings for short-circuit protections devices. The instantaneous-trip settings must be high enough to prevent nuisance tripping of the circuit breakers during motor starting, yet low enough to cause tripping for the minimum short-circuit current. The maximum fault current will occur at the secondary bus (Bus 9 in Figs. 6 and 7) of the longwall power center, while minimum fault currents will occur at the extreme points of the system, specifically the tailgate conveyor motor (Bus 12 in Figs. 6 and 7). The length of distribution cable from the borehole to the primary of the longwall power center has an effect on the minimum and maximum fault currents. To determine the maximum fault current, the minimum length of distribution cable should be used for calculating a three-phase fault. Whereas, for calculating minimum fault currents, the maximum length should be used for a line-to-line fault. For this paper, only the maximum cable lengths shown in Figs. 6 and 7 will be used.

Calculations were performed for three fault durations—1/2 cycle, 1.5–4 cycle, and 30 cycle. The 1/2 cycle duration represents the highest value of fault current for a given fault and location. This current is calculated before the ac and dc components decay toward steady-state values. Subtransient reactances are used for all motors. The 1.5–4 cycle fault current generally represents the value of current that will be interrupted by high-voltage breakers. Transient reactances are used for all the induction motors. The 30-cycle fault current is the lowest value of fault current for a given fault type and location. After 30-cycles, the fault current has reached its steady-state value, and the fault contributions of all motors are ignored.

The results of the short circuit calculations are shown in Tables II and III for the 4160-V and 2400-V systems, respectively. For determining the interrupting capability for a type of circuit breaker, the values of 7386 A for the 4160-V system and 11 252 A for the 2400-V system would be used. These values are the 1.5–4 cycle fault currents, which the
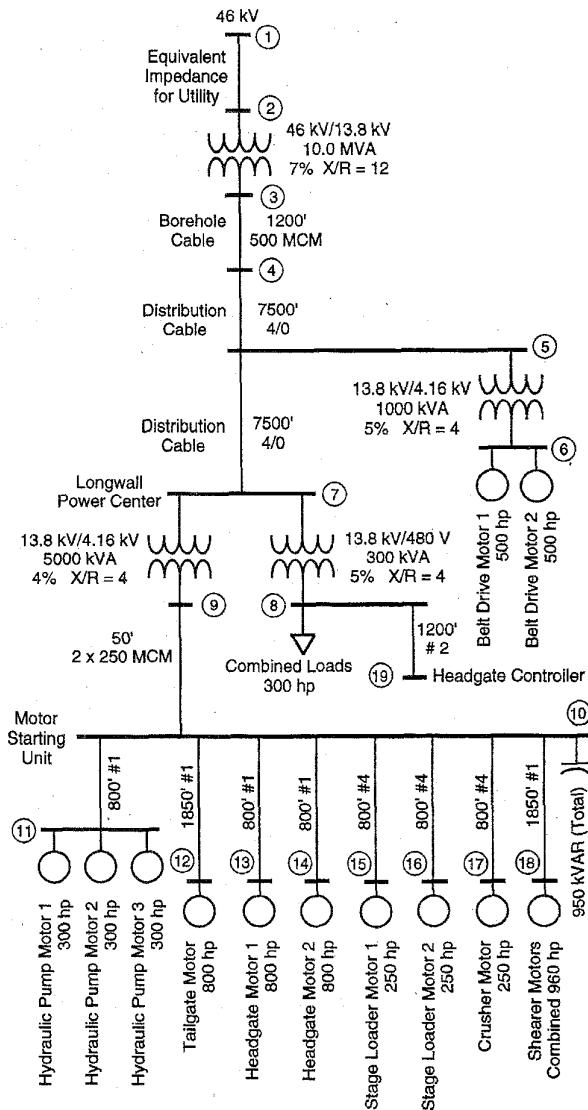
Fig. 6. One-line diagram of a 4160-V longwall power system.

Fig. 7. One-line diagram of a 2400-V longwall power system.

breaker would experience during interruption. Vacuum circuit breakers typically have a symmetrical current interrupting rating at a specific power factor. As an example, one type of vacuum breaker with a continuous current rating of 630 A has an interrupting rating of 16 kA at a power factor of 0.15 and at voltages of 4.16 kV and less. Thus, for the systems illustrated in Figs. 6 and 7, these types of breakers are more than adequate. However, keep in mind that the length of the distribution cable is at a maximum for this example. If the longwall was located close to the bottom of the borehole, the maximum fault current for the 2400-V system may approach or exceed the interrupting rating of the circuit breaker. For the 4160-V system, no problems should be encountered regardless of the longwall location.

For determining maximum instantaneous trip settings, the minimum fault currents (30-cycle line-to-line fault at the tailgate motor) of 3149 A and 4718 A would be used for the 4160-V and 2400-V systems, respectively. Although an
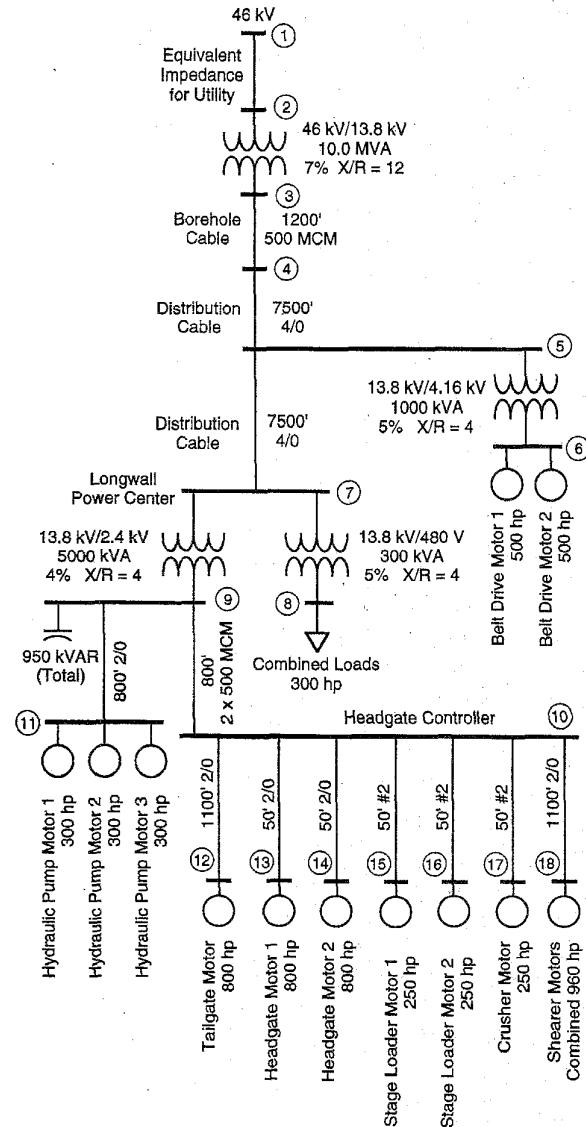
instantaneous element may actuate within the first cycle, the 30-cycle fault current should be used because a time delay (maximum of 0.25 s) is permitted for backup short-circuit protection at the power center. Maximum allowable circuit-breaker instantaneous settings for low-voltage and medium-voltage circuits are specified by Paragraph 75.601-1 of Title 30, *Code of Federal Regulations*. These settings are based on cable size. However, Proposed Decision Orders for approval of high-voltage systems have specified that instantaneous settings be limited to 75% of the minimum line-to-line fault current at the motor terminals. Thus, for our example, the 4160-V system would have a maximum setting of approximately 2300 A. The same method applies to the 2400-V system, but MSHA does not permit the circuit from the longwall power center to the longwall controller to have a trip setting in excess of 2500 A. Thus, for our example, this limitation would define the maximum setting for the 2400-V system.

TABLE II
FAULT CURRENTS FOR THE 4160-V SYSTEM

Location	Bus	Duration	Three-Phase Fault [A]	Line-to-Line Fault [A]
4160-V Secondary	9	1/2 Cycle	9,324	8,075
		1.5 - 4 Cycle	7,386	6,396
		30 Cycle	5,737	4,968
Tailgate Motor	12	1/2 Cycle	5,011	4,339
		1.5 - 4 Cycle	4,329	3,749
		30 Cycle	3,636	3,149

TABLE III
FAULT CURRENTS FOR THE 2400-V SYSTEM

Location	Bus	Duration	Three-Phase Fault [A]	Line-to-Line Fault [A]
2300-V Secondary	9	1/2 Cycle	13,165	11,402
		1.5 - 4 Cycle	11,252	9,745
		30 Cycle	9,943	8,611
Tailgate Motor	12	1/2 Cycle	6,824	5,910
		1.5 - 4 Cycle	6,022	5,215
		30 Cycle	5.448	4,718

TABLE IV
PARTIAL LOAD-FLOW RESULTS FOR 4160-V SYSTEM

Bus	Base Voltage [kV]	% Voltage	Line Currents [A]			
			From	To	Current	%PF
1	46.00	100.00	1	2	68	98.9
3	13.80	98.47	3	4	249	91.3
7	13.80	95.04	9	7	647	94.1
9	4.16	92.91	9	10	647	94.1
10	4.16	92.82				
12	4.16	91.41	10	12	112	87.2
13	4.16	92.24	10	13	111	87.1
18	4.16	91.12	10	18	135	87.3

TABLE V
PARTIAL LOAD-FLOW RESULTS FOR 2400-V SYSTEM

Bus	Base Voltage [kV]	% Voltage	Line Currents [A]			
			From	To	Current	%PF
1	46.00	100.00	1	2	69	98.8
3	13.80	98.40	3	4	251	91.1
7	13.80	94.94	9	7	1134	93.8
9	2.40	92.76	9	10	1005	86.9
10	2.40	91.61				
12	2.40	89.89	10	12	198	87.2
13	2.40	91.54	10	13	194	87.0
18	2.40	89.54	10	18	238	87.3

B. Voltage Drop at Full Load

To compare voltage drops of the two systems, computer load-flow analyses were performed with all equipment operating at rated load. The partial results of the load-flow analyses for selected buses are presented in Tables IV and V for the 4160-V and 2400-V systems, respectively. A comparison of Tables IV and V shows only a slight improvement in voltage drop for the 4160-V system, as compared with the 2400-V system. As expected, the bus voltages up to the primary of the power-center transformer are essentially the same for both systems. The insignificant difference is caused by the 2400-V motors operating at a per-unit voltage slightly less than the 4160-V motors, thus causing a slightly higher per-unit current. Even the differences in the percent voltages at the tailgate and shearer motors are relatively minor. The load-flow analyses also shows that the 2400-V power center would require a 1200-A or two 630-A breaker for the outgoing cables that feed the headgate controller, whereas one 630-A breaker would suffice for the 4160-V system.

C. Voltage Drop at Conveyor Startup

The voltage drop that occurs when the conveyor motors are started is a critical concern [5]. Maintaining an adequate voltage at the face-conveyor motors is important because of the relationship between voltage and motor torque—torque

is directly proportional to the voltage squared. Thus, severe voltage drops at starting can cause difficulty in starting a loaded face conveyor. The tailgate motor of the face conveyor experiences a more severe voltage drop than the two headgate motors. However, all three motors must be started within a very short time span. The motors are started sequentially, with the tailgate motor started first. The time delay between each start generally ranges between 0.5 to 1.5 s. It is difficult to simulate the maximum voltage drop during the sequential starting of all three motors, since this depends upon the characteristic and fill angle of the fluid couplers, the moment of inertia of the load, and the time delays. Therefore, for the purpose of this paper, only the starting of the tailgate motor will be considered for comparing the two systems.

To determine the tailgate motor voltage at startup, the motor must be modeled as a static load, rather than a dynamic load. In other words, the motor is modeled as a constant impedance rather than a constant apparent power. Modern face-conveyor motors have typical starting torques in excess of 175% of rated torque. Also, their breakdown torques can range from 260% to 350% of rated torque. These high torque requirements result

TABLE VI
MOTOR VOLTAGES AT TAILGATE DURING STARTING

Base Voltage [V]	% Voltage	% Starting Torque	Locked-Rotor Currents [A]
4160-V	84.76	71.84	605
2400-V	82.53	68.11	1021

in high starting currents with some motors having symmetrical locked-rotor currents in excess of seven times their rated currents. A lock-rotor current of seven times rated and a power factor of 0.25 was assumed for modeling the tailgate conveyor motor at startup. The stage loader, crusher, and hydraulic pumps were modeled at rated loads with the shearer turned off. Table VI shows the tailgate motor voltages at locked-rotor conditions. An improvement occurs with the 4160-V system, but again, the improvement is only slight. The 4160-V system has a 5.5% increase in starting torque, compared with the 2400-V system. A review of Table VI also reveals that the calculated locked-rotor current is less than seven times rated. The reason is because of the voltage drop at the motor terminals and modeling the motor as a fixed impedance. Seven times rated current only occurs if the terminal voltage is kept at its rated value during starting.

D. Inrush Currents

In the previous section, it was stated that the starting current can be seven times rated current. However, this value is the symmetrical locked-rotor current. The first-cycle asymmetrical inrush current can theoretically approach two times the locked-rotor current. The multiplying factor is dependent upon the reactance-to-resistance ratio. A multiplying factor of 1.8 is generally a conservative value for estimating asymmetrical inrush current.

Since instantaneous trip elements can operate within the first cycle, it is important to account for inrush currents. Table VI shows a locked-rotor current of 1021 A for the 2400-V system; thus, assuming a multiplying factor of 1.8, the first-cycle inrush current would be 1839 A. It should be noted that this value would even be higher with a shorter length for the 13.8 kV distribution cable. Keeping in mind that the three conveyor motors are started in a very short time span, one would need to closely scrutinize the arrangement of the 2400-V system to ensure that the trip settings of instantaneous relays are not exceeded during conveyor startup. This is not a problem with the 4160-V system.

IV. CONCLUSIONS

The general design of an outby 4160-V longwall power system was discussed, and some comparisons of its operational characteristics were made with those of a similar inby 2400-V system. Fault-current analyses were performed, along with load-flow analyses with the system operating at full-load and for the starting of the tailgate conveyor motor. Asymmetrical

inrush currents with respect to maximum instantaneous trip settings were also discussed.

Some of the advantages of the outby 4160-V are the following:
- 4160 V is a standard voltage rating, whereas 2400-V is considered off-standard.
- The motor-starting switchgear is located near the power center more than 150 ft outby the longwall face; therefore, the switchgear does not have to be housed in an explosion-proof enclosure.
- Maintenance on the motor-starting switchgear can be performed in a roomier, less confining area.
- Smaller cable sizes can be used with the 4160-V system. Since lower back injuries comprise a significant portion of accidents which occur in underground mining, reduced cable weight may play a role in reducing this type of injury.
- The master controller is relatively small, thus saving space at the headgate. Also, the controller only contains low voltage (less that 660 V) components.
- A 4160-V system has lower fault currents, therefore the interrupting capacity of circuit breakers is less of a concern.
- The load-flow analyses showed slight improvements in voltage drop with the 4160-V system, at rated conditions and at motor starting. But because of the differences in system arrangement and cable sizes, the improvements are only marginal.
- 4160-V motors have less inrush current; therefore, problems with exceeding the maximum trip settings of instantaneous relays is significantly reduced.

Some of the disadvantages of the 4160-V system are the following:
- Three separate pieces of equipment (power center, motor-starting unit, and master controller) are required for the outby 4160-V system, whereas, only two are required for the inby 2400-V system.
- A more complicated control system is required to communicate with the additional equipment.
- The cost of an outby 4160-V system is significantly higher than a comparable inby 2400 V system. The cost of the 4160-V system described in this paper is estimated at approximately $400 000, whereas, the cost of the 2400-V system is estimated at $350 000.
- The monorail cable-handling system for the 4160-V system must handle significantly more cables (8 versus 2 for the example in this paper).

REFERENCES

[1] C. M. Boring and K. J. Porter, "Criteria for approval of mining equipment incorporating on-board switching of high-voltage circuits," in *Proc. Ninth WVU Int. Mining Electrotechnol. Conf.*, July 1988, pp. 267–274.
[2] P. C. Merritt, "1993 U.S. longwall census," *Coal*, pp. 26–35, Feb. 1993.
[3] L. A. Morley, T. Novak, and I. Davidson, "The application of 2400-V to longwall face equipment," *IEEE Trans. Ind. Applicat.*, vol. 26, no. 5, pp. 886–892, Sept./Oct. 1990.
[4] *Mining Cable Engineering Handbook*, Anaconda Wire and Cable Company, 1977, p. 69.

[5] D. E. Bibbee, "Design considerations for the electrical distribution system for an American retreating longwall," *IEEE Trans. Ind. Applicat.*, vol. IA-20, no. 6, pp. 1405–1411, Nov./Dec. 1984.

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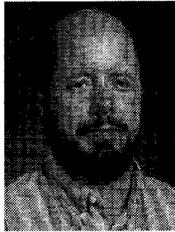
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