David B. Durocher, Eaton, USA, evaluates ways of increasing the effectiveness of protective devices in underground mining.
Traditional ‘above-ground’ applications of circuit breakers for overcurrent protection in the mining industry are generally understood. Defined standards for design and testing vary somewhat across the globe, providing a framework for the proper application of low- or medium-voltage circuit breakers in power distribution assemblies. Attention to detail in maintenance of these circuit breakers generally ensures these devices will operate reliably and safely across multiple industries.

However, when circuit breakers are applied in underground coal mines, traditional design and test standards give way to in-country mining safety authorities that typically dictate requirements for special applications. Because of this, ratings and test standards for low-voltage moulded-case circuit breakers, low-voltage power circuit breakers and medium-voltage vacuum (or sulfur hexafluoride (SF6)) circuit breakers in underground mining are notably different. Due to this complexity, users must be aware of issues specific to the application to ensure these devices operate reliably and safely.

This article reviews some unique characteristics of underground mining applications in relation to circuit protection, discusses new and innovative approaches to circuit protection within underground mines, and recommends methods to maximise the effectiveness of protective devices in this environment.

Focus on standards
Because of universal applicability across many industries, robust standards exist for above-ground power distributional assemblies. Typical standards for low-voltage power circuit breakers – such as ANSI C37.13 ‘IEEE Standard for Low-Voltage AC Power Circuit
Breakers Used in Enclosures’, standards for power distribution assemblies such as UL1558 ‘Metal-Enclosed Low-Voltage Power Circuit-Breaker Switchgear,’ and IEC Standard 61439 ‘Low-Voltage Switchgear and Control Gear Assemblies’ – include clearly defined requirements.

Performance and test requirements, such as defined clearances between conductors in three-phase systems, short-circuit and interrupting tests, and even performance tests defining how a power distribution assembly responds in the event of an arc flash event, are all included in the scope of these standards. Underground power distribution systems or mining power centres are unique to the mining industry and fit best into the definition of a specialty application.

**Mining power centres**

The mining power centre is an engineered assembly designed to transform and distribute electrical power, brought to the underground from the surface. Typically, this assembly includes a three-phase medium-voltage incoming circuit breaker or switch with a current limiting fuse. This device feeds and protects a close-coupled, dry-type, vacuum-pressure impregnated power transformer used to convert the medium voltage to a lower distribution voltage. The transformer then feeds low-voltage circuit breakers, which in turn feed and protect external underground loads at the mine face, connected to the power centre via extended trailing cables. These trailing cable conductors can often span hundreds of metres in length.

The first notable difference in mining power centres versus their above-ground counterparts is form factor – primarily, assembly height. Both are metal enclosed, but to satisfy clearance requirements in underground mining applications, mining power centres are typically half the height of those above ground, which are 2000 – 2286 mm (90 in.) high. Because the application involves long lengths of trailing cables, the issue of voltage drop on generally soft power systems dictates that the application voltage is higher. Above-ground IEC application voltages are typically three-phase 415 volts alternating current (AC) and ANSI/NEMA systems operate at 480 or 575 volts. In mining power centres, it is not unusual for secondary distribution voltages to be three-phase 1000 volt AC in the US, while in China or Australia for instance, distribution voltages can be up to 1240 volts AC. With these unique assemblies and application voltages for mining power centres and their protective circuit breakers, performance and test requirements are in most cases left to the discretion of the in-country mining authority. Although some regulatory authorities have issued specific mandates (such as the US Mining Safety & Health Administration’s (MSHA) mandate banning use of remanufactured third-party low-voltage moulded-case circuit breakers), defined test requirements for underground electrical assemblies have generally been vague or undefined.

Two of the most significant miner safety hazards for mining power centres include shock and arc flash. An electrical shock occurs when the human body comes into contact with an energised conductor. During a shock event, electrical current travels through the body toward ground. It takes only milli-amperes of current to cause serious injury or death. Higher operating voltages applied in underground mining significantly add to the risk of injury by electrocution.

Fortunately, mining power centres are constructed with steel enclosures and adequate barriers to shield operators from exposed terminations that are energised. That said, on occasion, a mining operator or electrician will remove an external cover or open an electrical door while the power centre is energised. Although the rationale noted for this activity might include testing/troubleshooting or keeping the power on to maximise production, these are excuses that simply cannot be justified. The author knows of no in-country mining authority that does not clearly mandate that power should be turned off before performing work on electrical systems.
Preventing injuries and deaths

Arc flash hazards pose an even greater threat than electrical shock. Unlike a shock incident, an arc flash begins with a spark or an arc that propagates into a rapid release of a high-energy, arcing fault between phase bus bars, neutral or system ground.

An arc flash event is typically the result of human error; while people are working on/or near energized electrical equipment, it is usually caused by a dropped tool or accidental contact of a test probe between an energised conductor and the ground. The energy discharge from an arc flash is effectively an explosion, delivering a gaseous release at temperatures exceeding that of the sun's surface. Solid copper conductors vapourise, expanding to 67,000 times their original mass, resulting in a superheated ball of plasma gas that can severely burn a worker's body. Industry standards, such as the NFPA70E-2016 ‘Standard for Electrical Safety in the Workplace’, have helped the industry make great strides forward in understanding arc flash. This standard, along with IEEE1584 ‘Guide for Performing Arc Flash Hazard Calculations,’ quantifies via calculations the heat energy release measured in calories/centimetre squared and the appropriate fire-rated protective clothing that must be worn to protect workers.

Mining power centres with three-phase 1000 volts AC secondary distribution voltages have historically applied specialty mining duty moulded-case circuit breakers. Protection for downstream trailing cable-fed circuits includes an internal circuit breaker mounted overcurrent relay to protect from short-circuit or fault conditions. Most trailing cables are also equipped with a signal conductor situated within the cable jacket, outside of the shielded power phase conductors. Another standalone ground conduction or ground check protective relay is used to shunt-trip the circuit breaker should the trailing cable signal conductor be severed.

New developments

New solid-state overcurrent relays have displaced mechanical thermal magnetic trip units, offering wider and more flexible protection setting adjustments to assure more accurate protection in harsh mining environments. Some solid-state trip units include ‘maintenance mode’ settings, a new feature that allows miners to select an enhanced protection setting while testing or troubleshooting. In the maintenance mode, the moulded-case circuit breaker clears the fault even faster than with the instantaneous trip setting. A reduced clearing time also significantly reduces arc flash energy should an arcing fault occur. The tradeoff using the maintenance setting is, that for the time while the mode is engaged, the selective coordination with downstream protective devices (often included in equipment at the mine face) will be overridden to achieve this fast clearing time. Protecting people when they are at risk of a potential arc flash event is considered a good tradeoff, so miners have been willing to accept possible circuit breaker nuisance tripping to keep themselves out of harm’s way.

New moulded-case circuit breaker designs are also now available with finger-safe terminals, offering a degree of added protection by reducing the likelihood of accidental contact with line and load-side cable terminations. As an additional safety enhancement, new enclosure-mounted flex shaft handle mechanisms for moulded-case circuit breakers offer mechanical isolation between the circuit breaker and those operating the device.

Another industry trend is a move to install vacuum circuit breakers...
where moulded-case breakers have historically been applied. Although vacuum breakers have traditionally been larger and more expensive than their moulded-case counterparts, new technology is making vacuum designs more size and cost competitive. Because vacuum circuit breakers interrupt faults in a vacuum-sealed bottle, the resulting arc across the device contacts occurs in a sealed chamber. Conversely, moulded-case circuit breakers interrupt downstream faults in air, using arc chutes to divide the arc across the main contacts between multiple steel plates until it is extinguished.

As underground trailing cables are frequently abused and severed by mobile equipment in the mine, cable short circuits and circuit breakers interrupting high-fault currents are common. Vacuum fault interruption is generally the better choice, since the arc is contained and the vacuum breaker is tested/rated to protect from a higher frequency of faults and higher fault currents.

One added advantage of vacuum circuit breakers is their ability to be electrically operated. This means the device can be opened and closed remotely, an advantage when above-ground switching is desired. Vacuum circuit breakers are also now applied on medium-voltage circuits of mining power centres. One new design offers a withdrawable carriage to enhance ease of maintenance and also an integral solid-state trip unit with maintenance mode settings to deliver improved performance and protection. This device in the primary circuit of the mining power centre is now being applied with special current sensors, which can be connected either at the medium-voltage primary (to protect the transformer) or at the 1000 volt secondary AC bus. When applied at the secondary, the device offers protection of the secondary bus bars, so a secondary main circuit breaker could be eliminated. Using the maintenance mode setting offers enhanced arc flash protection when miners are working on or near the energised equipment.

One final note regarding medium-voltage sulfur hexafluoride (SF6) circuit breakers applied in underground mining: this technology is similar to the vacuum circuit breaker design because the arc interruption is contained, but in this case the arc is extinguished in a sealed SF6 gas chamber. SF6 is an inert gas during normal use and these circuit breakers can be smaller and lower cost than their vacuum counterparts. However, when electrical discharges occur within SF6-filled equipment, toxic byproducts can be produced that pose a threat to the health of workers who come into contact with them. Also, by weight, SF6 gas is approximately five times heavier than air and tends to diffuse toward the pull of gravity and pools in low places. As a result of this pooling, the gas displaces oxygen and can cause suffocation without warning if the oxygen content of air is reduced from the normal 20% to less than 13%. Although local in-country mining authorities may not prohibit the use of SF6 circuit breakers underground, for the reasons stated here, the author strongly recommends against their use in underground applications.

Safety

The necessary focus in recent years on underground mine safety has translated into performance and safety improvements in underground electrical equipment. One area where this trend seems to be making a positive turn is in Australia, where Australian Standard AS4871 [10]. ‘Appendix H – Test Methods’ requires that manufacturers of mining power centres complete type testing of electrical assemblies, including surface temperature rise limits, short circuit withstand tests and verification of protective ground circuits tests. This additional testing is typically performed in a third-party high-power test laboratory where the equipment manufacturer is required to show certification of the specified tests.

Another excellent example of forward progress is a newly developed mining power centre offered by global manufacturer Becker Mining Systems, which is now tested to ANSI/NEMA Standard C37.20.7 “Guide for Testing Metal Enclosed Switchgear Rated up to 38kV for Internal Arcing Faults.” Adding these requirements for type testing is expensive, but the end result will be a much safer installation with verified testing to ensure underground coal electrical systems will perform when called upon during a fault to protect people and property. This is a welcome and necessary change, as electrical accidents are the fourth leading cause of death in mining and have proved to be disproportionately fatal compared with most other types of mining accidents.

Reference

1. Image supplied courtesy of Becker Mining Systems.

Mining power centre with secondary moulded-case breakers and external flex shaft handle mechanisms, along with primary vacuum circuit breakers.