

Understanding circuit breaker design and operation to improve safety and reliability in underground mining

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Abstract

Traditional “above ground” application of circuit breakers for overcurrent protection in industry are generally well understood. Defined design and test standards, which vary somewhat across the globe, provide a framework for users of these devices to ensure they are not misapplied. Attention to detail in circuit breaker maintenance generally assures that these devices will operate with reliability and safety across the industry. However, when circuit breakers are applied in underground mining applications, traditional design and test standards give way to in-country mining safety authorities who typically dictate requirements in these special applications. Because of this, ratings and test requirements for low voltage molded-case, low voltage power circuit breakers, medium voltage vacuum and medium voltage sulphur hexafluoride (SF₆) circuit breakers in underground mining are typically different. In this environment, the user must be aware of specific application issues to ensure that these devices operate such that they assure miner safety and operations reliability. This paper will discuss specific circuit breaker applications in underground mining and recommend methods to maximize the effectiveness of these protective devices in this environment.

Introduction

There have been many excellent papers written about circuit breakers applied in industry [1]. These electrical components, designed to provide overcurrent protection for electrical conductors and equipment, have been successfully applied across thousands of installations in the process industries. In most applications, these devices are installed into an electrical assembly and in electrical rooms throughout the facility. A typical assembly rated at three-phase 480 Vac as applied in North American markets is shown in **Figure 1**. The assembly shown is low voltage metal-enclosed switchgear that is manufactured and tested to American National Standards Institute and National Electrical Manufacturers Association (ANSI/NEMA®) standards.



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In this case, ANSI/NEMA Standard C3720.1 [2] dictates the design and test requirements for this assembly, including low voltage power circuit breakers that are manufactured and tested to a similar standard. This assembly can also include an arc-resistant rating when it is manufactured to another “adjacent” test standard, ANSI C3720.7 [3]. This standard defines design and testing requirements to ensure an arc-flash event is channeled or redirected up and away from personnel working on or near the assembly while it is energized.



Figure 1. Low Voltage Metal-Enclosed Switchgear Manufactured to ANSI/NEMA Standard C3720.1

Likewise, a typical assembly rated at three-phase 380 to 415 Vac as applied in markets outside of North America is shown in **Figure 2**. The assembly shown is low voltage metal-enclosed controlgear, which is manufactured and tested to the International Electrotechnical Commission (IEC) Standard 61439 [4]. Again, this standard dictates the design and test requirements for circuit breakers and control equipment including arc rating requirements as defined in the standard.



Figure 2. Low Voltage Metal-Enclosed Controlgear Manufactured to IEC Standard 61439

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The assembly shown in **Figure 3** is a typical power center applied in underground mining applications. The power center assembly takes on several different forms and ratings dependent upon where the underground mine resides across the world. The underground power center is an engineered assembly designed to transform and distribute electrical power brought to the underground from the surface. Typically, this assembly includes a medium voltage incoming circuit breaker or switch with current limiting fuse. This device protects a close-coupled dry-type vacuum pressure impregnated power transformer that is used to convert the medium voltage to a lower distribution voltage. The transformer then feeds low voltage circuit breakers that, in turn, feed and protect external underground mining loads connected to the power center via extended trailing cables. These conductions can often span thousands of feet (meters) in length. The first notable difference in this assembly versus those shown in **Figure 1** and **Figure 2** is the low-profile design. Whereas the low voltage metal-enclosed ANSI/NEMA switchgear assemblies are typically 90.00 inches (2286 mm) high and low voltage metal-enclosed IEC controlgear assemblies are typically 78.75 inches (2000 mm) high, underground power centers are typically less than half this height in order to satisfy clearance requirements in underground mining applications. 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 generally higher. In the United States, it is not unusual for secondary distribution voltages to be three-phase 1000 Vac, while in China or Australia for instance, operating voltages can be up to 1240 Vac. Most importantly, the design codes and standards for this assembly are not dictated by ANSI/NEMA or IEC standards. Instead, the in-country local mining authority generally reviews and approves these assemblies for application in underground mines. In the United States, this authority is the U.S. government’s Mine Safety and Health Administration (MSHA). MSHA dictates written regulations and in the event of a mining accident or a fatality, they are the authority having jurisdiction who will investigate the incident and issue citations or other penalties by law. In Australia, mine safety and inspection regulations are dictated by the Australian government.



Figure 3. Low-Profile Underground Power Center Including Primary Fused Switch, Transformer, and Low Voltage Circuit Breakers

Special circuit breaker applications for mining

Circuit breakers are used in underground mining equipment including the machines used to perform the mining, such as shears and continuous miners, and also in power centers that typically feed electrical power to the underground mining equipment. It is interesting that the circuit breaker components are not necessarily manufactured or tested to traditional standards that otherwise apply for assemblies used in industry above ground. One variable is the operating voltage of the device itself. Other issues pertaining to necessary fault current ratings, operating conditions, circuit ground (earth) protection, and harsh environment all need to be considered.

Molded-case circuit breakers in mining

Today's modern molded-case circuit breakers (MCCBs) are applied throughout most, if not all, industries. MCCBs offer a safe and economic means of connecting and disconnecting loads from the electrical source and provide both overload and short-circuit overcurrent protection. Although there are many types of molded-case circuit breakers, all are comprised of five major components including the molded-case or frame, an operating mechanism, arc extinguishers, contacts, and trip components. A cutaway view of a typical MCCB is shown in **Figure 4**.

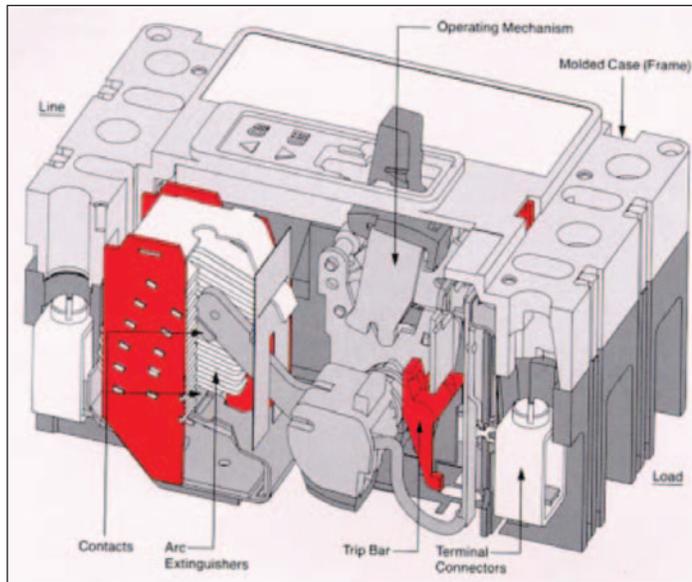


Figure 4. Cutaway View of a Molded-Case Circuit Breaker Identifying the Main Components

Unique issues exist in identifying when an MCCB should be considered for replacement. By nature of the component itself, manufacturers of these products assemble, calibrate, test, and then many times seal the molded cases of these devices. There are typically no internal serviceable parts, and breaking the factory seal generally results in jeopardizing the manufacturer's warranty. Because of issues inherent to the product design, historically the maintenance of MCCBs by the end user has been limited to mechanical mounting, electrical wiring, and manual operation of the mechanism. Although beyond the scope of this paper, further information on maintenance of molded-case circuit breakers can be found in reference [7].

Low voltage molded-case circuit breakers manufactured for the U.S. markets are designed and tested to UL® 489 Standard [5]. This standard covers devices rated at 600V or less, so the standard does not apply for underground mining applications that are above 600V. The relevant IEC Standard 60947.2 [6] does include circuit breaker testing for applications at rated voltage that does not exceed 1000 Vac or 1500 Vdc. So, this standard could perhaps apply to some applications of low voltage circuit breakers in mining applications up to and including 1000 Vac.

Both the UL 489 and the IEC 60947.2 Standards require that all designs of MCCBs be subjected to many thousands of endurance test operations at 100% rated current.

MCCBs are also subjected to two interruption tests at "limited" fault current as defined by the UL 489 Standard. The word limited is defined as 10 kA for 101–800A breakers, 14 kA for 801–1200A breakers, 20 kA for 1201–1600A breakers, 25 kA for 1601–2000A breakers, and 60 kA for 4001–5000A breakers. MCCBs are subjected to two interruption tests at maximum rated short-circuit current in accordance with UL 489. The UL 489 Standard requires that both the test circuit be closed on the circuit breaker and that the circuit breaker be closed into the maximum fault, both times safely interrupting the fault at maximum rated short-circuit current. Likewise under IEC 60947.2, MCCBs are subjected to short-circuit interruption tests that verify the MCCB's short-circuit breaking capacities (I_{cs}) and (I_{cu}) meet the manufacturer's published ratings. For a device rated at 100 kA interrupting current, this means the breaker would be required to clear this rated current once.

Application of molded-case circuit breakers in underground mining requires the site electrical manager to consider many additional issues beyond ratings and tests performed to existing standards. As mentioned previously, most application of MCCBs in mining involve application at higher voltages, typically 1000 Vac. **Figure 5** shows a photo of a typical MCCB applied in power centers for underground mines.

Note: This circuit breaker is tested for application at 1000 Vac. The manufacturer includes an orange molded-case cover plate, designating the product is designed for mining industry applications.



Figure 5. 1000V, 800A Molded-Case Circuit Breaker Designed and Tested for Underground Mining Applications

In addition to higher operating voltages, global standards for the mining industry require consideration for both ground (earth) fault and trailing cable protection. MCCBs applied in underground mining applications will typically require an overcurrent relay for phase-to-earth protection. Also, a special ground (earth) monitor relay is applied that senses the integrity of the trailing cables used to connect mining machinery to the underground power center. Trailing cables can typically extend beyond 500 meters, and because they are continuously exposed to mobile equipment used for mining operations, they are susceptible to being severed while energized. The ground (earth) monitor relay protects the circuit by sensing the continuity of a pilot wire included in the shielded cable that is connected through a ground (earth) conductor returning back to the origin. Should this “loop” be severed, the monitor relay detects this and trips the MCCB to assure personnel are not injured and exposed to electrical shock or potential fire.

In both the phase overcurrent protection and the trailing cable ground (earthing) protection circuit, the MCCB is relied upon to trip to protect the circuit. The trip circuit must be fail-safe as required by the standards. To accomplish this, an internal undervoltage release coil is included in the MCCB. The contacts are opened on a fault condition by de-energizing the undervoltage release coil, which actuates a plunger that causes the MCCB to trip.

MCCB operational issues—trip resets that can cause failure

One application issue that should be considered here is how mining operators address resetting of the MCCB in the field after it trips via initiation of a signal to the undervoltage release coil. Typically after a trip, the MCCB handle is moved to the lowest OFF position; this effectively resets the mechanism. Then the breaker handle is switched to the ON position to reset the device. An important consideration here is the availability of control power to the UV release coil. Oftentimes, the control power for this circuit is fed from a power source that also was cleared during the fault condition. When the operator tries to reset the breaker mechanism with the undervoltage release coil plunger still resting on the trip bar, the breaker is effectively being requested to initiate a trip while the operator is trying to reset and energize the device. The result is that the breaker will “trip-free,” and the main contacts will never close.

Trip-free operation of a molded-case circuit breaker is intended to protect the operator and the circuit from closing into a potential fault. It is very important to understand the design of the MCCB mechanism in this application condition. The breaker mechanism includes an over-toggle feature that stores a significant amount of energy in the springs. The design assures when the contacts close; they close with sufficient pressure and force to energize and protect the circuit. When the breaker mechanism trips free, all of the stored energy is released internally, causing significant stress on the mechanical assembly. Test standards discussed previously do not include mechanical testing for trip-free operation. In actual practice, consistent reset attempts of an MCCB that results in a trip-free operation will very quickly destroy the breaker, often after only 50 or 60 operations. In a mining application environment, 4–5 breaker reset attempts per shift is not uncommon. Multiple reset attempt operations without undervoltage release control power imparts cumulative damage to the MCCB mechanism. The most common failure modes include bent rotational reset pins or broken/cracked components in the steel frame of the mechanism.

One simple method to ensure the MCCB is never called upon to be reset and trip-free is the addition of an internal undervoltage trip LED indicating light. The added feature on the breaker tells the operator that the UV trip coil has control power, assuring that when the reset action is initiated, the device will properly reset.

MCCB safety issues—avoid the perils of third-party remanufactured product

Harsh environments in underground mining applications have a significant impact on the reliability of MCCBs. When an MCCB is used to clear a downstream high level fault with frequent resets, along with a generally high temperature environment with dust, dirt, and moisture, breaker failures can occur frequently. More often than not, a breaker in obvious poor condition should be scrapped in the field and replaced. At times, an MCCB might be repairable, but the site maintenance and operations group should avoid MCCB repair centers from third-party companies. Repairs, refurbishing, and modifications of MCCBs by independent third parties should not be used because:

- The components used are not manufactured to factory specifications
- Damaged breaker frames are not serviceable
- Processes used by third parties remove lubrication, coatings, insulation, and plating required for proper breaker performance
- Abrasive processes promote corrosion and weaken components
- Solvents, paints, and other foreign materials deteriorate breaker insulation and degrade breaker performance
- Counterfeit labels disguise third-party service and may not accurately describe breaker ratings

In the United States, the government’s regulatory body, MSHA, issued the following warning in April 2011 regarding a group of remanufactured circuit breakers:

MSHA has been made aware of a hazardous condition that may exist in 600 volt and 1000 volt circuit breakers. This includes all frame sizes. The circuit breakers may appear to be new or rebuilt, but they have been changed from the manufacturer’s original design. These mining circuit breakers may have been purchased either directly from the 3rd party or through a mining supply company. There is evidence that some of these circuit breakers have been modified by a 3rd party rebuilder with knock-off 600 volt and 1000 volt covers. The covers are of unknown construction and were not manufactured by the original manufacturer. The labeling affixed to the breakers was also reproduced by the 3rd party rebuilder in an effort to make the circuit breakers look new and legitimate.

Because these covers do not meet manufacturer specifications, it is possible that they will not contain an event within any of these circuit breakers, such as phase to phase or grounded phase. In addition, the frames that the 1000 volt covers were assembled onto may only be rated at 600 volts. Also, the frames used for both 600 volt and 1000 volt have been rebuilt and may contain parts, such as tips and springs, of unknown origin and specifications. Because of the potential for injury and/or death from the failure one of these circuit breakers can cause, they should be removed from service immediately.”

Mine operators are ultimately responsible for all repairs and modifications made to circuit breakers. The mine operator must confirm that all repairs are made in accordance with factory specifications, that the refurbished product is fully tested, and that any modifications will not adversely impact the performance of the circuit breaker. **Figure 6** shows one of the several tests performed at a field-based MCCB service and repair facility owned and operated by the original circuit breaker manufacturer. In this case, the manufacturer performs service/repair using factory-trained personnel and genuine parts designed to the manufacturer’s specifications, and then fully tests the repaired circuit breaker, offering a new factory warranty for the serviced product. This type of facility is the ONLY place where a circuit breaker should be returned for service or repair.



Figure 6. Final Testing is Performed at the Original Manufacturer's Field-Based Circuit Breaker Service Center

Vacuum circuit breakers in mining

Although low voltage molded-case circuit breakers have been applied in underground mining equipment and power centers for many years, recent changes in system design have opened the door for application of medium voltage vacuum circuit breakers as well. System voltages for underground applications appear to be slowly creeping upward in addition to source MVA in underground systems. Where underground power centers have historically operated based on use of an internal 1.0 MVA transformer, or perhaps a maximum of 1.5 MVA at 1000 Vac distribution voltage, newer designs for power centers are growing to as high as 5 MVA at voltages of 3.3 kV and beyond. This change is being driven by new larger continuous mining and conveying equipment being applied underground.

The impact of these changes in underground electrical systems is an upward pressure on circuit breaker designs. MCCBs that have been applied at 1000 Vac with full load current ratings of 150, 250, 400, 600, 1200, and 2000A with interrupting current ratings from 10 kA to 25 kA are now being used to operate at higher operating voltages from 1.2 kV up to 3.3 kV with interrupting ratings to 25 kA and beyond. Circuit breaker manufacturers are pushing the limits of MCCB design. MCCBs employ arc interruption in air via a proven technology that draws an arc developed across opening contacts into an arc-chute that divides the arc into several smaller components, eventually cooling and extinguishing it to interrupt a fault. Higher rating requirements are pushing the physics of the ability to successfully interrupt an arc in air. This opens the door to other circuit interruption methods including vacuum and SF₆ designs that must be considered. **Figure 7** shows one available vacuum circuit breaker, a new design presently being introduced into underground mining applications.



Figure 7. New Design Fixed-Mount Vacuum Circuit Breaker Applied in 1.2 kV Low Voltage and up to 24 kV Medium Voltage Underground Mining Systems

Both vacuum and SF₆ circuit breakers are also used extensively in many industrial applications. These technologies extinguish a fault by interrupting the arc in either vacuum (the absence of air) or in sulphur hexafluoride (SF₆), a gas that will be discussed later in this paper. When the circuit breaker contacts part to open the circuit or to interrupt the arc during a fault condition, the interruption occurs in a sealed chamber or bottle. Because the arc is contained and has no opportunity to ionize in air, the arc is more readily extinguished and the fault is cleared. Thus, higher voltage current and interrupting ratings are possible with this alternate technology. The vacuum or SF₆ circuit breaker is generally larger and more costly than its MCCB counterpart, but these designs offer some advantages in this application. The first being voltage ratings up to 5 kV and current ratings of either 800A or 1200A. This breaker has totally encapsulated pole units and is designed for 30,000 operations. Also, this circuit breaker can be electrically operated with an internal mechanism and optional spring charging mechanism. Electrical operation allows the operator to open and close the circuit breaker via a remote panel as opposed to operating the mechanical toggle type mechanism of a typical MCCB. Remote operation greatly improves the safety for this product because the operator can be well outside the flash protection boundary as defined in NFPA® 70E [8] in the event that an arcing fault occurs while the operator is resetting the breaker. Because the arc interruption occurs in a sealed chamber, harsh environmental conditions in underground mining are less of a concern. Also, the new design is available in a similar form factor in voltage ratings up to 15 kV. This would allow circuit protection in underground power centers for both the secondary distribution and for primary medium voltage protection at the transformer primary.

Type testing for underground power centers

As discussed previously in this paper, testing requirements from underground electrical assemblies such as power centers have largely been defined by the in-country authority that regulates the mining industry. Although some regulatory authorities have issued specific mandates, such as MSHA's mandate regarding remanufactured third-party MCCBs, defined test requirements for underground electrical assemblies have generally been unclear or undefined. Although there has been a much improved and necessary focus on underground miner safety, in the aggregate, this focus has not translated into safety improvements in underground electrical equipment. This is unfortunate as electrical accidents are the 4th leading cause of death in mining, and they have proved to be disproportionately fatal compared with most other types of mining accidents [9]. One area where this trend seems to be making a positive turn is in a newly issued Australian Standard AS4871 [10]. "Appendix H—Test Methods" of this new regulation in Australia requires that manufacturers of underground equipment complete type testing of electrical assemblies including surface temperature rise limits, short-circuit withstand tests, and verification of protective earth circuit tests. This additional testing is typically performed in a third-party high-power test laboratory, and the equipment manufacturer is required to show certification of the specified tests. In addition to type tested assemblies, AS4871 Section 2.1.8 "Arc Blast Protection" makes reference to existing standards focused on arc-flash hazards including IEEE® 1584 [11] and NFPA 70E [8] discussed previously in this text. In contrast, although both of these electrical workplace safety standards originated in the United States, the MSHA has yet to reference these standards in U.S. mining regulations. Adding new requirements for type testing is expensive, but the authors believe the end result will be a much safer installation with proven capability when electrical systems are called upon to perform in the event of a downstream fault or arc-flash event. One power center manufacturer in New South Wales is looking toward an AS4871 approved standard in application of both molded-case and vacuum circuit breaker technology. Type testing of a standard design will minimize the cost to manufacture and market new assemblies and also the cost to upgrade existing power centers in the field using the same common design.

SF₆ and environmental issues

Sulfur hexafluoride (SF₆) has excellent dielectric and as a result it is used as an insulating and interrupting medium in electrical equipment including medium voltage circuit breakers. Although SF₆ is inert during normal use, when electrical discharges occur within SF₆ filled equipment, toxic byproducts can be produced that pose a health threat to workers who come into contact with them.

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%. In the presence of moist air, noxious decomposition products have a characteristic odor of rotten eggs.

SF₆ has been identified by the Intergovernmental Panel on Climate Change (IPCC) as the most potent non-CO₂ greenhouse gas, with an ability to trap heat in the atmosphere 23,900 times more effectively than CO₂. The product naturally absorbs infrared radiation, and it is largely immune to chemical degradation. SF₆ is considered the most potent of greenhouse gasses as identified in a report issued by the United States Environmental Protection Agency [12]. Some of the prominent global health and safety organizations including Hazardous Substances Data Bank (HSDB), Occupational Safety and Health Administration (OSHA), American Conference of Governmental Industrial Hygienists (ACGIH), and The National Institute for Occupational Safety and Health (NIOSH) have all warned of the toxicity hazards of compounds formed by SF₆ when the gas is subjected to electrical discharges. These are shown in **Table 1**.

SF₆ has been in existence for nearly 50 years, and this technology continues to be applied where no alternatives exist, primarily in the utility industry at higher voltages above 100 kV. Risk, recovery, and disposal costs have dramatically reduced the usage of SF₆ in North America and across the globe. In addition, numerous governing agencies have very detailed requirements regarding tracking usage, maintenance, and proper disposal of SF₆. Because there are no underground applications discussed in this paper where application voltages exceed 100 kV, the associated risks and costs of SF₆, including recovery, cleaning, and gas disposal, typically will prohibit the use of SF₆ from a total cost perspective. Underground mining by definition involves restricted space, limited oxygen, high degree of moisture/contaminants, and severe duty interruption, due to the aforementioned trailing cables frequently being severed by the equipment. For these reasons, it is the author's opinion that there is simply no place for the application of SF₆ in electrical equipment applied in underground mining systems—vacuum technology should be used exclusively. Interestingly, Australian Standard AS4871 that requires type testing of underground power centers does not exempt the application of SF₆ circuit breakers.

Table 1. Toxicity of Compounds Formed by SF₆ When the Gas is Subjected to Electrical Discharges

Byproducts	Toxicity (as defined by various agencies mentioned below)			
	HSDB	OSHA	ACGIH	NIOSH
Sulfur-tetrafluoride (SF ₄)	Extremely irritating to the eyes, nose, and throat	—	Irritation of the respiratory tract	Highly toxic
Sulfur-pentafluoride (SF ₅)	—	Toxic, but non-hazardous	—	—
Sulfur-dioxide (SO ₂)	Extremely irritating to the eyes, nose, and throat	Toxic	Very toxic	Highly toxic
Hydrofluoric acid (HF)	Extremely irritating to the eyes, nose, and throat	Hazardous	Toxic	—

Conclusion

Low voltage molded-case and medium voltage vacuum circuit breakers operate reliably in countless industrial settings. When properly applied, these devices are designed to safely protect distribution systems for many years. In mining applications, it is important to understand specific application issues and to establish operational procedures to assure both people safety and system integrity over the life of the product. Miner safety requires that site operations do not install circuit breakers that have been serviced or repaired by nonauthorized service centers. Only factory service operations should be used. Furthermore, application of circuit breakers employing SF₆ gas can be used, but only after all associated risks have been addressed. Adequately addressing the safety and maintenance risks of SF₆ will most likely be cost prohibitive when a non-SF₆ alternative exists. Epoxy encapsulated vacuum interrupters/pole units offer significant benefits when compared to gas-insulated products and should be considered.

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