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ELECTROMAGNETIC INTERFERENCE (EMI) IN UNDERGROUND COAL MINES: A LITERATURE REVIEW AND PRACTICAL CONSIDERATIONS

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ABSTRACT

Modern smart mining increasingly depends on the use of sophisticated electrical and electronic systems for improved safety and better productivity. With more electronic systems being introduced underground, the mining industry is facing electromagnetic compatibility (EMC) issues caused by electromagnetic energy emitted by one device adversely impacting the normal function of another. This paper provides an overview of EMC and electromagnetic interference (EMI) research for underground mining. The paper first starts with an overview of EMI in other industries applicable to mining, followed by a literature review on published EMI research pertaining to mining applications. Some representative EMI incidences and related EMI legislation in mining are reviewed. Finally, mitigation strategies that can be potentially used to cope with EMI issues are discussed and some practical considerations and best practices to overcome EMI in mining are provided. This paper is aimed at helping the mining industry to better understand the challenges posed by EMI and to promote EMC in underground coal mines.

INTRODUCTION

The MINER Act of 2006 mandates wireless two-way communication systems in underground coal mines in the United States. In addition, in 2015, the Mine Safety and Health Administration (MSHA) issued a final rule that requires operators of underground coal mines to equip place-changing continuous mining machines (CMMs) with proximity detection systems (PDSs) that generally use electronic sensors on both mining machines and miners to detect motion or the location of one object relative to another (MSHA, 2015). These are two examples of the electronic systems that were recently introduced into underground coal mines. While the mining industry is moving towards automation and autonomous equipment for improved safety and better productivity, it is anticipated that more and more electrical and electronic systems will be used in underground mines in the future.

With the ever-increasing use of electrical and electronic systems in underground coal mines, one concern that must be taken into consideration is the change of the electromagnetic environment (EME) associated with the introduction of these new systems. It is known that all electrical and electronic systems emit some level of electromagnetic (EM) energy. These emitted energies can adversely impact the performance of other electronic systems, depending on the level of the energy emitted and the susceptibility of the systems that were affected. Electromagnetic interference (EMI) occurs when EM energy from one system interferes with the proper operation of another system. As shown in the EMI triangle model in Fig. 1, an EMI instance is usually associated with three key components: a source, a victim, and coupling/propagation paths from the source to the victim. These three elements must be present in order for an EMI instance to occur. All three elements in underground mining environments are unique as compared to those elements in other environments and thus the EMI in underground mining deserves special consideration. The effects of EMI in underground coal mines are diversified for the different devices involved, ranging from minor annoyances due to nuisance alarms to potentially fatal accidents due to corruption of critical safety systems such as a PDS.

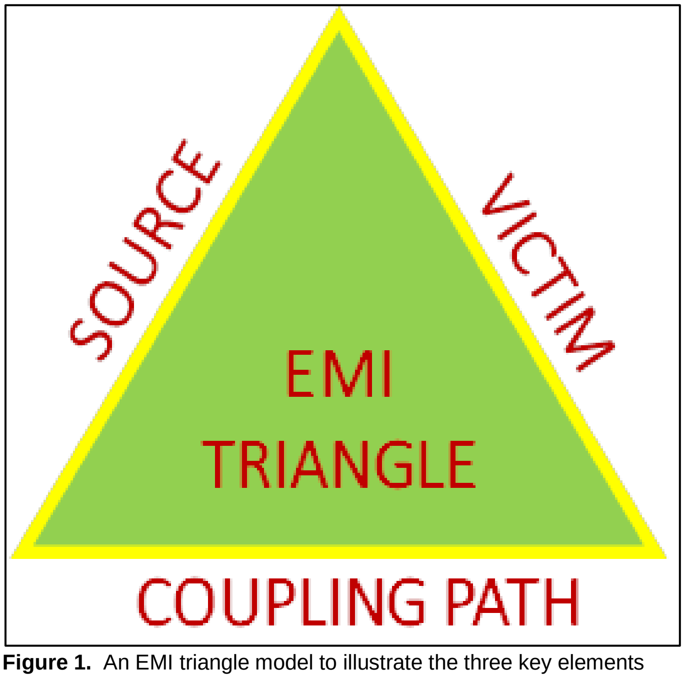

Figure 1. An EMI triangle model to illustrate the three key elements for an EMI instance to occur.

Electromagnetic compatibility (EMC) is the absence of the effects due to EMI. Specifically, EMC refers to the ability of a device or system to function satisfactorily in its intended EME without introducing intolerable EM disturbance to any devices operating in that environment. EMC has two aspects. From the EMI source perspective, the system should not generate radio frequency (RF) disturbances that cause a malfunction in another system. This is usually referred to as the emissions aspect. From the victim perspective, the system should be able to operate in its intended EME without showing malfunction which is usually referred to as the immunity or electromagnetic susceptibility (EMS) aspect.

Fig. 2 illustrates the different concepts (i.e., EMI, EMS, EME, and EMC) discussed in this paper. The source of the EMI in Fig. 2 is a personal dust monitor, (PDM, shown on the left as the Emission Source) and the victim of the EMI in this example is a PDS (shown on the right as the Victim (Receiver)). Both the PDS and PDM operate in the same EME. EMC is achieved if there is no adverse effect caused by EMI in the EME.

EMI and EMC have been widely investigated in many industries other than the mining industry (Noble, 1994). In this paper, we will first start a review of EMI standards in other industries, and then present some representative examples of EMI instances occurred in the mining industry, followed by a literature review of published EMI research in mining, and then a discussion on mitigation strategies and practical considerations related to EMI in mining.

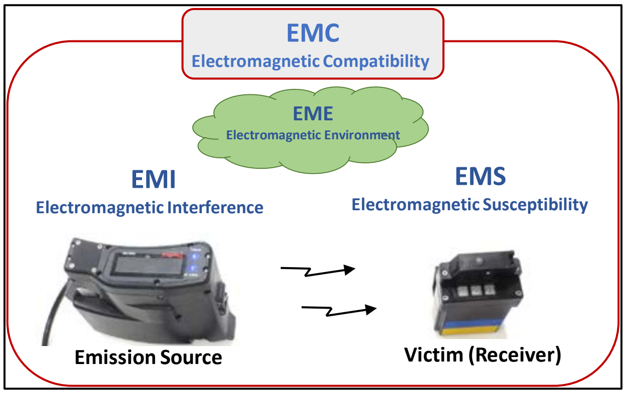

Figure 2. Using a PDM and a PDS as an example to show the concept of EMI, EMS, EME, and EMC.

EMI IN OTHER INDUSTRIES APPLICABLE TO MINING

Currently, a standard or set of requirements for dealing with EMI specifically in underground mining does not exist. However, numerous organizations have attempted to resolve EMI issues by developing standards for emissions and immunity testing in other industries, and some requirements contained within these standards could be applicable to mining.

For example, in the United States, the U.S. military created the standard MIL-STD-461 to control the EMI issues in subsystems and equipment used in military environments. The most recent version, MIL-STD-461G, was released in 2015 and has test methods and limits for conducted and radiated emissions and susceptibility. For consumer goods, the Federal Communications Commission (FCC) sets EMI standards for emissions that all electronic devices must pass before they can be sold in the United States. These restrictions are contained within Title 47 of the Code of Federal Regulations, Part 15. Surface mining equipment should already comply with FCC regulations, but underground devices are exempt because the surrounding earth attenuates the radiated signal. More details of the FCC regulations in the underground will be explained in a later section of this paper focusing on existing EMI regulations pertaining to mining. For safety critical systems such as a medical device, EMI standards have been in place to manage the risk in device manufacturing as well. It is required that devices must be able to work together in a relatively tight space without performance being compromised by EMI. The Center for Devices and Radiological Health (CDRH), part of the Food and Drug Administration (FDA), has regulatory authority over medical devices, manufacturers and variations of devices. The FDA issued a federal register notice in 2013 that recognizes a few voluntary consensus EMI standards. The European IEC 60601-1-2 standard is one of the EMI standards recognized by the FDA. Some of the EMI standards for regulating medical devices might be applicable to devices in the mining industry as they are all critical safety systems for which risks need to be carefully managed, and need to operate in a relatively tight space without any adverse effects caused by EMI. A good example illustrating critical safety systems that work in tight spaces in mining is that safety systems such as handheld radios, PDSs, and PDMs that a mine worker carries on their belt often operate next to each other.

In addition to U.S. organizations, there are international committees that are working to standardize EMI requirements across borders. The International Electrotechnical Commission (IEC) 61000 series is a comprehensive set of EMI standards that covers various types of electromagnetic disturbances. The 61000-4 series includes test methods for immunity tests, including 61000-4-3, which describes measurement techniques for radiated electromagnetic field immunity. Another two standards of interest from IEC are 61000-6-2 and 61000-6-4, which are immunity and emissions requirements for industrial environments. The International Special Committee for Radio Protection (CISPR) was formed by the IEC in 1934 with the sole purpose of setting standards to achieve electromagnetic compatibility in electronic devices. They have many standards to choose from, but CISPR 11 is one that has some applicability to mining. CISPR 11 provides limits and test methods for industrial, scientific, and medical radio-frequency equipment. Finally, the International Organization for Standardization (ISO) has many standards covering automotive EMI issues. ISO 13766 deals with earth-moving machinery, which is relevant to larger mining equipment like the continuous miner.

These are a few of the standards in other industries that could be applicable to mining, and some of their requirements for test methods and limits might be useful in developing mining-specific EMI recommendations. A more thorough discussion on existing EMI standards applicable to mining can be found in (Girman et al., 2021). There are also papers and reports focusing on summarizing and comparing existing EMC standards and regulations, and some good examples can be found in (Ewing et al., 2016; Ewing et al., 2003; Gubisch, and Holz, 2007; Ma, 1992).

In addition to EMI standards, EMI has been extensively investigated as an active research area in many other industries including:

- Medical
- Military
- Automobile
- Nuclear plant
- Railway

Every year there are numerous papers published pertaining to EMI in different applications in those sectors. These published papers provide a wealth of good literature that can be helpful for investigating EMI in mining. For example, (Ferrari et al., 1999; Halgamuge et al., 2010; Mariscotti, 2007) presents methods and results pertaining to measuring radiated fields from trams, electrical rotating machinery and large-power electrical machinery, which may find a direct application to measuring the radiated emissions from electrical mining machinery.

EMI IN MINING: SCOPE, REPORTED INSTANCES AND RELATED REGULATIONS

Scope of EMI

EMI standards are formulated to ensure that electronic devices and systems are able to tolerate a specified degree of interference and not generate more than a specified amount of interference. As a result, the scope of EMI typically includes two broad categories: susceptibility and emissions. As shown in Fig. 3, the susceptibility category includes characterizing a victim's susceptibility to conducted emissions, radiated emissions, lightning and electrostatic discharge (ESD) and comparing them to the corresponding given regulatory limits. The emission category then covers characterizing and regulating conducted and radiated emissions from a device across the spectrum.

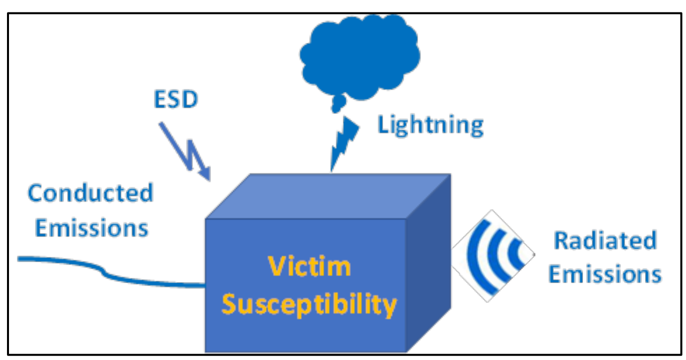

Figure 3. A picture illustrating the scope of EMI.

Reported EMI instances

With the increasing use of electrical and electronic systems, EMI is not new to the mining industry. Historically, there have been a variety of EMI instances reported in underground coal mines. One of the most recent notable EMI instances is that the magnetic fields emitted from a PDM interfere with the normal operation of a PDS. Both PDSs and PDMs are mandated by MSHA for use in underground coal mines in the US to protect the safety and health of coal miners. However, it has been discovered that PDMs can produce harmful EMI that cause PDS to stop working without any notice. Specifically, the EMI can disable the protections from a PDS designed to stop the machine before a miner is contacted. With the discovered EMI problem from PDM to PDS, MSHA issued a number of safety notices to coal operators in 2016 to raise the awareness of the possible EMI from PDM to PDS. Meanwhile, PDS manufacturers started to issue safety notices to their customers. For example, Matrix issued a safety notice (Matrix Design Group, 2016) warning that an ultra-high frequency (UHF) radio with a five-watt transmission output can cause the Intellizone proximity system locator to stop functioning. Under this interference, the locator will appear to be functioning but may not be detected by a PDS. In addition, the functionality of a locator will not resume until it is reset by placing it on the charger.

Another documented EMI instance is that the magnetic fields produced by portable radios used within several inches of a Joy model TX3 remote control transmitter activated certain functions of the remote controller transmitter. (MSHA, 2009).

There are some other MSHA-evaluated and confirmed EMI-related incidents such as portable radios adversely affecting the performance of atmospheric monitoring systems, machine-mounted methane monitors, and miners' cap lamps (MSHA, 2014). Researchers from the National Institute for Occupational Safety and Health (NIOSH) have demonstrated that radio emissions from a portable hand-held radio can also interfere with the normal function of multi-gas detectors and LED cap lamps.

In addition, cases of EMI have been reported in published scientific literature involving devices used in mines. A few cases have been reported in which a lack of immunity caused unintended consequences (Kałuski et al., 2013; Kałuski et al., 2014). These include a case in which a belt conveyor stopped unexpectedly when subjected to radiated fields during an EMI test and a case in which a methane sensor showed false alarms due to exposure to RF fields.

RELATED EMI REGULATIONS IN MINING

A. FCC regulations pertaining to EMI in mines/tunnels

The Federal Communications Commission (FCC) is the major regulatory agency in the United States with respect to EMI and spectrum management for non-federal use. The FCC generally requires a license for the frequency that a radio system can operate on (except those specific frequency bands known as unlicensed bands) and regulates the maximum radiated emission permitted from a system to ensure that the system will not cause any harmful interferences to other systems nearby. Electronic systems used in the U.S. for non-federal usage need to follow FCC rules. One exception to such requirements is tunnel radio systems that are contained solely within a tunnel, mine, or other structure that provides attenuation to the radiated signal due to the presence of naturally surrounding earth and/or water. Based on FCC rules pertaining to tunnel radio systems specified in CFR part 15, radio systems used in a mine may operate on any frequency without the need for a license, provided the system meets requirements listed in Section 15.211 CFR part 15. In addition, radio systems in an underground mine can also transmit a very large power that is above the limits specified by the FCC for systems used on the surface, as long as the exterior field strength measured outside of the mine is less than the limits set by the FCC. Considering the extreme attenuation caused by the earth overburden of a mine, electronic systems used in an underground mine are basically excepted from the frequency and emission power requirements that the FCC enforces on the surface.

B. MSHA guidance pertaining to EMI

Currently, MSHA has not issued any rule that would require standardized EMI testing before an electronic or electrical system can be used in underground mines. In many of the final rules issued, however, there is often a general statement pertaining to EMI requirements on the equipment to be mandated in the underground. For example, MSHA's final rule on PDSs for CMMs in underground coal mines requires that PDSs be installed to prevent interference that adversely affects performance of any electrical system (30 CFR § 75.1732(b)(5)). It is also stated in the preamble to the final rule that the mine operator is required to evaluate the PDS and other electrical systems in the mine and take adequate steps to prevent adverse interference (MSHA, 2015).

Another example of EMI-related MSHA requirements is maintaining minimum safe separation distance between an RF emitter (such as a wireless communication and tracking systems) and blasting circuits, explosives and detonators. The minimum distance required is usually provided by the manufacturer when an RF emitter device is submitted to MSHA for the required intrinsic safety (IS) approval. Although this minimum separation distance regulation was not originally written around radiated power necessarily, there has been a great concern that radiated RF energy from an emitter may couple into the leg wires (leads) of blasting caps or circuits and cause an unintended explosion in a gassy environment. RF radiation hazards to electric detonators have been documented in detail in a safety library publications (SLP-20) published by the Institute of Makers of Explosives (IME) titled "Safety Guide for the Prevention of Radio Frequency Radiation Hazards in the Use of Commercial Electric Detonators (Blasting Caps)", which has been cited in an MSHA program policy letter (MSHA, 2011) for calculating the required minimum distance between an RF emitter and blasting circuits.

It should be noted that even without the presence of blasting caps, radiated RF energy can still cause a hazardous situation as it may couple to nearby conducting objects and create a spark that ignites the methane-air mixture. This is sometimes referred to as hazards of EM radiation to fuel (HERF). As a result, RF power radiated from an electronic device in underground gassy environments should be limited. Currently there is no regulation from MSHA limiting the radiated power from an RF emitter. Radiated power, instead, is limited in permissible battery powered equipment due to the inherent lower power of intrinsically safe circuitry and the amount of power that can leave from an explosion proof enclosure.

EMI IN MINING: PUBLISHED RESEARCH

Although it has been extensively investigated in many other industries, EMI has received much less attention in the mining industry, and the corresponding published research pertaining to EMI in mining is relatively scarce. The aim of this section is to provide an overview of those published studies regarding the EMI/EMC of electronic and electrical systems in mining applications.

United States Bureau of Mines (USBM)

One of the earliest interests in investigating EMI in mining can be traced back to research on electromagnetic noise measurements in the 1970s sponsored by the USBM (part of which now became Pittsburgh Mining Research Division in NIOSH). Realizing that machinery used in mines can create a wide range of intense EMI that may impair the performance of communication systems used in mines, the USBM awarded a few contracts to third parties such as the National Bureau of Standards (NBS, now National Institute of Standards and Technology) and the Arthur D. Little Inc. (ADL) company to conduct measurements characterizing the magnetic fields and electric fields in operating coal mines.

Extensive EMI measurements were then conducted by USBM contractors in different operating mines and the results were presented in the form of spectral plots and amplitude probability distribution plots in a series of reports which are available to the public (Adams, 1973; Adams et al., 1974; Adams et al., 1974; Bensema, and Adams, 1973; Bensema et al., 1974; Bensema, 1977; Bensena et al., 1974; Kanda, and Adams, 1973; Kanda et al., 1974; Lagace et al., 1974; Scott et al., 1974). The types of mines where EM noise was surveyed were very diversified ranging from coal mines with different mining techniques and different entrance heights (i.e., low coal versus high coal) to hard rock mines. The measurements encompassed operating and quiet conditions for different machines, locations, power centers and boreholes, in working sections, haulage ways and on the surface. It is interesting to note that in addition to magnetic fields (received by a loop antenna) and electric fields (received by an active dipole antenna), voltages between two roof bolts were measured and the corresponding spectrum was presented in some of the reports. The motivation for measuring the voltage between two roof bolts in a coal mine was for electrode-based through the earth (TTE) communications which are suitable for emergency communications following a mining disaster when conventional communication systems become unavailable. EMI for electrode-based TTE systems has received renewed interest recently from researchers at NIOSH (Zhou, and Damiano, 2021), and in other institutions (Muñoz et al., 2011).

The USBM also awarded a contract to the ADL company to conduct an in-depth assessment of existing (prior to 1974) EM noise measurements and data for use in the design of operational and emergency mine communications, along with the remaining data gaps, appropriate measurement instruments and methods tailored to mining in harsh environments. The corresponding findings and conclusions were summarized in a comprehensive report (Lagace, Emslie, Roetter, and Spencer, 1974).

Overall, the early EMI research sponsored by the USBM was mainly focused on characterizing EM noise in mines at relatively low frequencies (generally up to ~ 1 MHz) at which TTE communication/tracking systems and mine rescue communication systems operate. In addition, the EMI of concern at the time was noise generated by equipment under different mining activities in typical mining environments or naturally generated EM noise in the air, rather than EM emissions generated by a particular electrical or electronic device.

NIOSH

One of the unique characteristics of EMI in mining is the propagation/coupling path of the EMI in the underground. Although not intended for studying the propagation of EMI in mines, researchers at NIOSH have conducted extensive field studies (Zhou et al., 2015; Zhou et al., 2016) to investigate radio propagation in underground mines. Theoretical models (Zhou, 2017; Zhou, and Jacksha, 2015; Zhou et al., 2013) were proposed to predict the decay of radio signals (in this case radio disturbances) in underground mines. Research has also been conducted to study how low frequency magnetic signals couple to nearby long cables/wires (Li et al., 2016; Li et al., 2013; Zhou et al., 2020).

While environmental EM emissions in a mine are generally treated as undesirable interferences that need to be avoided, NIOSH researchers also investigated the possibility of taking advantage of environmental emissions by using radio emissions from a deep mine as a warning indicator to detect potential rock failure (Scott et al., 2005).

Another important research area that falls into the scope of EMI is lightning and its impact on mining safety. For example, there has been reported incidents showing that lightning can cause premature detonation of explosives, visible sparking from underground equipment, electric shock due to elevated voltages, failure of radio communications, and methane explosions (Checca, and Zuchelli, 1995; D'Alessandro, 2014; Geldenhuys, 1987; Geldenhuys et al., 1985; Geldenhuys, 1995; Zeh, 1989). In a report of investigation published by MSHA (MSHA, 2007), it was concluded that "lightning is the most likely ignition source for the explosion" occurred in the Sago Mine in 2006. This conclusion was based on an extensive report (Higgins, and Morris, 2007) submitted by researchers at Sandia National Laboratory who were contracted by MSHA to investigate whether lightning energy may have entered the mine. While the vast majority of reported incidents occurred in shallow mines with a depth of 300 ft or less and the possibility of those hazards decreases with increasing mine depth, NIOSH researcher Novak conducted simulation studies to investigate the two mechanisms of lightning propagation through the earth and showed that lightning strikes are capable of initiating an explosion in a coal mine with a significant depth of 600 ft, depending on the arrangement of conductors and physical conditions within the mine area (Novak, and Fisher, 2001).

More recently, the NIOSH Mining Program conducted research into the EMI challenges presented in the interaction between health and safety systems such as PDMs and the PDSs. Specifically, the research focused on characterizing unintended PDM emissions that affected the miner wearable component that detects a mine workers proximity to moving mining machinery. The result of this interaction was that the PDS functionality was compromised to the point where the detection of mineworkers was inaccurate and, in some cases, failed to detect a person encroaching on the safety zones. NIOSH researchers conducted a series of experiments to characterize emissions from different electronic devices, evaluate administrative controls such as separation distances and design engineering control mitigation strategies such as filtering and shielding of components (Li et al., 2020; Li et al., 2019; Noll et al., 2018).

Research in Poland

EMI in mining has been investigated by researchers from different institutions outside the United States. For example, in Poland, Krasucki and colleagues studied EMI in mining, particularly the EMI due to power networks, electric traction networks, and mine communication networks that exist in underground mining (Miskiewicz et al., 2012). Kasprzyczak conducted tests to investigate the EMI of a mining mobile inspection robot (Kasprzyczak, and Pietrzak, 2014). Some practical examples of underground mining equipment that lack of EMC were given in (Kałuski, Michalak, Spalt, and Szafrańska, 2014). Electromagnetic disturbance measurements recorded in working mine conditions were presented and EMC standardizations for testing mining equipment were discussed in (Kałuski, Michalak, Spalt, and Szafrańska, 2013). Alternative methods for measuring EMI from large mining equipment were investigated in (Michalak, 2018; Szafranska, 2018). EMI generated by locomotives in underground mines were characterized in (Michalak, and Szafrańska, 2016). In addition, some preliminary results of the in-situ measurements of EM disturbances that were observed in mine underground power networks were given in (Kałuski et al., 2012).

Research in China

In addition to Poland, EMI in mining has also been studied by researchers in China. For example, there has been published research papers from China on measuring EMI from different mining equipment, including Pantograph arcing (Pan, and Liang, 2008), an inverter drive system (Sun et al., 2010), AC motors (Sun et al., 2014), and a substation (Feng et al., 2016). The EMEs in coal mines were characterized in (Sun et al., 2010). Methods to cope with EMI in mining were discussed in (Liao et al., 2012; Ma, 2010; ZHANG, 2006).

EMI MITIGATION STRATEGIES, PRACTICAL CONSIDERATIONS AND MINING-SPECIFIC EMI STANDARDS

EMI Mitigation Strategies

As shown in Fig. 1, there are three key elements for an EMI instance to occur. Consequently, methods to mitigate EMI generally attack one or more of the three elements to prevent EMI effects from occurring. In other words, changes can be made to the source, the victim, and the coupling path to offset EMI effects. Typical EMI mitigation strategies include shielding, filtering, and distancing.

A - Shielding: RF shielding is the practice of mitigating EMI effects by placing a conductive or magnetic surface around a device or component to prevent RF energy from escaping from or entering into the device/component. The shielding effect is achieved by the mechanism of reflection and absorption. The effectiveness of the shielding depends on factors such as the shielding material used, its thickness, the size of the shielded volume and the frequency of the fields. Shielding can be either applied to an EMI source, or a victim, depending on the convenience and applicability. For example, for intentional radiators, such as a hand-held radio, shielding is usually applied at the victim end since the transmitted power from those intentional radiators should not be compromised by shielding. On the other end, in another case of mitigating the EMI from a PDM to a PDS, shielding should be applied to the EMI source (i.e., the PDM) as the victim's (i.e., the PDS's) sensitivity to detect magnetic fields should not be affected by shielding.

B - Filtering: Filtering is another effective way commonly used to mitigate the harmful impacts caused by EMI. The primary purpose of an EMI filter is to suppress the transmission of selected frequencies of a given signal. In the world of EMC, "filtering" almost always means low-pass filtering which passes low frequency signals while blocking out unwanted higher frequency noise. EMI filtering is achieved by adding filters of which capacitance and inductance values are carefully selected to achieve the desired cutoff frequency and frequency response. EMI filtering is usually applied to an EMI source to reduce the RF emissions from the source.

C - Distancing: Unlike shielding and filtering, which fall in the engineering control category that is typically applied to the EMI source or the victim, distancing is a mitigation strategy belonging to the administrative control category that directly attacks the third element of the EMI triangle: coupling/propagation path. The RF energy from an EMI source decreases dramatically with increasing distances so maintaining a minimum separation distance between the source and the victim can be another effective way to reduce the EMI effects. Furthermore, this mitigation strategy sometimes can be very attractive as it does not require any change/modification in the design of the source or the victim. This method, however, adds a burden to the user as they need to worry about the minimum separation distance when they use the product.

Practical Considerations

Since currently electronic devices are not regulated in terms of EMI in underground coal mines, it is highly recommended that mine operators should be mindful about the potential EMI issues in underground coal mines. Particularly, mine operators should consider EM environments changes and EMC among different devices when introducing new equipment to the underground and stay alert about the EMI effects when operating the existing and newly introduced equipment. Some examples of known EMI effects in underground coal mines include unexpected alarms or readings from a gas sensor, false alarms from a PDS, unintentional movement of mobile equipment controlled by a remote controller, and unintended cap lamp shutdown.

Mine workers should consider the EMI triangle (i.e., source, victim, and path) when examining a suspected EMI incident and stay alert when operating electronic devices in the vicinity EMI sources. Some practical examples of potential EMI sources in the mining industry are:

- Wireless communication and tracking systems (e.g., hand-held radios)
- Electronic systems (e.g., PDMs)
- Power centers
- Variable Frequency Drive (VFD) systems
- Electric motors
- Lightning (effects can penetrate the earth overburden and reach areas inside a mine)

Mine workers should follow the best practices to maintain manufacturer-recommended separation distances (if any) between electronic equipment and EMI sources to minimize EMI effects. Although it is not currently required, it is highly recommended that equipment manufacturers design equipment with the consideration of immunity to EMI.

Electronic devices are particularly vulnerable to the interferences in the same frequency bands so both equipment manufacturers and mine operators should be aware of the existing frequency bands used in underground coal mines such that they can design and use the equipment properly to reduce the adverse effects caused by EMI. It would be helpful if equipment manufacturers could provide EMI information such as the frequencies it may emit or to which it may be vulnerable. Mine owners should incorporate this information into their decision when purchasing new equipment and avoid equipment that operates in frequency bands that are already used in the mine, if possible.

Mining-specific EMI standards

In addition to the three mitigation strategies discussed above, EMI effects and associated safety concerns can be ultimately reduced by developing and applying EMI standards across the mining industry. The formulations of EMI standards often are related to the equipment and operational environments in a specific industry. As such, different EMI standards are formulated for different industries. Compared to other industries, the mining industry has some unique characteristics in terms of its geological and EM environments that one must consider when developing a mining-specific EMI standard. Examples of such characteristics are:

- Confined environments formed by long relatively straight mine entries interconnected by periodic crosscuts
- Hazardous atmospheres due to the presence of flammable gas mixtures and coal dust
- The presence of many long-run conductors such as power lines, water pipes, wire mesh, signal and communication wires which facilitate radio interference to be coupled in and coupled out
- The possible accumulation of multiple large metallic mining equipment in a limited narrow space
- The presence of hazardous devices that are vulnerable to RF energy (e.g., blasting caps)
- The possible accumulation of many electronic devices/sensors in a very tight space (e.g., PDS, PDM, and gas monitor carried on a belt by the miner)
- High-voltage mining machines operated at high currents, great voltage and current changes during rapid switch on/off operations
- Harsh environments that are dynamically changing: humid, dusty, poorly lighted physical environments, mining face that progressively changes, and mining equipment that is regularly reconfigured

These characteristics make all three elements in the EMI triangle unique and thus the EMI in underground coal mines deserves special considerations. A good example to illustrate the needs for a mining-specific EMI standard is that PDMs which have been certified under general EMI standards on the surface still cause EMI issues in the underground. To be more specific, according to the information provided in product manuals, PDMs which cause interference to PDSs have been certified that they operate in compliance with EN61326-1: 2005 and FCC part 15 subpart B in reference to electrical emissions and immunity.

Mining-specific EMI standards could be considered as a way to overcome the adverse effects associated with EMI in the mining industry. Such a standard would define allowable levels of interferences (conducted or radiated) produced or sustained by a device, along with the methods, procedures, and equipment needed for measuring them. To facilitate a uniform understanding and application of a mining-specific EMI standard, the notations used would also be defined.

When developing a mining-specific EMI standard, considerations should be given to miner safety and health, along with the intended function and efficiency of the devices and systems operating under typical EMEs in a mining environment. In addition, the balance between the risk and the cost associated with the standard should also be taken into consideration. While more restrictive standards tend to reduce the risks associated with the EMI, such restrictive standards often come at the price of increased equipment cost.

CONCLUSIONS

With the rapid changing EME in the underground environment, there exists a need to investigate the impacts and practical solutions of EMI that can affect the health and safety of mine workers. This paper provides an overview of EMI in underground coal mines, with the goal of raising the awareness of EMI in the mining industry. The paper begins with a summary of EMI standards in other industries that can possibly be adapted to the mining industry and then presents a literature review on the published research on EMI in mining. Some representative EMI incidents and related legislations are also discussed. In addition, three common EMI mitigation strategies that can be used to reduce the adverse effects caused by EMI are presented, along with some practical considerations and best practices related to safely operating mining equipment in the underground. It is concluded in the paper that similar to EMI standards that were developed in many other industries decades ago, ultimately mining-specific EMI standards may need to be promoted to overcome the increasing EMI issues in underground mining.

This paper highlights some key issues and considerations pertaining to EMI in mining that would be of interest to mining stakeholders. The information presented in this paper can help the mining industry to better understand challenges posed by EMI and to help reduce the risks associated with EMI in the underground mining environments.

DISCLAIMER

The findings and conclusions in this paper are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health (NIOSH), Centers for Disease Control and Prevention (CDC). Mention of any company or product does not constitute endorsement by NIOSH.

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