An Introduction to Lightning Risk in Underground Mines

Franco D’Alessandro
PhysElec Solutions Pty. Ltd., Australia
Hobart, AUSTRALIA
Email: info@physelec.com

Abstract—Effective mitigation of direct and indirect lightning discharges is an important aspect of the reliable operation of any mining operation. Whilst a systematic protection plan can be implemented relatively easily for above-ground operations, the circumstances are rather more complex for underground mines.

The counterintuitive nature of assessing the risk lightning poses to underground mining operations will be developed in this paper. It commences with an overview of the key characteristics of lightning and then outlines the main variables and transfer mechanisms of relevance to underground mines.

The paper provides some examples of calculations carried out by the author in numerous consultancy projects for some of the world’s largest mining companies.

Keywords—lightning risk; underground mines; attenuation; frequency dependence; soil resistivity dependence; depth dependence.

I. INTRODUCTION

In Australia, lightning is a significant cause of economic loss each year. It is also responsible for the loss of human life, posing a greater threat to individuals than almost any other natural hazard. On average, there have been 5-10 deaths and more than 100 injuries in Australia each year.

Whilst any typical above-ground commercial or industrial facility can incur both economic loss and loss of human life, the methodology for protecting those facilities is relatively well-understood and well-developed [1, 2, 3, 4, 5].

There is no single, practical technology that can eliminate all of the risk due to the direct and indirect effects of lightning. Hence, 100% prevention of damage cannot be guaranteed. However, a large reduction in the risk can be effected via a systematic, checklist approach to lightning protection. This approach is comprised of a number of distinct steps covering the major damage mechanisms and potential losses due to lightning.

The approach commences with an effective means to capture, conduct and then safely dissipate the energy in direct lightning strikes down to ground, and then continues with clamping and diverting transients that are induced in the electrical systems or which arrive at the site from external sources, most often due to “indirect” lightning strikes [5].

The relative weight each aspect of lightning protection could or should be given when implementing a solution for most projects involving buildings, sites and facilities is shown in Figure 1. It highlights the importance of earthing and bonding, which is the basis of all other protection strategies.

Figure 1: Simple graphical representation of the relative importance and impact each group of the lightning protection plan has within typical commercial and industrial facilities.

On the contrary, the risk that lightning poses to underground mining operations is not well understood. This subject forms the main focus of the remainder of this paper.

The remainder of the paper outlines the key characteristics of lightning and the main variables, transfer mechanisms and hazards relevant to underground mines. It then provides some examples of calculations carried out to quantify the dangers lightning poses underground.
II. LIGHTNING CHARACTERISTICS

Nowadays, lightning activity is specified in units of “flashes per square kilometre per year” and the quantity is called the “ground flash density” (GFD). The GFD is a fundamental parameter that is used to quantify the risk posed by lightning.

The coal mining areas of Australia, where most of the underground mining operations are based, are located in NSW and Queensland, where the GFD is typically in the range of 2 to 3 flashes/km²/yr.

It is important to note that a negative lightning flash, the most common type (about 90%), is comprised of one or more “strokes”. The median number of strokes per negative flash is 3-4, but up to 30 strokes have been recorded in a single flash. These strokes are separated in time by ten’s of milliseconds [1,4].

So, any infrastructure struck by lightning is most likely subjected to more than just one “strike”. The first stroke usually delivers the largest peak current but subsequent strokes are also dangerous because they have a very high rate of rise of current. This means that inductive reactance and hence potential rise on conductors is significant.

Some of the additional characteristics of lightning discharges that present dangers to assets in all industries include:

- Extremely high space voltages (10’s to 100’s of millions of volts) with resulting:
  - Charge transfers to ground up to 400 C;
  - Peak “return-stroke” currents up to 200 kA;
- These voltages and currents are characterized by extremely fast rise times, with peak values being reached in as little time as a fraction of a microsecond, as shown in Figure 2;
- Stroke multiplicity is less common in positive flashes but they are more dangerous because they deliver more charge to ground and are more random in the way they strike a ground point;
- “Continuing currents” of 200-500 Amperes, lasting 1-2 seconds, may also be present.

![Figure 2: Characteristics of the lightning impulse.](image)

Whilst the above characteristics and statistics have been known for over half a century, the availability of better and faster instrumentation over the last decade has uncovered a new lightning phenomenon known as “multiple ground terminations” (MGT). This characteristic has significant implications for lightning protection. It is manifested as lightning striking two or more distinctly separate locations (up to 10 km) in a single cloud-to-ground flash. If this phenomenon is ignored, the consequences can be severe.

III. REPRESENTATION OF LIGHTNING

Most of the lightning characteristics outlined above are quantified via various parameters, each of which has a very large statistical spread. Therefore, it is not a trivial exercise to compute the effects of lightning because it is difficult to isolate a single parameter for the calculations.

Past authors [6,7] have used the standard lightning voltage waveshape (1.2/50 μs) to represent the lightning surge current injected into the ground. This may be an erroneous use of the standard lightning voltage impulse. Furthermore, it is not appropriate to use a single waveshape to determine the effects of lightning as the actual waveshape can vary over a huge range. At the most basic level, first strokes have the highest peak current and a moderate rate of rise of current (\(\frac{di}{dt}\)), whilst subsequent strokes deliver a lower peak current and a higher \(\frac{di}{dt}\).

The degree of attenuation of the lightning impulse in soil depends on the soil resistivity. Regardless of the resistivity, the higher frequency components of a lightning impulse are more heavily attenuated. There is very little energy transferred deep underground by frequencies above about 5 kHz, so “slower” wave-shapes present a more dangerous situation underground, i.e., they result in higher voltages.

Hence, before choosing a single, arbitrary waveshape which may not represent the spread of values inherent in published lightning statistics, some preliminary calculations can be carried at a range of specific (sinusoidal) frequencies, e.g., 50 Hz, 500 Hz, 5 kHz and 50 kHz. The variation of voltage and current underground can then be evaluated by comparing the results. Also, differences in the results for different locations readily become apparent.

The peak current delivered by a lightning stroke also has a very broad distribution, ranging from about 3 kA to more than 200 kA. The median stroke current is usually taken to be about 30 kA [1,4]. If the median current is used, then one is accepting the fact that 50% of all incident lightning flashes will exceed the calculated values. Clearly, this is an unsatisfactory situation from a risk management viewpoint. On the other hand, the use of a peak current of, say, 200 kA, which exceeds 99.9% of all stroke currents, is most likely too harsh.
Ideally, thousands of calculations should be performed with random values of the stroke current between the aforementioned limits. Monte Carlo simulations are often performed for this purpose. However, according to Table B1 of AS/NZS 1768-2007, the 95th percentile lightning current occurs at about 100 kA. Hence, under the assumption that the use of this current covers 95% of all possible lightning strikes to a particular mine site, it is suggested that 100 kA is a reasonable value to use from a risk management perspective.

IV. UNDERGROUND HAZARD ASSESSMENT

There are various energy-transfer mechanisms by which lightning can enter an underground mine, including conduction through the soil, direct transfer via conductors (such as a borehole casing), corona discharge from a conductor and magnetic coupling resulting in induced over-voltages.

The most direct route for lightning undoubtedly occurs via conductors that begin at the surface and go all the way to the underground workings of the mine. For underground coal mines, the two main hazards in relation to this mechanism are:
1. Ignition of methane in a part of the underground mine where the methane-air mixture is at a dangerous level.
2. Touch voltage (electric shock) hazard as a result of elevated voltages underground due to lightning strikes above ground.

A. Methane Ignition

Even though they diminish with depth, lightning voltages and currents can create an ignition source for an explosive mixture of methane and air in three fundamental modes:

I. **Sparking** due to the existence of a significant voltage difference between two nearby points, e.g., an insulated conductor extending into the mine which is at an elevated voltage due to a lightning strike near its source and the local ground in the mine which is at a low relative voltage;

II. **Surface arcing** from current flow through conductors with discontinuities, such as resistive joints and points of contact, e.g., current flowing on the overhead roof mesh;

III. **Corona discharge** as a result of an elevated voltage on an “electrically-sharp” geometry (where the electric field is sufficient to ionise air), e.g., off the end of a borehole casing.

Methane ignition is a potential risk when conductive gas drainage pipes, borehole pumps, etc. are located on the surface **above goaf areas** of the mine. A typical goaf contains a methane-air mixture at levels varying between 60% in the rear and 1% near the operating face. Typically, to avoid coal in the goaf spontaneously combusting, gases are allowed to increase in order to exclude oxygen from the goafed area. However, this means that there is an explosive goaf fringe between the face and the goaf at all times, requiring constant monitoring.

An explosion can occur if the energy source (lightning in the present case) dissipates sufficient energy in a methane/air mixture with the methane content between 5 and 15% [8], provided the oxygen content is at least 12%. The minimum energy requirement for ignition is only 0.3 mJ for a methane concentration of 8.5%. Pockets of explosive methane/air mixtures can occur in abandoned and even sealed areas of coal mines [6].

B. Unsafe Touch Voltages

A touch voltage hazard is a potential risk with any conductive surface-to-underground services and boreholes. Services reaching the underground operations typically protrude through the heading ceiling and connect to other metallic equipment within the mine. They may also be bonded to the roof mesh, which can extend horizontally over long distances.

If a worker is touching any such equipment when lightning strikes, it is possible that the elevated voltage present may be sufficient to cause an electric shock [9].

In order to perform touch voltage calculations, the duration of the elevated voltage must be determined (or assumed). The duration of a lightning stroke is very short (less than 1 ms) but a lightning flash is typically comprised of 3 or 4 of these strokes separated by tens of milliseconds. Unfortunately, there are no standards anywhere in the world that provide guidance on how to deal with the impulsive touch voltages due to lightning, not even [10], which specifically deals with lightning hazards.

Safety calculations using Australian and international standards such as [11,12,13,14] are applicable to power frequencies. However, according to a recent analysis by Amiri et al [15], the approach in these standards is valid for step and touch voltage hazards due to lightning.

Calculations show that for mining personnel wearing PPE and with a body mass of at least 70 kg, in the relatively low-resistivity environment expected in the area of a coal seam, the permissible touch voltage is in the range 200 – 600 V (depending on the standard used and the specific assumptions made).

V. TYPICAL CALCULATION RESULTS

Taking into account the aforementioned lightning characteristics, transfer mechanisms and hazards, detailed calculations can be carried out on the impact of lightning discharges in underground mines. Such calculations must also take into account several important methodological issues, including but not limited to the:

- Exact conductor layout above- and below-ground at the mine site, e.g., boreholes, roof mesh, conductive services, power cables, etc.;
- Transmission line effects when dealing with transients on conductors;
- Lossy characteristics of the dissipative medium (i.e., the soil, particularly the resistivity profile);
- Coupling mechanisms (conductive, inductive and capacitive);
- Time- and frequency-domain techniques (FFT, inverse FFT).

The details of these computational aspects are outside the scope of the present paper. However, the following paragraphs present some of the results obtained from various calculations performed for typical mine site scenarios.

**Effect of frequency**

![Figure 3](image1.png)

**Figure 3:** Example of the effect of frequency content on the voltage appearing between a borehole and the roof mesh in an underground mine. The soil resistivity in this case was 200 Ωm.

**Effect of soil resistivity**

![Figure 4](image2.png)

**Figure 4:** Example of the effect of soil resistivity on the voltage appearing between a borehole and the roof mesh in an underground mine. The frequency in this case was 5000 Hz.

**Effect of mine depth**

![Figure 5](image3.png)

**Figure 5:** Example of the effect of mine depth on the voltage appearing between a borehole and the roof mesh in an underground mine. The frequency in this case was 500 Hz and the soil resistivity was 50 Ωm.

**Borehole transfer and waveshape distortion (full FFT analysis)**

For this detailed calculation, it is assumed that an item of conductive infrastructure with a height of 5 m above ground extends underground to a depth of 150 m. The soil resistivity profile at the location is represented by a 3-layer model as follows:

<table>
<thead>
<tr>
<th>Layer</th>
<th>Resistivity (Ωm)</th>
<th>Thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer 1</td>
<td>4.4</td>
<td>1.2</td>
</tr>
<tr>
<td>Layer 2</td>
<td>193</td>
<td>11.3</td>
</tr>
<tr>
<td>Layer 3</td>
<td>12.4</td>
<td>∞</td>
</tr>
</tbody>
</table>

With regard to the waveshape to be injected into the conductor system to simulate a lightning strike, IEC 62305-1 Annex A shows that a 100 kA, negative first stroke has front and tail times of about 18 and 200 μs respectively. Hence, an 18/200 μs waveshape is used in this example.

The resulting impulse 150 m underground is shown in Figures 6 and 7, corresponding to the peak potential of a conductor and the surrounding soil respectively. It can be seen that the original 18/200 μs impulse becomes “stretched” in time, with an overall duration of about 3 ms. This effect is due to frequency-dependent attenuation of the impulse after it travels more than 150 m on the conductor system whilst leaking current into the adjacent soil.

Figure 6 shows the voltage variation for the conductor underground whilst Figure 7 shows the elevated soil voltage at a distance of 1 metre from the conductor. A distance of 1 m was chosen as it represents the standard value for assessing “touch voltage” between a conductor at an elevated voltage and the soil over a typical “reach distance”.

![Figure 6](image4.png)

![Figure 7](image5.png)
The relevant value to be obtained from Figs. 6 and 7 is the peak voltage difference between the conductor and soil 1 m away. This value occurs at the main peak of the impulse and is about 1500 V. This voltage is obviously higher than the permissible touch voltage level mentioned earlier, namely 200 - 600 V, and hence a touch voltage hazard may exist in this case.

Finally, it is noted for this example that a potential difference of 1500 V may also be capable of causing sparking underground and hence pose a serious risk in areas where explosive concentrations of methane-air mixtures exist.

**VI. CONCLUSIONS**

This paper has presented an introduction to the risk that lightning poses to underground mining operations. The key characteristics of lightning were reviewed and the main variables and transfer mechanisms of relevance to underground mines were discussed.

A selection of example calculations of lightning transient coupling to conductive workings underground via conductive, capacitive and inductive mechanisms, all of which must be taken into account for lightning, showed that:

- Voltages of up to ten’s of kV can be coupled onto the underground roof mesh when a conductive borehole extends from the surface to the underground workings.
- The dependence of voltage underground on frequency is non-monotonic, with the peak value occurring at a few kHz.
- The “most damaging” frequency depends on soil resistivity (the higher the soil resistivity, the higher the frequency that results in the largest potential), but there is also a dependence on depth.
- Attenuation of the lightning current and voltage on the borehole casing increases as soil resistivity decreases, i.e., voltage decreases as soil resistivity decreases.
- The voltage underground decreases as the depth of the roof mesh increases.

It can be concluded that lightning poses a considerable risk to safety underground via the elevated voltages that can be transferred or coupled onto conductive elements of the workings. The main hazards for underground coal mines are considered to be methane ignition and touch voltage.

**REFERENCES**


[14] IEEE Std.80, 2000, “IEEE guide for safety in AC substation grounding”, Institute of Electrical and Electronics Engineers, USA.