Review of Lightning Impacts on Power Supply of Productive and Extractive Industry in South Africa and Such Ways of Production Loss Mitigation as Installation of Line Lightning Protection Devices

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Abstract — ***This paper focuses on a review of lightning resulted issues in electric power supply of productive and extractive industry in South Africa. The article presents the interview result among representatives from companies in the industry above. Analysis of interviews showed that it is essential to prevent any interruptions of technological processes. Possible ways of lightning consequences mitigation are presented. Line lightning performance before and after installation of lightning protection means is being evaluated. Also the paper presents an economic analysis of such protection benefits based on mitigation of production losses by reduction of lightning outages quantity and their cumulative duration.***

Keywords — ***productive and extractive industry; lightning consequences; overhead lines; outages; Line Lightning Protection Devices.***

I. Introduction

For electric power supply, the most dangerous lightning is those that strikes on the overhead line or close to it. This creates overvoltage on the line and subsequent flashover of insulator. Overvoltages and short-circuits cause outages and damages on the lines, such as failure of transformers, conductor breakage, insulator breakage. Therefore, the time in which companies remain without electricity can be very long. It is essential to understand that during periods of electrical outage, processes of producing and extracting mineral products stop and working staff could face hazardous situations if underground. Additionally, due to the heavy load and machine starting process, it will take several hours after the electrical interruption to restore all the processes fully.

As an example, in Saudi Arabia in the Khurais region, there are about 15 days of lightning per year within April-May and on a lower scale November. For the oil and gas industry, lightning is responsible for about 14 hours loss of production on average for each electrical outage. After an outage, 24 hours are required in order to come back to the full production rate. Khurais region is the second largest oil field in Saudi Arabia. It produces more than 1 million barrels a day. Hence the yearly production loss due to lightning can be counted in millions of barrels.

II. Overview of Lightning in South Africa

The Republic of South Africa is a very vast territory which covers an area of 1,221,037 square kilometres. Across South Africa, there are some areas, which experience lightning almost daily throughout summer and other areas that only experience lightning 3 days a year [1].

A. Ground flash density map

The lightning ground flash density map for Southern Africa is shown (Fig. 1). The data displayed on this map was obtained over the 11 years from 2006 to 2017. The lightning Ground Flash Density (GFD) is defined as the number of flashes from cloud to ground occurring on or over a unit of area in a unit of time, generally flashes per square kilometer per year. GFD value is commonly used to describe a lightning activity [1].

The Southern African Lightning Detection Network (SALDN) identifies a many areas with GFD values higher than

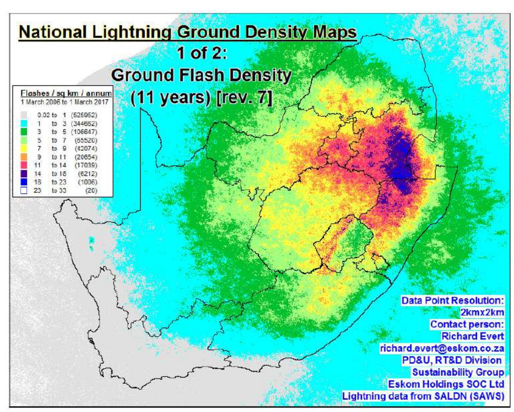


Fig. 1 Lightning Ground Flash Density map showing results obtained over 11 years

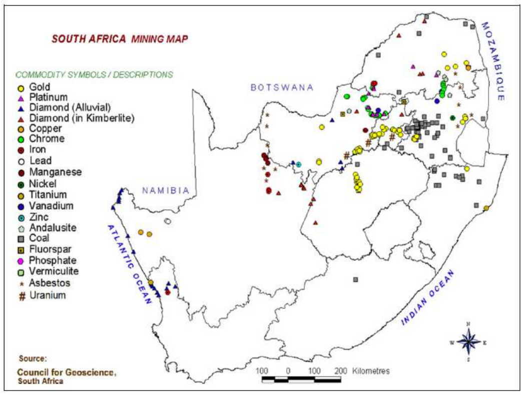


Fig.2 Map showing mining areas in South Africa

of 14 flashes/km2/year. And SALDN also detected areas with GFD values of up to 23 flashes/km2/year [1].

Map with mining areas in South Africa is shown on Fig.2 [2]. Comparing two maps from Fig.1 and Fig.2 shows a clear match between two areas: area with high ground flash density (with 7-22 flashes km2/year) and area where many mines of coal, gold, chrome, diamond are located. It means that this area and particularly the mines will need a critical lightning protection approach in order to ensure safe operation and minimize production losses resulted by power outages.

B. Lightning danger for productive and extractive industry

South Africa is the world's third-largest coal exporter and is number 5 in gold. It is the world's largest producer of chrome, manganese, platinum, vanadium, and vermiculite. There are over 1 800 mines and quarries across the country. Lightning poses a severe threat to the safety and productivity of these operations but there is a tendency to understand the ways for improved application of lightning and explosion protection means [3].

The consequences of lightning can be production losses for these companies. Losses are caused by lack of electricity during a certain period and can be evaluated. However, the most crucial risk from lightning is safety hazards. It is essential to prevent any security risks to staff.

One of the central systems responsible for safety is ventilation, which ensures low concentration of methane in underground mine in order to prevent various dangerous situations. Needless to say that clean air is also vital for workers.

III. Consequences of lightning on mining industry

For the preparation of this article, a list of questions was asked to 5 representatives of companies in productive and extractive industry to obtain statistical data on lightning and its consequences for production:

- Coal mines in South Africa;
- Platinum mine in South Africa;
- Diamond mine in Angola;
- Coal mine in China;
- Gold mine in Colombia.

This information allows to estimate production and financial losses and consequences from lightning. Full interviews are presented in Annex 1.

In order to compare power sustainability actions of South African companies with worldwide practice, also mines in following countries were contacted: Angola, China, Colombia. It turned out that the level of issue is more or less the same and does not directly depend on type of extracted material, but only on production losses.

All these considered mines are located in area facing 7-15 flashes/ km2/year.

The interviewed experts mentioned that in their mines there could be from 3 to 20 outages per year due to the lightning.

Amount of outage and its duration is different from mine to mine and depends on the ways of ensuring of the power supply during the outages, on lightning protection on the mine lines, on pole footing resistance reduction, and on the presence of overhead ground wires.

The mine representatives during the interviews mentioned that the average duration of the outage on their mines could be from 30 seconds to 10 hours.

Normal operation work in mines during the outage is ensured by backup power supply: double power lines and powerful generators up to 3,2 MVA.

The most reliable way to ensure the shortest outages possible is dual power supply lines. This option is utilized in Platinum mine in South Africa, Coal mine in China and Gold mine in Colombia. In these mines production processes can be continued thanks to a second line in situations of outage on the main line. But building two lines is extremely expensive and not always possible. This type of power supply should be initially planned by design of the mine electrical network. Not every mine can afford such a way to ensure guaranteed power supply in case of outages.

The second option for ensuring normal operation work during an outage, is a backup high-power generator. For the needs of the mine, a very powerful generator is needed and the price for this generator is quite significant.

It should be also noted that for some open mines it is possible to continue production during outages thanks to the availability of diesel machines. This type of machines can work independently from the electricity supply.

However, paper also presents an interview with representative from open cast mine, where during an outage the majority of the staff is not able to work. Since the production depends for about 90% on electricity supply. During the outage for this mine all production processes will be stopped.

For the most case, all excavating processes are also depending on the electricity in underground mines. And if in underground mine there is no generator, all excavating works will be stopped during the outage.

Also one representative from coal mine in South Africa mentioned indirect consequences of outages, such as possible cable theft. This leads to additional spending for buying and installation of new cables and this also increases the outage time and therefore the production loss.

Safety hazards due to outage mentioned during the interviews are: security system shutdown; safety system shutdown (water recirculation system, fire system); power failure of the underground fan; injury of people; accumulation of gases; damages due to the sudden shutdown of coal mining equipment; the inability of personnel to evacuate when personnel transportation equipment is stopped.

It is obvious from the interviews that the effects of lightning in the mines are significant. In many mines the entire production operation is stopped because of outages and there are many safety hazards during outages. Thus, dual lines and generators are not available for all existing mines and lines, for ensuring continuous power supply hence it is necessary advised to utilize lightning protection means.

IV. Possible Ways of Lightning Mitigation on Medium Voltage Electrical Overhead Lines

A. Shielding wire

This wire has the function of improving lightning protection performance line.

Shielding wire on medium voltage has one major function: to catch the Direct Lightning Strikes (DLS) that would have otherwise directly hit one of the phases. When lightning strikes directly on the shielding wire, the discharge will travel along the wire and will be discharged at the next grounding locations.

But the shielding wire also has an influence on induced overvoltage when the lightning strikes is only hitting close to the line. As an example mentioned in reference [4] it is showed a reduction in the peak values of induced overvoltage (IOV) thanks to the presence of shielding wires in the range of 25 to 35%. Indeed, the shielding wire provides a good way to the ground for the IOV.

As shown in references [5] and [6], installing overhead ground wire, grounded every 200 m (every three to five poles) with a footing resistance below 5 ohms on MV lines can reduce the number of outages by up to 30%. The limited improvements are due to the absence of grounding on every pole. Indeed, reference [7] states that the effectiveness of shielding wire is clearly dependent on the quality of grounding on every pole.

Besides, in case of direct lightning strokes, according to footing resistance and due to low level of insulation of medium voltage lines, back-flashover occurs.

In most cases in the previously discussed mines, wooden poles are used with insulators grounded on the same ground lead than for shielding wires. However, the ground resistance is very rarely as low as 5 Ohm hence we could still witness lightning outages and damages even with shielding wire.

B. Metal-Oxide Arrester

Originally, the surge arresters are installed in a distribution system to effectively protect equipment insulation, such as transformers and regulators [7]. Arresters may be used to protect distribution-line insulation to prevent flashovers and circuit interruptions, especially for covered distribution lines.

During the interviews mine representatives mentioned that for lightning outages mitigation they install Metal-Oxide Arresters (MOAs). But mostly these MOAs are installed at the end and beginning of line, close to cables and transformer.

In the case of partial MOA installation on poles in the line, there could be only partial protection line from induced overvoltages, but there would be no protection effect on direct lightning strikes.

Adding surge arresters against direct strokes is difficult because of the high currents, steep rates of rise, and large energy content in lightning flashes. Arresters should be added at every pole and every phase to be efficient. Also the lightning discharging energy can easily exceed the rated energy absorption capability of surge arresters in a distribution system, and this would lead to high failure probability of the distribution arrester.

To virtually eliminate flashovers, surge arresters should be added on every pole and every phase in conjunction with shielding wire. The shielding wire will divert most of the lightning current to the ground, so the arresters are not subject to a high energy input. The arresters make the shielding wire design less dependent on insulation level and grounding. If there is no shielding wire on the distribution line the failure rate of arresters can be 32% [8].

As stated in reference [7], the efficiency of arresters strongly decreases when they are spaced (even one pole span apart). And for normal MOA operation it is better to have low soil resistivity.

The interviews carried for this paper proved that partial equipment of lines with surge arresters cannot ensure a total absence of lightning trips and outages.

C. Line Lightning Protection Device

Nowadays, there is another way for lightning protection of overhead lines: it is Line Lightning Protection Device (LLPD). LLPDs have several advantages for cutting voltage along distribution lines, including fast arc quenching, minimal maintenance, and long lifetime [9].

The main objective of the LLPDs is preventing breakage of conductors, insulators, but also drastically decreasing power outages by preventing flashovers of insulator caused by direct and indirect lightning strikes. Moreover, special grounding and low soil resistivity are not required for this type of device, hence it can be implemented literally everywhere [6].

The operating principle of the device is as follows: an overvoltage surge (a few hundred of kV to a few MV) is traveling on the overhead line after an indirect or direct lightning strike; when it reaches the insulator it will flashover on the LLPD thanks to its lower Basic Insulation Level; afterwards a short circuit current is establishing from phase to ground through the LLPD; this short circuit is then quenched by the LLPD in less than a half period.

Inside the silicone rubber body there are metal electrodes. There are cavities between the electrodes, leading to the outside. These cavities form miniature gas-discharge chambers (see the operation principle in Fig. 3).

Lightning surge encounters the LLPD; the gaps between the electrodes breakdown, thus providing an ionised pre-set path (discharge channel) for fault current establishment inside the chambers.

The discharge channel expands with increasing holdover value, creating high pressure in the chambers. While the arcs are occurring between the intermediate electrodes inside the low volume chambers, the sparks between the electrodes is pushed to the surface of the insulation body due to increase air pressure.

The pressure continues to increase thanks to the high current so the sparks are blown further outside around the LLPD. This blowing effect creates an elongation of the channels between the electrodes. Due to the outside air an intensive cooling takes place which increases the short circuit electrical resistance. Total resistance of the product is increased, enabling quenching of the fault current before its first passage through zero. Such type of fault current quenching is conditionally called zero quenching

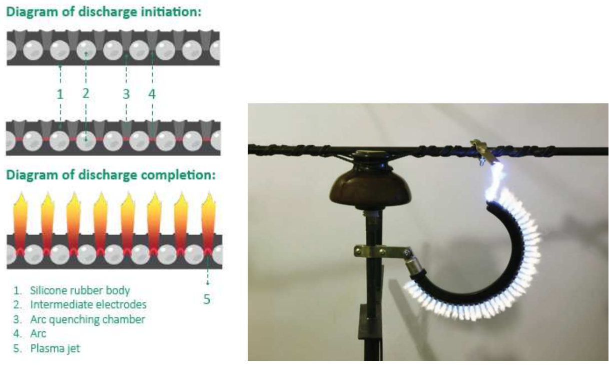


Fig. 3 LLPD operation principle

D. Lightning protection comparison between MOA and LLPD

It is important to note that contrary to MOA, LLPDs cannot be used to protect equipment such as transformers or cables against switching overvoltage but they can only be used for the protection of overhead line against lightning events. In addition, LLPDs cannot directly protect, but can protect the arresters protecting such equipment. Although MOA can be used for more diverse purposes, LLPDs are more efficient in terms of lightning protection.

The comparative characteristics of the two devices are shown in the Table 1.

TABLE I. PERFORMANCE COMPARISON BETWEEN MOA AND LLPD

Characteristics	**Compliance with**	
	MOA	***LLPD***
Ability to operate with a high level of footing resistance	-	+
No maintenance required: “Fix&Forget” concept	-	+
High reliability and life span, device is self-protected	-	+
Withstands direct lightning strikes (high discharge capabilities)	-	+
Will not facilitate line outage when damaged	-	+
Quenching of follow current	+	+
Protection against switching overvoltage	+	-

V. LIGHTNING OUTAGE CALCULATION OF A MINE OVERHEAD LINE

To assess the economic efficiency of LLPD usage, an analysis of the lightning performance of a typical 11 kV overhead line feeding a coal mine has been carried out. A power line with the following parameters has been considered:

- 15 km of overhead line;
- two overhead ground wires;
- span length between poles 80 m;
- insulator type Polymer FXB1-22 (Fig. 4) V_{CFO} = 200 kV;
- wooden pole (Fig. 4, 5);
- pole footing resistance R = 20 Ω;
- GFD = 10 fl/1km^2/year.

Groza software has been used for the lightning outage calculation of the mine power line. Groza software is based on analytical formulas method to assess the lightning performance

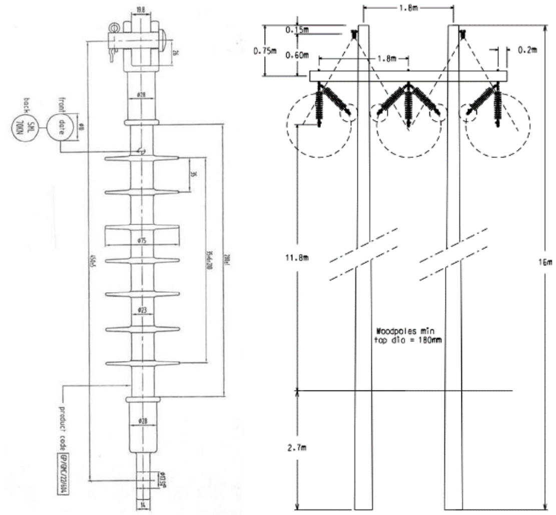


Fig. 4 Insulator and pole parameters

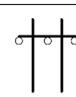
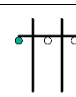
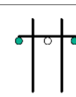
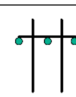
of overhead lines. The method is based on the classical representation of overhead lines and poles as an equivalent circuit to calculate a critical lightning current for flashover of the line insulation or LLPD and uses IEEE Std. 1410 [10]. This software allows performing calculations using LLPD in various configurations and quantities and choosing the optimal arrangement option.

The calculation takes into account DLS into the ground wire, the probability of back flashover and from IOV from lightning strikes near the line.

The results of the lightning performance assessment are shown in Table 2. The first row shows the number of outages from the DLS and from the IOV in the configuration according to the described parameters of the OHL. The total estimated number of outages is 8.4 per year per 15 km of line length, which is a significant level for the mine supplier company. The installation of two overhead ground wires on this line is not a sufficient means of protection due to the low CFO voltage of the insulation and the high footing resistance of the poles.

The following rows in Table 2 show the change in the number of lightning outages on the line using the LLPD against DLS from one to three pcs per pole. The lightning performance of the OHL improves by 1.7-12 times depending on the number of installed devices.

TABLE II. CALCULATED LIGHTNING PERFORMANCE OF 15 KM 11 KV OHL

LLPD arrangement		**Number of lightning outages per year**		
		DLS	***IOV***	***Total***
no LLPD		6.3	2.1	8.4
1 LLPD		4.2	1.1	5.3
2 LLPD		1.9	0.1	2
3 LLPD		0,7	0	0.7

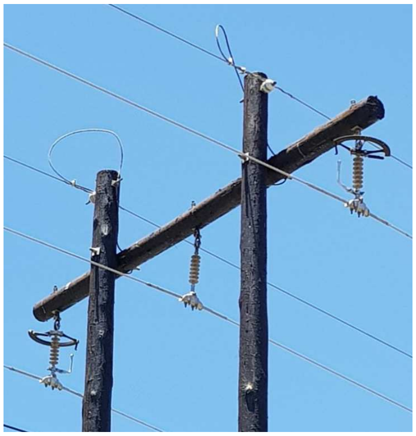


Fig. 5 LLPD installation on the coal mine OHL

According to the algorithm of efficient arrangement of protective devices from [10], we can obviously see that the more LLPDs are installed the lower becomes the lightning outage rate on the line. But the most cost effective option seems to be the installation of 2 LLPD per pole. Thus, with this option the number of outages is reduced by 4 times from 8.4 to 2 outages.

Figure 5 shows an example LLPD installation against DLS according to the proposed scheme on an 11 kV line feeding a coal mine in the north-eastern part of South-Africa.

VI. Economical study of LLPD installation

In this chapter will be considered economic efficiency of LLPD installation and calculated how much money could be saved if the number of outages on the line had been reduced thanks to LLPDs.

For example, we will suppose that the mine mentioned in the chapter V produces 5 Mt of coal per year, i.e. 571 t per hour. The price per ton can vary from $70 to $150 but we will consider here $70 per ton as coal mine representatives told us that the selling cost of coal for their company was 1200 South African Rand (on July 25, it was $70,6) per ton. The worldwide price of coal is however much higher.

In this mine will we consider 1000 people of manpower working in 2 shifts. Their average hour rate is $9,5.

Previous chapter showed that this typical coal mine overhead line could face an average of 8,4 outages due to the lightning per year without any additional lightning protection. A representative from coal mine in South Africa told us that each outage can remain from 1 to 10 hours of outage with an average of 5 hours. We will choose this average value for our calculation.

Taking these two hypothesis, we can calculate that the mine will lose in average 42 hours of production per year which would represent about 24'000 tons of coal. At 70.6 USD it represents a loss of 1.7M$ per year. If we also count for the same amount of hours lost for half of the manpower, we can add 200'000 USD of losses per year.

Considering the basic parameters of the line from the chapter V, we can consider to install 2 LLPD per pole, for a total 374 pcs of LLPD on the line. Including installation costs, it will cost about 0,17 million $ to upgrade the line with line lightning protection devices. In this way, ROI (return on investment) will be just a few months.

These calculations are estimated and generalized, but they show quite clearly that installing LLPDs on a mine overhead line could generate a saving of several millions of USD over 5 years. Such large amount of lost profits will be in the case when coal production at mine depends entirely on the availability of electricity and there are no powerful generators. The interviews show that in some cases partial production without electricity can be realized. However, in any case, the cost of installing LLPDs is much lower than the possible losses of profits of the mine when a lightning outage arises.

VII. Conclusions

Consequences of lightning strikes on power lines are always severe, but especially for productive and extractive industry. We showed in this paper that the consequences could be various but they surely include hazardous situations for the mine staff and great financial losses in production outage or material damage.

If we consider South Africa, having a very important amount of mine, we showed that unfortunately the main mining region in this country is also one of the highest lightning density area worldwide. Therefore, these mines are facing these issues and are in need of lightning protection solutions.

By reviewing the main available solutions to protect overhead lines against lightning we could show that the most adapted would be the Line Lightning Protection Device.

A theoretical calculation showed clearly that the installation of two LLPDs per poles on a mine overhead line would reduce by more than 70% the number of lightning related outages in this mine.

Finally adding an economical study on this showed clearly that the installation of such product would be easily paid for thanks to the savings generated by the reduction of production losses.

Acknowledgment

Acknowledgement must go to the representatives from mines in South Africa, Angola, Colombia and China who gave an interview for these paper.

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ANNEX 1

Full interviews with mine representatives

A. Coal mines in South Africa

1) General information about the mine: This group of coal mines locates in the northeastern part of South Africa. There are 4 mines on this place: underground and open casts. Total in all 4 mines excavated 6 Mt of coal per year.

2) Lightning flash density: 10 flashes/ km2/year that in this area.

3) What should staff do after receiving a storm hazard notification: There is a weather station on each mine. When lightning is closer than 20 km, there is a signal from alarm system. When lightning is closer than 5 km, all mine operations should be stopped, this is organized according to the South Africa's laws.

4) Amount and average duration of annual outages due to the lighting: The representative from one of the mine told that from October to March there is a rainy season and while one month in this place can be about 8 lightning cases. The power supplying of this group of mines has some specificities. Due to the load shedding, mines could stay without electricity during a few hours per day. Load shedding could reach up to 100 days per year.

During a year it could be 10 times when one of four mines stay without electricity due to the lightning. Usually, the duration of lightning outages is from 1 to 10 hours. It depends on the consequences of the lightning. Then autoreclosing is impossible, the representatives from electricity utility have to make visual inspection of all lines and repair breakages. Mine's operation will start immediately after electricity recovery.

5) Is there any lightning protections on the line? There are surge arrestors and ground wire on these lines.

6) What will happen with production processes in case of outages? In mines staff can continuously work just when lightning is not closer than 5 km. In underground mine, all excavating processes depending on the electricity. And if in underground mine there is no generator, all excavating works will be stopped.

In open mines excavation works can be continuing without electricity because the main work is made by diesel machines. This type of machines can work independently from the electricity supply.

7) What ensures a continuous production process in case of line outages? In open mines due to the diesel machines all production processes continue. The continuation of these processes at underground mines can only be ensured by generators. But not all mines have them. It is needed to have 1,5 MVA generator for each mine. Also in all underground mines exist additional generator which provide ventilation.

8) Safety hazards in case of outages:

1. Electrical cable theft. There is no power supply, it is easy to theft them for taking cooper.

2. Security system doesn't work (cameras, alarms, communication systems, also some database could be lost if outage is longer than 4 hours).

3. Safety systems doesn't work (water recirculation system (pumping water), fire system).

4. Injuries of people (without electricity there will not be illumination in mines, and it is impossible to work in the darkness).

5. If all additional generators don't work in underground mine, gases can be accumulated, that can lead to explosion.

B. Platinum mine in South Africa

1) General information about the mine: In this article is presented the case of underground mine in the northwest part of South Africa. In this mine is excavated platinum.

2) Lightning flash density: In this region about 10 flashes/ km2/year.

3) What should staff do after receiving a storm hazard notification: During the storm staff continue working in mines. People, who are on the surface, should go to the shelter.

4) Amount and average duration of annual outages due to the lighting: During last year on these lines were 4 trips due to the lightning. This mine opened not so long ago and during this time there was not any cases when mine left without electricity.

5) Is there any lightning protections on the line? These two lines are equipped by surge arresters in 15 points.

6) What will happen with production processes in case of outages? This mine has never seen such a case before.

7) What ensures a continuous production process in case of line outages? The power sustainable supply for this mine ensures by two lines with length about 4,5 km. Avoidance of safety hazards in this mine is guaranteed thanks to the generator with 3.2 MVA. But this kind of generator have a big size and an enormous price.

8) Safety hazards in case of outages: Representative of this mine highlighted two main safety hazards in case of outage: shutdown of underground fans and flooding water.

C. Diamond mine in Angola

1) General information about the mine: Diamonds in this mine excavated from open cast. Per year in this mine excavated about 1,6 tons of diamonds, that means that every minute people extract 3 grams of diamonds.

2) Lightning flash density: In place there this mine locate, can be from 7 to 10 flashes/ km2/year.

3) What should staff do after receiving a storm hazard notification: No information.

4) Amount and average duration of annual outages due to the lighting: According to the analysis results of the last year it was registered 10 outages. Among them 7 times outages occurred because of the lightning. The average lightning outage duration is 11,3 minutes.

5) Is there any lightning protections on the line? There is lightning protection on the line.

6) What will happen with production processes in case of outages? In this mine during the outage all parts of the staff are not able to work. Because the result of mine's activity depends quit 90% of energy use. During the outage all production processes will be stopped.

7) What ensures a continuous production process in case of line outages? In some areas backup power supply exist.

8) Safety hazards in case of outages: In this mine the main equipment which ensure safety for stuff is emergency generators and solar illumination. And for these systems there are backup power sources.

D. Coal mine in China

The representative from anthracite mine in China was also interviewed.

1) General information about the mine: There is underground mine, where anthracite is excavated.

2) Lightning flash density: No information.

3) What should staff do after receiving a storm hazard notification: No information.

4) Amount and average duration of annual outages due to the lighting: During one year in this mine can be around 3 trips due to the lightning out of all annual 5-6 outages in 35 kV system. But during last three years there were not any power outage accidents in mines.

5) Is there any lightning protections on the line? No information.

6) What will happen with production processes in case of outages? Most of the time works can be continued.

7) What ensures a continuous production process in case of line outages? Sustainable power supply in this area ensures by dual power supply lines in 90% of 35kV substations. As the representative of this mine told, that even with double-line tripping special weather such as lightning strikes and strong winds could occur to regional power outages and underground mine production stoppages.

8) Safety hazards in case of outages: For this mine safety hazards in case of outages are: the power failure of the underground fan, that can cause insufficient oxygen supply; power failure of safety facilities; damage to the sudden shutdown of coal mining equipment; the inability of personnel to evacuate when personnel transportation equipment is stopped.

E. Gold mine in Colombia

1) General information about the mine: This open pit mine, there gold is excavated. In this mine excavated about 2 tons of gold every year.

2) Lightning flash density: In this region the lightning flash density is even higher than in South Africa, about 15 flashes/km2/year.

3) What should staff do after receiving a storm hazard notification: During storms, operations are not stopped, because the main work is done by dredges, which can continue working without workers during storms. No one staff activities in the field while there is storm.

4) Amount and average duration of annual outages due to the lighting: In this mine during previous year were 25 trips, and 20 trips from them was due to the lightning. Average lightning outage duration is 30 sec, but the mine in operation could be back in 8 min. Nevertheless, not always time is 8 min, due the change of the line is very fast that the operation continues working.

5) Is there any lightning protections on the line? No information.

6) What will happen with production processes in case of outages? Staff is waiting for the energy reactivation.

7) What ensures a continuous production process in case of line outages? Power supply on this mine ensures by two lines. And in case when there is an outage on the one line, the second line will be used for supplying. And this company is the owner of one line because they have a hydraulic generation and somewhere in the transmission system, they connect with another line to the national grid system.

8) Safety hazards in case of outages: No information.