Research on Electromagnetic Immunity Design of Coal Mine Instruments Based on Wireless Sensors

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Abstract: For a long time, one of the factors that perplex the safety problem of coal mine is the interference of electromagnetic signals on underground instruments, which affects the normal work of underground instruments. In this paper, we firstly elaborate the causes and hazards of electromagnetic interference on coal mine instruments, and then explore the electromagnetic immunity characteristics of wireless sensors. Finally, we propose to construct an electromagnetic shielding model for coal mine instruments with wireless sensor, and discuss on design of hole and joint structure and slot array spacing of the shielding cavity. We conclude that a shielded body with a symmetrical form of open-cell structure, such as circular and positive, generally has higher shielding effectiveness, and to increase the gap spacing of the shielding cavity can slightly improve the shielding effectiveness.

1. Introduction

Downhole monitoring is one of the important links in modern coal production. In recent years, with the continuous improvement of coal production technology and production management level, higher and higher requirements for monitoring technology have been put forward. With the improvement of the level of coal mining equipment, the power supply capacity of coal mines is also increasing. However, these devices make the grid load vary greatly at startup, causing fluctuations in the grid. The use of variable frequency speed control soft start to control the equipment can reduce the impact of high power equipment on the grid when starting, but this will produce many spikes. These electromagnetic interferences can cause malfunction of the downhole smart meter or affect normal operation. Therefore, in the case of increasingly widespread use of electronic equipment and increasing electromagnetic pollution, electromagnetic compatibility has become a technical evaluation indicator that electronic products must consider, and the level of electromagnetic immunity is the key factor that restricts the monitoring effect of underground mine.

To solve electromagnetic interference, we can start from three aspects: first, reduce the interference; second, cut off the spread of interference sources; third, take attempt to improve the electromagnetic immunity of downhole instruments. The underground environment is very complicated, and some electromagnetic interference sources cannot be eradicated in a short period of time, so this paper mainly focus on improving the anti-electromagnetic interference ability of underground instruments and meters. We utilize the electromagnetic immunity characteristics of wireless sensors, and propose to construct an electromagnetic shielding model for coal mine instruments with wireless sensor, and discuss on design of hole and joint structure and slot array spacing of the shielding cavity.
2. Causes and hazards of electromagnetic interference on coal mine instruments

2.1 Causes
Coal production is one of the high-risk industries. Due to the complex geography environment of the coal mine and the harsh underground working environment, there are many potential safety hazards and it is easy to accident. In the past, the way of coal mining has been blasting mining, while at present, China's large and medium-sized mines mostly adopt fully mechanized mining. However, the use power of fully mechanized machine is very large. Especially when the fully mechanized mining machine starts, it needs a lot of electric power, so the voltage of power supply network in coal mine fluctuates. Meanwhile, underground winch, large water pump and other equipment need soft start, but the use of soft start will generate pulse voltage in the mine power supply network, and eventually these electromagnetic signals will interfere with the normal operation of mine instruments and meters, and even lead to accidents.

That is to say, the main cause of electromagnetic interference to underground intelligent instruments and meters is the fluctuation of grid voltage caused by the start and shutdown of high-power equipment in coal mines. In addition, the use of soft start will cause charging and discharging of inductive and capacitive devices in mine equipment, and then produce huge peak pulses, which will affect the reading errors of mine instruments and instruments. Nowadays, underground intelligent equipment is used more and more frequently so thus electromagnetic pollution has become a huge obstacle to the realization of automatic production in coal mines.

2.2 Hazards
Firstly, electromagnetic interference produces voltage fluctuations that last several cycles. The use of underground transformers, winches and large pumps will cause voltage fluctuation of mine power grid. Voltage fluctuation of coal mine power grid will lead to errors in underground instrumentation measurement, and the action device is malfunctioning or even stuck. In general, voltage drop is a frequently encountered problem.

Secondly, electromagnetic interference can produce a sudden surge, which will make the grid voltage rise suddenly and last several cycles. For example, when large underground electrical equipment suddenly stops operating, the voltage in the transmission network will suddenly increase, to form a sudden wave, and the formation of the sudden wave will cause the recording data of underground instruments and meters to appear disorderly code, and even damage the underground instruments and meters. According to statistics, more than half of the downhole instrumentation failures are due to the interference of sudden waves. At the same time, electromagnetic interference will produce sharp waves, which are mainly caused by large underground electrical equipment switches and arc discharge. The average spike voltage is 5 kV and the duration is 0.3-4ms. The sharp wave is harmful which can not only interfere with downhole instruments, but also destroy the input filter of electrical equipment.

Thirdly, electromagnetic interference can cause waveform distortion. The main reason for the distortion of mine voltage waveform is the use of rectifier and electronic speed control equipment. In addition, secondary power supply itself can also cause waveform distortion. The distortion of mine network waveform will not only cause the misoperation of underground high and low explosion switches, but also cause the reading errors of instruments, such as gas meter, carbon monoxide meter and so on. Moreover, waveform distortion can interfere with the underground communication system, affecting the communication of the central control room to the personnel command.

Finally, electromagnetic interference can cause catenary interference. Catenary interference refers to the continuous impulse group generated in the underground strata. The reason for the interference of catenary is that the wheel rubs against the rail when the material is transported back and forth by the rail car. The disordered current is generated. These currents are dispersed randomly in the rock stratum, and then the impulse interference is produced to the instrument and instrument in the mine, which results in the inaccurate reading of the instrument and instrument in the mine, and even causes the instrument to crash.
3. Electromagnetic immunity of wireless sensors

Through the study of electromagnetic protection technology, we aim to reduce the impact of electromagnetic interference on coal mine instruments. In coal mine instruments, the physical dimensions of the circuits formed by the various components, wires, components and wires determine the interference of electromagnetic disturbances on the signal circuit of the wireless sensor. The antenna effect is generated when a certain wavelength of the electromagnetic interference signal is close to the length of the trace. At this time, the long signal line, control line, input and output leads in the wireless sensor signal loop are easy to receive high frequency electromagnetic interference signals, due to antenna effect, and thus affect the normal operation of components in the wireless sensor signal loop.

Electromagnetic shielding used in wireless sensors has two purposes: one is to prevent the radiated electromagnetic interference outside the device under test from being coupled to the internal electronic circuit, resulting in a decline in the performance of the device under test; the other is to prevent the radiation generated by the electronic circuit of the device under test from being emitted to the outside world. Electromagnetic shielding technology is surrounded by partial or complete metal materials to achieve the electromagnetic vibration of the electromagnetic wave from the side of the shield through the inside of the shield to the other side after being partially or completely attenuated. It is an effective electromagnetic protection technology.

The reflection of electromagnetic interference wave occurs when it is incident on the interface of different media, and the reflection loss is the electromagnetic energy lost through the interface. When electromagnetic interference propagates through the shielding material, part of the energy loss occurs, and the electromagnetic energy is converted into heat, which is the absorption loss.

The shielding effectiveness characterizes the degree of attenuation of the shielding electromagnetic wave by the shielding body, which can be used to measure the shielding effectiveness of the shielding body. It refers to the ratio of the field strengths $E_0$ and $H_0$ of a certain measuring point of an unshielded casing to the field strengths $E_s$ and $H_s$ of the same observation point plus a shielded casing, shown as the following formula.

For electric field: \[ SE_e = 20 \log \left( \frac{E_0}{E_s} \right) \]

For magnetic field: \[ SE_m = 20 \log \left( \frac{H_0}{H_s} \right) \]

In fact, the shielding is often incomplete. When there are gaps, cable holes and ventilation holes in the shielding body, the electromagnetic waves will enter through these gaps and holes. In this case, the integrity of the shield is broken and the overall shielding effectiveness is correspondingly reduced.

If there is a gap in the shield, length and width of the gap as $L$ and $W$, frequency of incident electromagnetic waves as $f$, then the shielding effectiveness at the gap is:

\[ SE = 100 - 20 \log \left( Lf / (1 + 2.3 \log(L/W)) \right) \]

If there is a hole with an area $S$ on the surface of the shield. In the case where the area $A$ of the shield is much larger than $S$ and the hole size is much smaller than the wavelength, the transmission coefficient of the electromagnetic disturbance through the hole is:

\[ T = H_p / H_0 = 4 \log(A/S)^{3/2} \]

4. Electromagnetic protection technology based on wireless sensor

The location of wireless sensor is usually in complex electromagnetic environment, and the shielding performance of its electronic circuit system directly affects its immunity characteristics. Here we propose a technology to improve the electromagnetic immunity to coal mine instruments with wireless sensor.

4.1 Construction of electromagnetic shielding model

The shielding structure of wireless sensor is quite different according to its function and size. The shielding structure of single function and small size usually do not require openings and seams, while for complex functions and large sizes, openings and slots are needed. In this paper, we consider the larger size of slotted structures with openings. An electromagnetic shielding cavity model and its coordinate system are constructed, as shown in Figure 1.
The thickness of shielding cavity made of aluminium is 0.2cm, and its length, height and width are $X = 25\text{cm}$, $Y = 25\text{cm}$ and $Z = 50\text{cm}$, respectively. Taking the space radiation field of discharge waveform as plane wave, it is incident on an open hole, a rectangular hole is opened on the surface of the cavity opposite the incident wave. The electric field is perpendicular to the long side of a rectangular opening, that is, $+Y$ direction. The finite-difference time-domain method is used to analyze the model. Grid partitioning is as: $\Delta x=\Delta y=\Delta z=1\text{cm}$; upper limit frequency $f=3\text{GHz}$.

The electromagnetic interference signal is selected as the partial discharge waveform with 500 ns time length, as shown in Figure 2.

![Electromagnetic shielding cavity model](image1)

Figure 1. Electromagnetic shielding cavity model

We use the method of modelling and simulation to verify the different effects of electromagnetic interference on wireless sensor communication without shielding case and with shielding case. The simulation results showed that the shielding shell has a significant effect on improving the anti-interference ability of wireless sensor.

4.2 Design of hole and joint structure

We design rectangular holes, T-shaped holes, cross holes and square holes respectively on the simulation model to make their area equal, as shown in Figure 3.
Figure 3. Openings of four shapes

The electromagnetic interference coupled into the cavity oscillates back and forth, and the energy attenuation is slow, so it produces a longer duration of oscillation. We only intercept part of the time interval to analyze the coupling field of electromagnetic disturbance. The smaller part of radiated electromagnetic interference can be coupled into the shielding chamber through four different forms of openings, and then it oscillates at high frequencies. The simulation waveform of the four different forms of openings is shown in Figure 4.

Figure 4. Simulation waveform of the four different forms of openings
4.3 Design of slot array spacing
Three slots with the same spacing and size (15cm×2cm) are opened on one side of the rectangular shielding cavity. The long edge of the slot is set in the direction of the X-axis. The influence of gap spacing on the coupled field in shielding chamber was studied by modelling when the gap spacing \( d \) was set to 1 cm, 2 cm, 3 cm and 4 cm, respectively.

The time domain waveform of coupled field is obtained by modelling and simulation. We found that the field strength of the coupled field in the cavity decreases with the increase of the gap array spacing on the shield, But the degree of influence is not obvious, as shown in Figure 5.

![Simulation waveform of the four different slot array spacing](image)

(a) Slot array spacing as 1cm                                      (b) Slot array spacing as 2cm
(c) Slot array spacing as 3cm                                   (d) Slot array spacing as 4cm

Figure 5. Simulation waveform of the four different slot array spacing

5. Conclusion
In this paper, the electromagnetic immunity characteristics of wireless sensor are studied. And then, we focus on the construction of electromagnetic shielding model for coal mine instruments based on wireless sensor, and propose the design method of hole and joint structure and slot array spacing. We study the characteristics of different shielding structures, by analysing the factors that affect the immunity performance of wireless sensor. Finally, we come to the following conclusion:

(1) Comparing the openings of different shapes, the electromagnetic interference coupling field strength in the shielding cavity is the largest in the case of rectangular opening, while the minimum coupling field strength is the case where the opening is square. A shielded body with a symmetrical form of open-cell structure, such as circular and positive, generally has higher shielding effectiveness.

(2) As the spacing of the gaps on the shield increases, the field strength of the coupled field in the cavity will decrease, but the degree of impact is not obvious. This shows that increasing the gap spacing of the shielding cavity can slightly improve the shielding effectiveness.
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