Hydraulic and Civil Engineering Technology VIII
M. Yang et al. (Eds.)

doi:10.3233/ATDE230866

Research on Intrinsically Safe Power Supply to Large Penetration Distance Radio Wave Penetration Transmitter in Mine

Yunbo LI [a,1] and Hongling PENG [b]
[a] *Guang'an Vocational & Technical College, China*
[b] *China Coal Science and Engineering Group Chongqing Research Institute Co., Ltd, China*

Abstract. Radio wave penetration is currently one of the most effective technical means for detecting geological anomalies. With the increase in width of the working surface, the penetration distance of commercially available detection instruments cannot meet the needs of detecting the working surface over 200m. For obtaining a greater penetration distance, it is a difficult task for radio wave transmission technology to further improve the transmitting efficiency and transmit electromagnetic wave signals with stable amplitude. In this paper, the intrinsically safe power supply protection technology, design of intrinsically safe power supply circuit, and protection and testing of intrinsically safe power supply are studied according to explosion-proof standard requirements in GB/T 3836.4. The results show that the intrinsically safe power supply protection circuit is effective in providing protection, with the pulse energy lower than the specified value; therefore, the intrinsically safe power supply meet the explosion-proof requirements stated in the national explosion-proof standard.

Keywords. Radio wave penetration, large penetration distance transmission, intrinsically safe power supply

1. Introduction

The function of the radio wave transmitter is to gradually amplify the fixed-frequency electromagnetic signal by an amplifier, make it reach the resonance point on the oscillation circuit, and then radiate it from the antenna to the coal seam medium [1, 2]. After over 30 years of research, radio wave transmitters have been updated based on the advancement of electronic technologies and development of high-performance electronic devices towards the direction of superior explosion-proof performance, wide bandwidth, high accuracy, large penetration distance, and small volume [3-6]. Currently, the four most widely used radio wave transmitters in China’s coal mines include WKT-E, WKT-0.03, YDT88 and YD175, which are developed by Chongqing Research Institute of China Coal Technology and Engineering Group, Institute of

[1] Yunbo LI, Corresponding author, Guang'an Vocational & Technical College, China; E-mail: 40666345@qq.com.

Geophysical and Geochemical Exploration, Chinese Academy of Geological Sciences, Huahong Technology, and Xi'an Research Institute of China Coal Technology and Engineering Group, respectively. The four instruments have their own advantages and disadvantages in terms of performance, with basically the same structure and mode of operation; they are superior to earlier pit penetration meters in the aspects of penetration distance, detection accuracy and explosion-proof performance, and support multiple operating frequencies. All the four instruments can effectively determine the anomalous areas on the comprehensive mining surface within the penetration distance of 200m [7-10].

2. Intrinsically Safe Power Supply Protection Technology

2.1. Intrinsically Safe Power Supply Explosion-proof Technical Requirements

The radio wave transmitter developed in this paper is a portable intrinsically safe device powered by a battery pack, which, however, is the non-intrinsically safe power supply that should be converted to intrinsically safe output by protection circuits through stabilizing the voltage, limiting the current, and cutting off the current, so as to ensure that the intrinsically safe devices in mines would not detonate gas mixtures by the thermal effect generated during normal operation or electrical sparks generated under fault conditions. Intrinsically safe power supply is an important power supply for all types of intrinsically safe devices in mines; therefore, when designing the intrinsically safe power supply, the appropriate protection mode and intrinsically safe parameters should be selected based on different load requirements for instruments, to ensure stable and safe operation, and maintain high efficiency of the instruments.

According to the requirements of GB/T 3836.4 for the charging part of the battery pack, the charging protection circuit should be designed for the battery pack, to avoid explosion caused by short circuit or reverse charging. The design of intrinsically safe power supply must adopt two-level protection mode. The battery pack output is connected to BUCK-BOOST module, to stabilize the output voltage at the rated value, and then the protection circuit is used to provide over-current and short-circuit protection for the upper level output. The corresponding charging protection circuit and two-level protection circuit are designed as required, to make the battery pack power supply intrinsically safe. The basic design diagram is shown in figure 1.

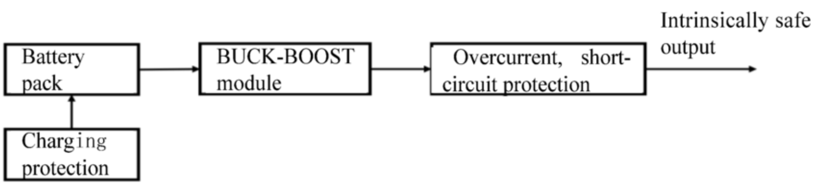

Figure1. Intrinsically safe power supply design diagram.

2.2. Over-current Protection Technology

The core of over-current and short-circuit protection technology for intrinsically safe power supply is to accurately detect the overload current, and limit the current within the range of the specified value. The main protection patterns include current limiting resistance protection, current blocking protection and current limiting protection. At present, current limiting and current blocking protection circuit are most widely used in the design of intrinsically safe power supply.

2.2.1. Current Limiting Resistance Protection

The traditional current limiting manner is to connect high-power current limiting resistance in series in the power supply circuit. As stipulated in GB/T 3836.4, only the membrane type and wire-wound type of current limiting resistance can be used. In addition, under normal operating and specified fault conditions, it should be able to withstand at least 1.5 times the maximum voltage or 1.5 times the maximum power. When the output terminal is short-circuited, it can limit the short-circuit current within the range of rated current, and the power supply can recover after resolving the fault. However, the large size of the high power current limiting resistor and the heat generated by short circuit would increase the internal resistance of intrinsically safe circuit, making the power supply output inefficient. The principle and power characteristic curve are shown in figure 2.

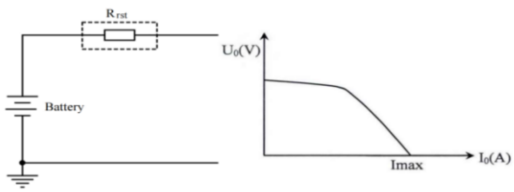

Figure 2. Current limiting resistance protection circuit and power characteristic curve diagram.

2.2.2. Current Limiting Protection

Current limiting protection circuit generally uses the integrated circuit solution with current detecting resistor, regulation transistor, field-effect transistor and current limiting linear regulator. The figure 3 characteristic curve shows that when there is a fault current at the load side, the regulation transistor, field-effect transistor and linear voltage regulator will act simultaneously, rapidly lowering the output voltage and current, and maintaining them within a small range. If the load-side fault is not resolved, the current limiting protection circuit will be in the protection state for a long time, and at this moment, the field-effect transistor, in the non-saturated region, will continue to generate heat; the linear voltage regulator is also subject to temperature rise, making the current limiting value unstable. Therefore, it is hard to set and regulate the intrinsically safe parameters for the current limiting protection circuit. The current limiting protection circuit is simple to design, and will slowly restore power supply after resolving the fault.

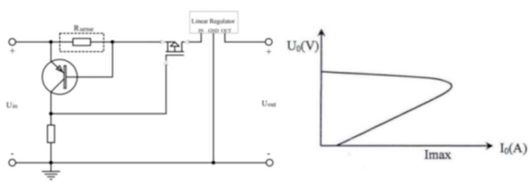

Figure 3. Current blocking protection circuit and power characteristic curve diagram.

3. Design of Intrinsically Safe Power Supply Circuit

3.1. Intrinsically Safe Power Supply Design Scheme

In this paper, a new intrinsically safe protection circuit based on current detecting chips and monostable delay circuit is proposed, and through changing the parameters in the circuit, it can flexibly design the protection current and protection this, meeting different load requirements of the instrument. MAX471 current detection chip is used as the core to determine the design scheme of the intrinsically safe circuit. This circuit is mainly composed of current detection, voltage comparison, monostable delay and switching output modules, and it can be used to regulate the protection current and slow start time. The design of intrinsically safe protection circuit can be adapted to different circuit modules according to different loads. The 16.8V lithium-ion battery is selected to power the device; the intrinsically safe power supply (UO1 = 12V and IO1 = 1.5A) is used to provide power supply for analog power amplifier circuit; and the intrinsically safe power supply (UO2 = 5V and IO2 = 1.3A) is used to provide power supply for the digital circuit. The two power supply protection circuits are designed with basically the same design principle, and the functional block diagram of the intrinsically safe power supply is shown in figure 4.

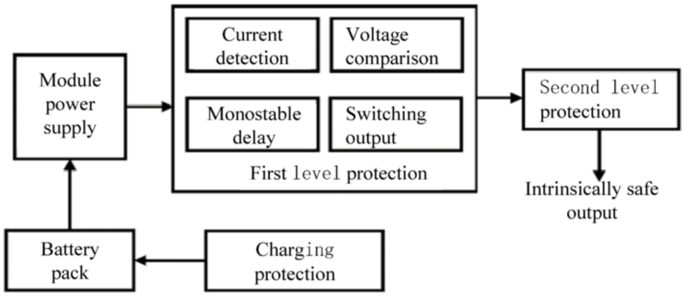

Figure 4. Power supply intrinsic safety protection circuit diagram.

3.2. Protection Circuit Component Selection

Battery pack: The power supply consists of four 4Ah lithium-ion manganate batteries in series, with the nominal voltage of 14.8V, and capacity of 4Ah. According to MT/T1051-2007 Lithium-ion batteries for cap lamp, the purchased batteries pass the following seven tests conducted by the statutory testing institution: Battery core crush test, battery core thermal shock test, battery core overcharging test, battery core forced discharging test, battery core short circuit test, and battery core pin-prick test; the relevant test qualification reports have also been issued. The battery pack also meets the requirements for batteries (primary batteries and accumulators) and battery packs in 7.4 of GB/T 3836.4, with the functions of preventing over-charging, over-discharging and over-current short-circuiting of the battery packs. In the case of any of the above malfunctions, the battery pack should not burn or explode.

Module power supply: It refers to URB2412LD-30WR and RB2405YMD- 10WR3 DC/DC module power supply provided by MORNSUN. URB2412LD-30WR3 module power supply, with the output power of 30W, the nominal input voltage of 9-36V, and input under-voltage protection voltage of 5.5V, can output the voltage of 12V and the maximum current of 2.5A, and reach an efficiency of up to 90%; VRB2405YMD-10WR3 DC/DC module power supply, with the output power of 10W, the nominal input voltage of 18-36V, and input under-voltage protection voltage of 12V, can output the voltage of 5V and the maximum current of 2A, and reach an efficiency of up to 83%. The two power supply modules can convert and regulate the 16.8V voltage from the battery pack, and then respectively output the voltage of 12V and 5V to the intrinsically safe circuit; meanwhile, both of the two modules have over-voltage, over-current and short-circuit protection functions at the output terminal. This is the initial protection for the intrinsically safe circuit.

Current detection: It is conducted with MAX471 chip, which is a bi-directional high-side current detection amplifier, with the internal current detection resistance Rsense of 35mΩ, and power consumption current of lower than 100μA. MAX471 normally runs within the voltage range of 3V-36V, and it can detect the load current of up to ±3A, meeting the requirements of the circuit parameters; it can output the voltage signals proportional to the load current, with extremely fast output response rate, rising edge time of 4μs, high accuracy, and only 2% of the maximum output error.

Voltage comparison: The single channel high-speed voltage comparator LM311 is selected to compare the logic judgment part of the circuit; with the falling edge fast response time of 165ns, it can have a high output drive capability. In order to maintain the consistency of protection current of the intrinsically safe circuit, the micropower voltage reference diode LM385-1.2 is selected to provide the reference voltage of 1.2V, with a tolerance of no more than 1% over the permitted temperature range. The detection chip outputs a detection voltage signal and compares it with the reference voltage, and then outputs the logic level to the monostable delay circuit.

Monostable delay: The monostable delay circuit is a monostable multi-vibrator based on the NE555 timer, and it can regulate the execution time of over-current protection.

Switching output: The switching device selects the control enhanced P-channel field-effect transistor IRF7404, with the maximum drain-source voltage UDSS of -20V, and maximum operating current ID of -7.7A, fully meeting the setting requirements of the circuit parameters. RDS(on) of the field-effect transistor is 40mΩ, with a turn-off rate of 100ns only.

3.3. Design of the Two-stage Protection Circuit

The radio wave penetrometer is a safety device of Class “ib”; the intrinsically safe circuit must be protected in a two-stage mode, with which, even in the event of a specified Class 1 fault, the secondary protection circuit can still enable the power supply to conform to the intrinsically safe performance. Therefore, the intrinsically safe power supply should be designed with a two-stage over-voltage and over-current protection circuit.

3.3.1. Design of the Charging Protection and Switching Control Circuit

The function of the switching and charging protection circuit is to control the switching of power supply, battery charging protection and conversion of battery voltage. It mainly consists of the battery pack, switch, power supply module and field-effect transistor. The schematic diagram is shown in figure 5. The two diodes, D12 and D13, can prevent reverse charging. The circuit controls the output of the battery voltage by a switch and a P-channel field-effect transistor. When it is switched on, R26 and R27 divide the voltage, lowering the grid voltage UG, and making the gate source voltage UGS greater than the turn-on voltage, and connecting the MOS tube. The output battery voltage is decoupled and filtered by two capacitors, C29 and C18, and then output to DC/DC power supply module, which converts the battery voltage to 12 V for output to the back-end circuit. The power supply module can provide protection against under-voltage at the input terminal, and also provide short-circuit, over-voltage and over-current protection at the voltage output terminal.

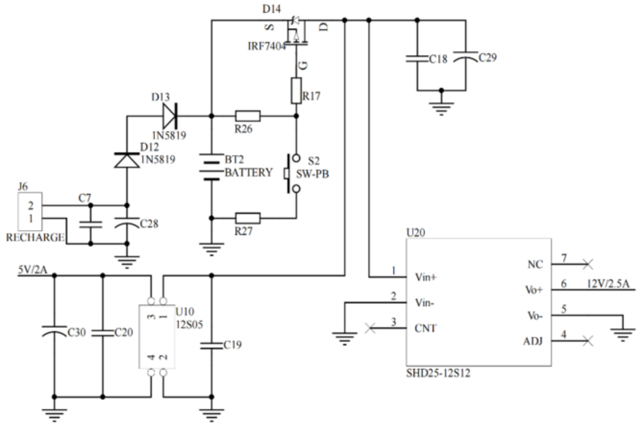

Figure 5. Schematic diagram of switching and charging protection circuit.

3.3.2. Design of Over-current Detection and Delay Protection Circuit

The first level protection circuit is the first-level protection of output back-end of the power supply module, which mainly consists of the current detection chip, voltage comparator, 555 timer, field-effect transistor and other related components. The principle of the first-level protection circuit is shown in figure 6, the 12V voltage of module power supply is filtered by the capacitor and input to MAX471; the OUT terminal needs to be grounded by a voltage gain setting resistor, for obtaining the output voltage signal. Intrinsically safe circuit protection current is about 1.5A, and the full scale voltage at the OUT terminal is required to be 1.2V; with Equation (3.1), the resistance of R18 can be calculated to be 1,600Ω. (In the case of a 5V output circuit, the protection current is 1.3A, and the resistance of R18 can be calculated to be 1,850Ω). The voltage signal VOUT1 is filtered by E1 and output to the inverting input of the voltage comparator LM311, and compared with the reference voltage of 1.2 V connected to the positive input. In the case of overcurrent, the comparator output jumps to a low level, which is lower than the threshold voltage triggering the timer, at this moment, the falling edge would trigger the monostable delay circuit to output a transient high level signal, breaking through the triode Q1, and making the gate source voltage |UGS| of PMOS tube lower than the turn-on voltage UGS(th); then Q2 turns off, truncating the voltage output. The duration of the unstable process of the monostable delay circuit is determined by the parameters of resistance R3 and capacitance C2. The time delayed as set for this protection circuit is about 0.33s, and the values of R3 and C2 can be changed as required to customize the protection time. If the circuit fault is removed after a number of protection cycles by time delay triggered by overcurrent, the power supply will be automatically restored. The fault current may be cut off about 5.465μs later. The protection cycle of the intrinsically safe protection circuit is the sum of the fault response time and the post-fault self-recovery time. In the event of a fault, the fault current pulse is only about one ten-thousandth of the entire protection cycle, which may only consume preciously little battery capacity. This circuit can provide the functions of precise current detection, voltage comparison, trigger off, and delayed self-recovery. The circuit is featured in high integration, reliable performance, high output efficiency and rapid protection action.

The schematic diagram of the second-level intrinsically safe protection circuit is essentially the same as that of the first-level protection circuit. The output voltage from the first-level protection circuit is input from J1 to the current detection chip of the second-level protection circuit; after current detection by MAX471, the signal is output to the voltage comparator, and the voltage signal is sent to the monostable delay circuit, thus temporarily controlling the cut-off of the second-level field-effect transistor, and truncating the output voltage. The intrinsically safe protection circuits at two levels are integrated in series, and the two external gain resistors, R18 and R19, are used to set the protection current at the two levels, for applying to circuit modules with different load requirements.

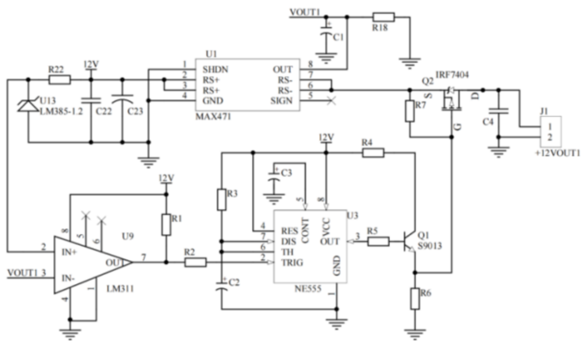

Figure 6. Schematic diagram of the first level intrinsic safety protection circuit.

4. Intrinsically Safe Power Supply Protection Testing

The battery pack used in the transmitter is composed of four 4Ah lithium manganate batteries connected in series. According to MT/T1051-2007 Lithium-ion batteries for mining lamps, the battery pack has passed the relevant tests conducted by the statutory testing institutes. The KC8512C DC electronic load is used to test the discharge of the battery pack, and the results show that the power supply duration is longer than 4 hours, with the maximum duration of 6 hours, basically meeting the use demand of instruments. The power supply protection board is divided into 12V/1.5A and 5V/1.3A for two levels of intrinsically safe protection outputs, and it is only required to test the final output of each intrinsically safe output. The power supply protection board is mainly tested in two aspects as below:

4.1. Cut-off Protection Test

The voltage of the voltage-stabilized power supply is adjusted to 16.8V, and connected to the input terminal of the power supply protection board; the KC8512C+ DC electronic load is successively connected to 12V/1.5A and 5V/1.3A outputs of the board for testing. The resistance of the electronic load is lowered from 50Ω, and the current and voltage values of the electronic load are read point by point. The test protocol is shown in figure 7.

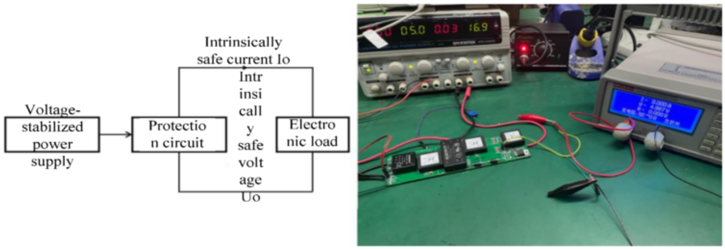

Figure 7. Intrinsically safe power supply output test.

Through recording and sorting the values of voltage and current of the two intrinsically safe protection circuits under each load resistance, the law shown in figure 8 can be determined. As shown in figure 9, the output voltages of the 12V/1.5A and 5V/1.3A intrinsically safe protection circuits remain relatively stable as the load resistance decreases; however, when the load resistance is too small and the output current exceeds the specified intrinsically safe current, the two intrinsically safe protection circuits can cut off the power output, thus protecting the circuit.

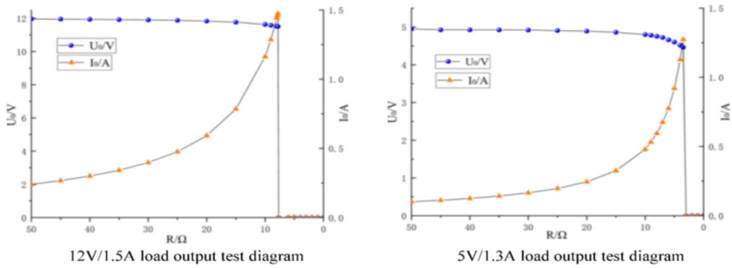

Figure 8. Intrinsically safe power load output test.

4.2. Cut-off Protection Output Pulse Test

The oscilloscope is connected in series to the output load circuits of the two intrinsically safe protection circuits, and set as the falling edge capture mode; then the load resistance is gradually reduced, until the intrinsically safe protection circuit triggers the cut-off protection, and the oscilloscope captures the falling edge pulse. The test obtains the circuit cut-off protection pulse output by 12V/1.5A and 5V/1.3A intrinsically safe protection circuits, as shown in figure 9.

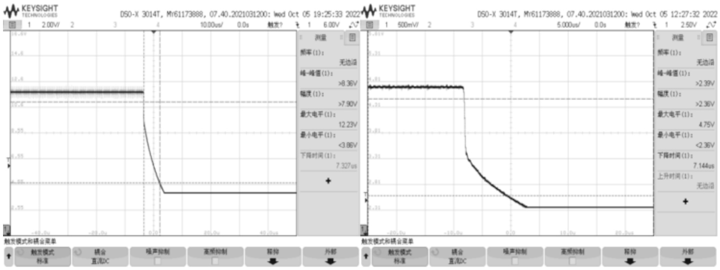

Figure 9. Intrinsically safe protection circuit cut-off protection pulse test.

5. Conclusion

(1) The short-circuit output pulses of 12V/1.5A and 5V/1.3A intrinsically safe protection circuits designed in this paper are 7.327μs and 7.144μs, respectively.

(2) The short-circuit pulse energy of the two intrinsically safe protection circuits is 114.3μJ and 46.4μJ, respectively.

(3) According to the national explosion-proof standard, the minimum ignition energy of Ex ibI Mb equipment is specified as 160μJ; the pulse energy of both circuits is lower than the specified value, which means that the intrinsically safe power supply designed in this scheme meets the explosion-proof requirements.

References

[1] Sun JP, Peng M, Pan T, et al. Research on the safety threshold of radio wave explosion-proof. Journal of Mine Automation. 2023; 49(2): 5.
[2] Yan GC, Xian PH, Luo H. Study on fine electromagnetic wave CT detection with large-aperture and high-resolution. Mining Safety & Environmental Protection. 2017; 44(05): 72-75.
[3] Zhang Z. Study on explore frequency of large penetration distance in mine shaft. China Energy and Environmental Protection. 2017; (03): 25-28+66.
[4] Liu XM. Research on the propagation law of medium and high frequency electromagnetic waves in coal rock media. China University of Mining and Technology, 2013.
[5] Wu YQ. Development of downhole explosion-proof long distance advanced detection technology and instruments, 2010.
[6] Jia Q. Development of the transceiver for inter-hole radio wave penetration system in mine. China Coal Research Institute, 2017.
[7] Wu CC. Research and design of radio wave perspective system in mine. Fuzhou University, 2016.
[8] Zhang J. Research on radio electromagnetic wave perspective detection method through borehole-roadway in mine. Journal of China Coal Society. 2020; 45(08): 2856-2864.
[9] Zhang J. Design and application of multi frequency radio wave perspective instrument. Automation & Instrumentation. 2022; (09): 248-250+256.
[10] Wu QY. Research on underground electromagnetic wave detection and application. Central South University, 2002.