The Analysis and Design of High-power Intrinsic Safe Forward Converter Based on Power-i Technology

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Abstract. The existing anti explosion measures and the intrinsic safety evaluation methods have become the bottleneck factors that restrict the further improvement of the output power of the native security. Therefore, This article is based on the latest anti explosion standard, the principle of realizing high power output by Power-i technology to suppress the spark discharge energy of switching power supply is analyzed, as well as the composition of the power supply system and its evaluation method. The forward converter is selected as the topology of the high-power local security power supply, according to the technical index of Power-i system, the circuit structure of high power intrinsic safe converter is put forward, and the double protection circuit of overcurrent, overvoltage and short circuit when the output is short circuited and open fault is designed. It has been tested that the output 24V/2A high power intrinsically safe positive converter based on Power-i standard can meet the requirements of explosion protection under type I environment. The experimental results verify the intrinsic safety of the designed high power intrinsic positive shock converter, and reflect the correctness of the theoretical analysis and design method.

1. Introduction

The With the development of coal mine Internet of Things technology, the number of underground safety inspection and monitoring equipment such as sensors and controllers has increased greatly, which has increased the requirements for the output power of intrinsically safe power supplies[1]. Most of the intrinsically safe switching converters currently used in hazardous locations are only a few dozen watts, and there is still much room for improvement.

The earliest intrinsically safe power supply in China is mainly composed of batteries. The current limiting resistor and the Zener diode are used at the output to form an overcurrent and overvoltage protection circuit, and its output power is small[2]. In the middle and late 1970s, scholars began to study series intrinsically safe power supplies (consisting of voltage regulator tubes and transistors) composed of electronic circuits and adding current limiting and voltage limiting links at the output end to improve intrinsic safety measures[3-4]. In the early 1990s, the explosion-proof power supply circuit mainly composed of the power frequency step-down transformer, rectifier circuit, current limiting resistor, three-terminal voltage regulator and output overvoltage and overcurrent protection circuit. In order to solve the self-recovery problem, a thyristor-protected intrinsically safe power supply automatic recovery device is proposed, but a series current detecting resistor is required to limit the output power[5-7]. In the late 1990s, a growing number of research on linear power supplies began to
turn to the study of intrinsically safe switching power supplies[6-10], which can improve the efficiency of the whole machine.

In the early days, scholars paid more attention to the influencing factors of minimum ignition energy, drawing the ignition curve, the design of circuit component parameters and its influence on the intrinsic safety performance of the circuit[11]. In recent years, the experts of the domestic and foreign have begun to study multiple protection circuits for intrinsically safe power supplies. By detecting the signal at the moment of circuit failure, the spark energy source is quickly cut off to prevent ignition and explosion, thereby improving the output power of the intrinsically safe power supply. The experimental results show that the perspective of reducing spark discharge time can be considered in order to suppress the spark energy released during circuit failure to improve the effective output power of the intrinsically safe switching converter. Based on the latest power-i technology, a scheme and circuit structure are proposed to improve its output power on the basis of its theoretical research.

2. Intrinsically safe explosion-proof power principle

2.1. Traditional intrinsically safe power supply limits the principle of spark energy

The voltage regulator or overvoltage protection circuit is usually used in the circuit to limit the voltage, and the current limiting resistor or current limiting protection current limiting resistor or a current limiting protection circuit use to limit the current. A circuit with dual protection for auxiliary protection circuits are shown in Figure 1. In the case of a conventional intrinsically safe circuit, the power supply supplies energy to the spark gap for the entire duration of the spark, suppressing spark energy only by limiting the maximum current and maximum voltage.

![Figure 1. Schematic diagram of the dual protection circuit with auxiliary protection circuit](image1)

2.2. Switch intrinsically safe power supply limits the principle of spark energy

When the switching converter detects an output short circuit during normal operation, the protection circuit cut off the switch tube. Taking forward converter as an example as shown in Figure 2, the energy of the input power source is completely cut off, and the energy composition at the output short circuit is mainly derived from the energy of the inductor and capacitor. When designing parameters such as inductance and capacitance, considering that the maximum discharge energy of the inductance and capacitance should not greater than the minimum ignition energy, the output power of the intrinsically safe power supply are still limited.

![Figure 2. Block diagram of the structure of the intrinsically forward converter](image2)

2.3. Switch intrinsically safe power supply limits the principle of spark energy

The protection method of Power-i technology is identifies the fault of the electrical system through the detection circuit. The power supply and the output circuit are quickly disconnected when the fault...
signal is detected and ensure that the fault spark energy does not detonate dangerous substances. The method can simultaneously cut off the energy stored by the power source, the inductor, and the capacitor, and quickly suppress the spark ignition energy by detecting the current change rate, so that the output power of the intrinsically safe power source with the same parameter can be greatly improved. The block diagram based on the power-i protection circuit is shown in Figure 3.

Figure 3. Is based on the power-i protection circuit block diagram

3. Design of high power intrinsically safe converter based on power-i technology

3.1. Design of main parameters
Intrinsically safe switching power supplies have low output power, and at this power level, a simple forward or flyback converter can be considered. Since the peak value of the output voltage and the inductor current of the forward converter is smaller than that of the flyback converter. Therefore, the forward converter topology is used to realize the intrinsically safe power output in this paper. In order to improve the output power of the intrinsically safe converter, it can be realized by connecting the switch tube in series in the output loop of the converter. When the fault occurs, the switch tube is turned off to limit the spark discharge time and thereby reduce the fault spark energy. A high-power intrinsically forward converter circuit structure is designed as shown in Figure 4.

Figure 4. High-power intrinsically safe converter circuit structure
Firstly, the value of the inductor \( L \) should be considered so that it operates in CCM mode to reduce the ripple voltage. For the design of the forward converter energy storage inductor \( L \), the CCM and DCM critical inductance \( L_{\text{min}} \) corresponding to the maximum input voltage and the minimum load resistance \( R_{L,\text{min}} \) can be used as the lower limit of the designed inductance value. That is:

\[
L_{\text{min}} = \frac{R_{L,\text{min}} (V_{\text{in},\text{max}}/n - V_i)}{2 f V_{\text{in},\text{max}}/n}
\]  

(1)

From the perspective of optimization design, the actual inductance \( L \) should be slightly larger than the minimum inductance value \( L_{\text{min}} \).

3.2. Selection of output filter capacitor \( C \)
The output filter capacitor can be designed according to specification of the ripple voltage. It is assumed that the value of the inductor satisfies \( L \geq L_{\text{min}} \), and the maximum output ripple of the corresponding dynamic range is the maximum output ripple of the CCM operating mode.

\[
V_{\text{PP, max}} = V_{\text{PP, min}} \frac{V_i (1 - d)}{8 L C f^2} = \frac{V_i (1 - d)}{8 L C f^2}
\]  

(2)
From equation (2), the required minimum output filter capacitance \( C_{\text{min}} \) is

\[
C_{\text{min}} = \frac{V_c(1-d)}{8LV_{\text{pp, max}} f^2} = \frac{V_c}{8LV_{\text{pp, max}} f^2}
\]  
(3)

In practice, considering the parasitic resistance of the electrolytic capacitor and other stray parameters in the circuit, it is necessary to select a filter capacitor larger than the minimum capacitance value to meet the requirements of the output ripple voltage, so the design value of the actual filter capacitor is

\[
C_{\text{min}} = \lambda C_{\text{min}}' = \frac{V_c(1-d)}{8LV_{\text{pp, max}} f^2}
\]  
(4)

Where \( \lambda \) is the margin factor, generally takes 2~4.

The withstand voltage \( V_c \) of the output filter capacitor is

\[
V_c = \lambda V_o
\]  
(5)

In the formula, \( \lambda 1 \) is the margin coefficient, which is generally 1.3~3.

According to equations (1) and (3), the maximum output ripple voltage is related to the values of \( L \) and \( C \). The minimum capacitance \( C_{\text{min}} \) is a function of \( L \) and is inversely proportional to the inductance \( L \). Therefore, the larger of the \( L \), the smaller of the \( C_{\text{min}} \).

3.3. Design of multiple protection circuits based on power-i technology

A schematic diagram of the multi-protection circuit based on power-i technology is proposed as shown in Figure 5. The monostable flip-flop and the driving resistors \( R_1, R_2 \), the transistors VT1, VT2, and the diode D1 form a logic module whose main function is respond to the output signal of the detecting module, thereby controlling the turning on and off of the S1 tube (consisting of PMOS). When the monostable flip-flop input is high, its output is low, the transistor VT2 is turned on, and the parasitic capacitance \( C_1 \) of the MOS transistor S1 charged by D1 and VT2. When the \( C_1 \) voltage exceeds the threshold voltage of the MOS transistor, the MOS transistor S1 is turned on, \( V_{o1} \) is directly connected to the load \( R_L \) through S1, and the power supply works in Power-i mode. When the monostable flip-flop input is low, its output is high, and the transistor VT2 is turned off. Then the parasitic capacitance \( C_2 \) of the MOS transistor S1 is discharged through the resistor \( R_1 \) and the transistor VT1, and the \( C_2 \) voltage rapidly drops below the threshold voltage, S1 Turned off, the power enters the shutdown mode.

![Schematic diagram of multiple protection circuit based on power-i technology](image)

Figure 5. Schematic diagram of multiple protection circuit based on power-i technology

4. Introduction of power-i performance test method for high power intrinsically safe converter

4.1. Response time and evaluation method

The components of general measurement equipment mainly include:
Connect the power supply to the universal test equipment shown in Figure 6. The positive pole of the power supply output connects to the 2 pins shown in Figure 6, and the power supply output ground connects to the 1 pin. Turn the switch $S_2$ of the universal test equipment to the OFF position, and adjust the $S_1$ to the position B. Start the pulse generator after the power supply works normally, and capture the voltage and current signals at the output through the oscilloscope.

4.2. Transient pulse experimental method

The Power-i source needs to verify the response capability of the fault signal at the moment of starting under different loads through the transient pulse experiment. The basic layout of the transient pulse test is shown in Figure 7. The Power-i source transient pulse test Proceed as follows:

- When the start button is pressed, the system generates a positive pulse to make the switches ES$_1$ and ES$_2$ turn on, and causes the Power-i source to connect with the maximum load. When the current value is 25%, 50%, 75%, and 100% of the maximum output current $I_0$, the reference voltage $V_{\text{variable-reference}}$ in Figure 7 is adjusted to cause the voltage comparator to be triggered. Press the start button to verify that the designed Power-i source responds and shuts down quickly, check the output current change with an oscilloscope for this verification.

5. Experimental verification

In order to verify the above theoretical analysis, a 24V/2A experimental prototype was produced as shown in Figure 8. The experimental parameters are shown in Table 1.

| parameter | Input voltage ($V_i$) | Output ($V_o$) | Transformer ratio ($n$) | Switch Frequency ($f$) | Inductance ($L$) | Capacitance ($C$) |
|-----------|-----------------------|---------------|-------------------------|------------------------|-----------------|------------------|
| Setting value | AC220V | 24V/2A | 4 | 150kHz | 50uH | 5uF |
5.1. Response time and evaluation coefficient measurement results

After the short-circuit fault occurs, the voltage and current at the output of the power supply respond to the action, and the response time test result is shown in Figure 9. It can be seen that the response time of the designed power supply is 1 us.

\[ AF_{power} = 20 \log \frac{2.32}{1.24} = 5.44 \]  \hspace{1cm} (6)

5.2. Transient pulse test results

When the load is 25%, 50%, 75%, and 100% of the rated value, the designed Power i source is subjected to the transient pulse test according to the above steps. The output current waveforms measured under different load conditions are shown in Figures 11, 12, 13, and 14. According to the
waveforms, it can be seen that the output current of the power supply drops to zero within 1us, indicating that the designed high-power intrinsically forward converter can make a quick response for transient pulses under different load conditions.

**Figure 11.** Current response waveform when the load is rated load

**Figure 12.** Current response waveform when the load is 75% of the rated load

**Figure 13.** Current response waveform when the load is 50% of the rated load

**Figure 14.** Current response waveform when the load is 25% of the rated load

5.3. *Transient pulse test results*
The simulation was carried out under the environment of a methane concentration of 8.3%. The converter with this parameter tested under the specified total of 3200 experimental conditions, and no explosion occurred. The experimental results show that the designed high-power intrinsically forward converter meets the intrinsic safety performance index.

6. Conclusion
The principle of the Power-i technology suppresses spark energy to realize high-power output and and evaluation methods and system composition of intrinsically safe power is analyzed in the paper, which lays the theoretical foundation for improving the output power of intrinsically safe power. Intrinsically safe power used in coal mine environments are divided into primary and secondary intrinsically safe power supplies. Primary intrinsically safe power supply is usually explosion-proof and intrinsically safe, which is characterized by large output power and multiple protection circuits. The secondary intrinsically safe power supply is entirely intrinsically safe, with the characteristics of small size and high efficiency and internal intrinsic safety. A high-power output intrinsically forward converter combines Power-i technology is designed, not only with the characteristics of primary intrinsically safe high power and multi-protection, but also secondary intrinsically safe power with small size and high efficiency. The high power output of 48W enable Meet the requirements of the explosion-proof performance of the intrinsically safe power supply under the coal mine.

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References
[1] Ming He Important characteristics and realization ways of wisdom mine[J]. Industry and Mine Automation, 2018, 44(3):31-34.
[2] Mingkai Wang, Zhi Qu, Xiaoyang He, et al. Real time fault monitoring and diagnosis method for power grid monitoring and its application[C]. IEEE 2017 Energy Internet and Energy System Integration (EI2), Beijing, China, Sept 28-30, 2017, 1-6.
[3] Yao Hua, Kang Zhao A Mine Explosion-proof and Intrinsically Safe Online Uninterrupted Power Based on Lithium-ion Batteries[J]. Instrumentation Technology, 2015(7),50-53.
[4] Hyosung Kim. Arcing Characteristics on Low-Voltage DC Circuit Breakers[C]. 2013 15th European Conference on Power Electronics and Applicati-on(EPE), 2013, Lille: 1-7.
[5] S. Erik Reynolds, Mihail Bantic. FMECA for Intrinsically Safe Devices[C]. 2016 Annual Reliability and Maintainability Symposium, 2016, 1-5.
[6] Dubaniewicz, Thomas H. DuCarme, Joseph P. Internal short circuit and accelerated rate calorimetry tests of lithium-ion cells: Considerations for methane-air intrinsic safety and explosion proof/flameproof protection methods[J]. Journal of Loss Prevention in the Process Industries, 2016(9):575-584.
[7] Yahui Liu, Design of mine-used power supply with super wide input voltage range[J]. Industry and Mine Automation, 2016, 42(6):57-60.
[8] Liebers L. Dynamic arc recognition and termination intrinsic safety without the power limits[A]. SICE Annual Conference (SICE)[C]. 2011: 13-18.
[9] Qinghai Meng, Jingjii Wang, Dual Normal Distribution of Arc Discharge Time for Inductive Intrinsically Safe Circuits[J]. Transactions of China Electrotechnical Society, 2017, 32(2): 119-124.
[10] Yuting Wang, Shulin Liu, Yibo Ma, Research on Digitization of the Minimum Ignition Voltage Curve of Simple Capacitive Circuit[J]. Transactions of China Electrotechnical Society, 2014, 345-350.
[11] Shulin Liu, Qiang Cui, Yong Li, Buck converter output short circuit spark discharge energy and output intrinsic safety criterion[J]. Acta Physica Sinica 2013, 62(16): 430-439.