Design and Analysis of Intrinsic Safety Power of Wireless Sensor Network Node*

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Abstract
Wireless sensor networks may be used in the explosion environment, such as underground tunnel in coal mine. In order to assure that nodes work normally, the power of the node must be intrinsic safety. An intrinsic safety power of nodes of which consists of power supply and intrinsic safety protection is developed. The power supply mainly consists of current-mode controller chip LTC1871 which controls the output voltage, can attains a stable output voltage. The intrinsic safety protection consists of a dual-stage electric current monitor chip and a voltage regulator tube, which is combined with an over-voltage protection that was integrated in LTC1871 to make up intrinsic safety protection circuit of double over-voltage and over-current protection. The theory analysis and simulation tests on discharge process of intrinsic safety power are described. The results display that the discharge energy is the nonlinear proportion of the current, increases with the current increasing, and the maximum discharge energy is less than 0.02mJ; the discharge power is the linear proportion of current, increases with the current increasing, and the maximum discharge power is less than 60W, which is within the permissible intrinsic safety standard, therefore the power is the intrinsic safety.
Keywords: Wireless sensor networks, Node, Power, Intrinsic Safety, Double Protection

1. Introduction

The wireless sensor networks (WSNs) consists of spatially distributed autonomous devices using sensors to cooperatively monitor physical or environmental conditions, such as temperature, sound, vibration, pressure, motion or pollutants, at different locations[1-2]. The development of wireless sensor networks was originally motivated by military applications such as battlefield surveillance. However, wireless sensor networks were now used in many civilian application areas, including environment and habitat monitoring, healthcare applications, home automation, and traffic control[1,3].Wireless sensor networks were also used to monitor environment and trace the locations of miners[4-6] in coal mine. A node, which is the physical platform of the wireless sensor networks, is capable of performing the processing, gathering sensory information and communicating with other connected nodes. The typical architecture of a sensor node is shown in figure 1[7].

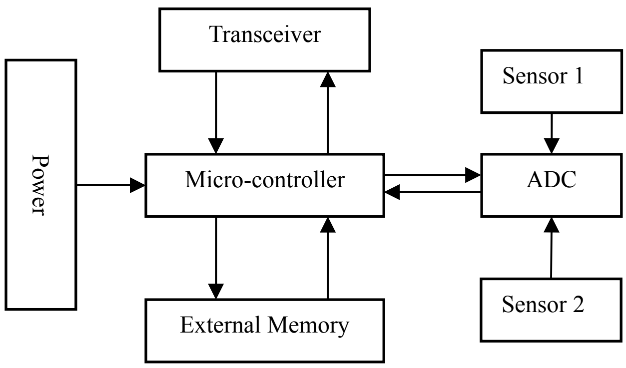

Fig.1. The typical architecture of a sensor node

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In a sensor node, power supplies energies to other parts of a node for the sensing, communication and data processing. Generally, batteries are the main source of power supply for nodes. Since there are combustible such as gas, coal dust in coal mine, which will easily cause severe fire and explosion, the discharge of energy of power should be restricted to be safe and reliable, namely intrinsic safety. Some wireless nodes were developed, such as Smart dust, Mica2, and et al., but they are not suit for the explosion environment like coal mine for non-intrinsic safety power. An intrinsic safety power of wireless sensor networks is designed, and it consists of power supply part and intrinsic safety protection part, which be double over-current and double voltage protection for the power.

The rest of the paper is organized as follows. Section 2 presented the structure of intrinsic safety power circuit. Section 3 describes the intrinsic safety power supply circuit. Section 4 describes the intrinsic safety power protection circuit. Section 5 analyzes the discharge properties of the intrinsic safety power. Section 6 concludes with a brief discussion.

2. Structure of intrinsic safety power circuit

The intrinsic safety power circuit consists of power supply circuit and intrinsic safety protection circuit, showed in figure 2.

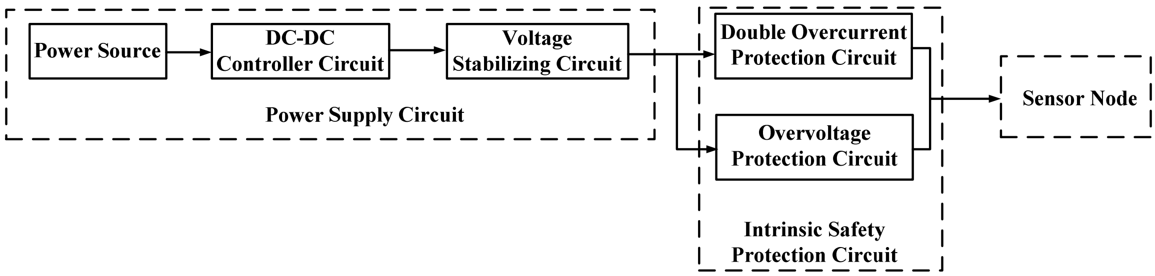

Fig.2. Structure of intrinsic safety power

The power of a node is supplied by two AA batteries of +3V. Power supply circuit mainly consists of DC-DC control circuit and voltage stabilizing circuit. The control chip of DC-DC control circuit is current-mode PWM control chip LTC1871 which can realize an over-voltage protection. The sustained, constant output voltage of power supply circuit can be attained by DC-DC control circuits, and a stable output voltage with small ripple voltage and ripple current value by voltage stabilizing circuit .The intrinsic safety protection circuit consists of the current monitor chip of two stage series and first order stabilivolt, which can realize double over-current protection and single over-voltage protection respectively.

3. Design of intrinsic safety power supply circuit

The power supply circuit is showed in figure 3.In figure 3, the left side circuit of the dashed line is DC-DC control circuit and the right side circuit is voltage stabilizing circuit.

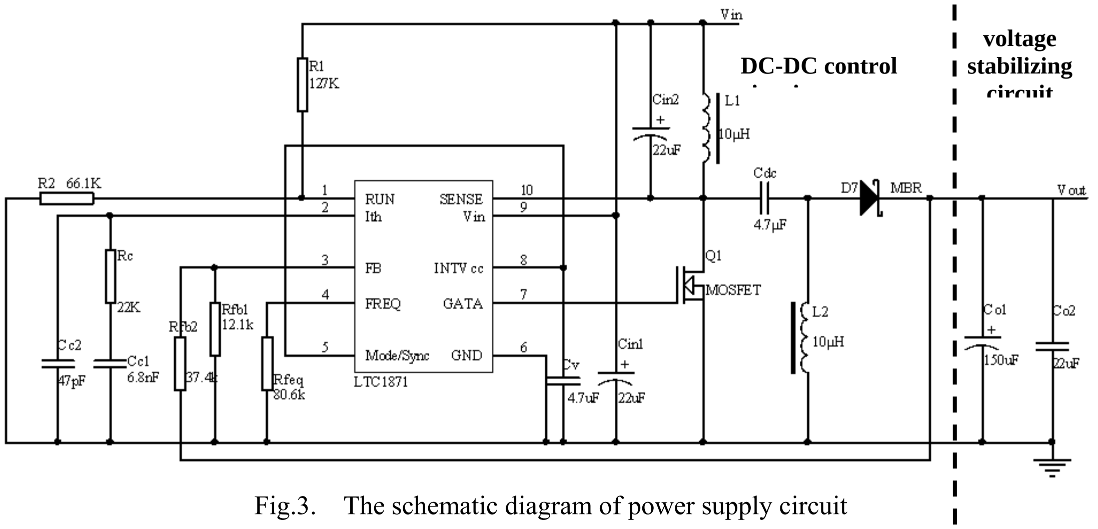

Fig.3. The schematic diagram of power supply circuit

3.1 Design of DC-DC control circuit

Firstly, it is necessary to design a varying voltage circuit to transform the power voltage(+3V) into the work voltage(+3.3V) of the single chip microcomputer, So DC-DC control circuit is charge of amplifying the input voltage and power of the power source. DC-DC control circuit consists of LTC1871 control chip, MOSFET, and some peripheral circuits.LTC1871 control chip is the main varying voltage components, and has the following characteristics:(1)a wide input voltage range, high duty cycle, small shutdown current;(2)over-voltage and over-current protection.

The startup of LTC1871 is controlled by the signal of RUN pin, which is the input port of internal comparator. When the voltage of RUN pin is below 1.248V, LTC1871 is being the small current shut down state, and doesn't start to work until the voltage of FB pin is 105% of the reference voltage. RUN pin is connected with the series circuit that is composed of *R1*, *R2*. When $U_{in}\cdot(\frac{R_2}{R_1+R_2})>1.248\,\text{V}$, where U_{in} is the minimum input voltage value of DC-DC control circuit, namely U_{in} >3.2V, LTC1871 starts to work, which can realize the under-voltage protection for the power. Reference [8] presented the maximum duty cycle, the variation value of current in inductance, the inductances of inductance, which are described the following:

Definition 1. The maximum duty cycle

$$D_{\max}=\frac{U_O+U_D}{U_O+U_D+U_{in\min}}, \tag{1}$$

where U_O is the output voltage value of DC-DC control circuit, U_D is the forward voltage drop of the diode D7 , *U*inmin is the minimum input voltage value of DC-DC control circuit.

Definition 2. The variation value of the current in inductance

$$\Delta I_L=X\times\frac{I_{O\max}}{1-D_{\max}}, \tag{2}$$

where X is the percentage of the ripple current, *Iomax* is the maximum output load current.

Definition 3. The inductances of *L1*、*L2* in DC-DC control circuit are equal, then *L1* and *L2* are denoted by *L*.

$$L=\frac{U_{in\min}}{\Delta I_L\times f}\times D_{\max}, \tag{3}$$

where *f* is the work frequency of LTC1871.

In DC-DC control circuit, X is 40%, $Iomax$ is 0.5A and the maximal output ripple voltage is 1%, U_{inmin} is 2.5V, f is 300kHz, U_O is 5V, U_D is 0.4V. So $D_{\max}$, $\triangle I_L$ and L are the following:

$$D_{\max}=\frac{U_O+U_D}{U_O+U_D+U_{in\min}}=\frac{5+0.4}{5+0.4+2.5}=0.684$$,

$$\Delta I_L=X\times\frac{I_{O(\max)}}{1-D_{\max}}=0.4\times\frac{0.5}{1-0.684}=0.633\text{A}$$,and

$$L=\frac{U_{in\min}}{\Delta I_L\times f}\times D_{\max}=\frac{2.5}{0.633\times 300\text{K}}\times 0.684=9\mu\text{H}$$ .Here, the inductances of L_1、$L_2$are 10μH for the encapsulation requirements of inductances.

3.2 Design of voltage stabilizing circuit

The voltage stabilizing function of the intrinsic safety power supply circuit is realized through DC-DC control circuit and voltage stabilizing circuit. The voltage stabilizing functions of DC-DC control circuit is realized by FB pin and SENSE pin. FB pin is a voltage feedback pin, and its feedback voltage is the output voltage of the resistance voltage divider. SENSE pin is a current feedback pin, and its sampling current is the on-current of MOSFET. LTC1871 controls the voltage of FB pin to 1.230V by regulating the pulse width. When the voltage of FB pin is higher than the reference voltage by 5%, or the current of SENSE pin is more than a rating value, LTC1871 controller turns off MOSFET to achieve over-voltage protection and over-current protection of the circuit. Voltage stabilizing circuit consists of two parallel capacitors Co1 and Co2.

4. Design of intrinsic safety protection circuit

4.1 Structure of intrinsic safety protection circuit

The basic requirement of intrinsic safety is to limit the power of circuit discharge spark which is realized through limiting the discharge current circuit and the discharge voltage and the discharge time. The intrinsic safety includes the internal intrinsic safety and output intrinsic safety.

The intrinsic safety protection circuit is shown in figure 4. Intrinsic safety protection circuit mainly consists of ZXCT1010 and the peripheral circuits. ZXCT1010 is an integrated chip which has

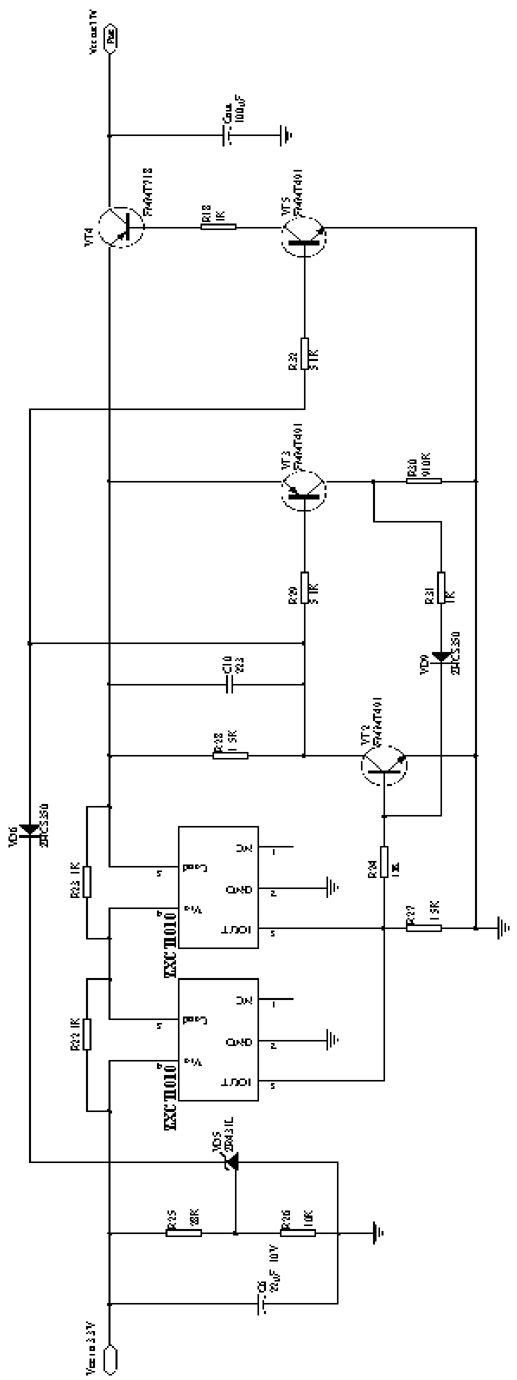

Fig.4. The schematic diagram of intrinsic safety protection circuit

over-current and over-voltage protection functions. Since DC-DC control circuit integrates one over-voltage protection, the intrinsic safety protection circuit only needs to realize the other over-voltage protection and double over-current protection, namely the releasing energy of the intrinsic safety protection circuit is less than 0.28mJ by choosing the reasonable parameters when there are failures in the circuit.

When the circuit works normally, triode VT2 and VT3 are off triode VT4 and VT5 are on, and VT4 outputs the voltage; when the circuit is over-current or over-voltage, the output current of the circuit increases, the external shunt resistor R27 converts the output current of the circuit to a certain output current after ZXCT1010 measures the end voltage of resistor R22,and then a reference voltage generated by the output resistor R24 makes triode VT2 and VT3 on, VT4 off. So, there are no current and voltage in the circuit outputs. That is to say that the circuit is protected.

In the intrinsic safety protection circuit, there are two series ZXCT1010 chip, which can assure that when a chip is short-circuit or damaging, the intrinsic safety protection circuit can work with another chip, which realizes the "double protection" functions of the intrinsic safety standard.

According to the above analysis, we can configure the impedance elements of the peripheral circuit to make the circuit be intrinsic safety.

4.2 Analysis on the internal intrinsic safety of the intrinsic safety protection circuit

Definition 4. The peak current of inductance for the internal intrinsic safety circuit [9,10]

$$I_{in}(peak)=(1+\frac{X}{2})\times\frac{I_{O\max}}{1-D_{\max}} \tag{4}$$

where the definitions of X, I_{Omax} and D_{max} are the same with in section 3.1.

Here in the intrinsic safety protection circuit, X is 40%. According to the section 3.1, I_{Omax} is 0.5A, D_{max} is 0.684，So $I_{in}(peak)=(1+\frac{X}{2})\times\frac{I_{O(\max)}}{1-D_{\max}}=1.2\times\frac{0.5}{1-0.684}=1.9\text{A}$.

When the input voltage is 3.3V, the value of inductance is less than 0.01mH, the maximum ignition current is 4.0A[9,10].Here I_{in} (peak)<4.0A, therefore the intrinsic safety protection circuit is internal intrinsic safety.

4.3 Analysis on the output intrinsic safety of the intrinsic safety protection circuit

The minimum ignition voltage curse of simple capacitor circuit gives the standard of the output intrinsic safety[9].

Definition 5. The protected capacitor value

$$C_p=C_{out}+\frac{LI_{in}^2(peak)}{U_O^2} \tag{5}$$

where C_{out} is the output capacitor value. When the output voltage of the circuit is 10V, the maximum output capacitor value is 500μF, namely C_p is less than 500μF.

Property 1. According to definition 5, the output capacitor value C_{out}

$$C_{out}=C_p-\frac{LI_{in}^2(peak)}{U_O^2}. \tag{6}$$

According to the given values of the intrinsic safety protection circuit, the maximum output capacitor

$$C_{\max out} = C_p - \frac{LI_{in}^2(peak)}{U_O^2} = 500 - \frac{10\times 1.9^2}{5^2} = 498.6\mu\text{F}\,. \tag{7}$$

Definition 6. The minimum capacitance value[11]

$$C_{\min out} = \frac{I_{O(\max)}}{0.01\times U_O \times f}\,. \tag{8}$$

According to the output voltage ripple requirements, the minimum capacitance value

$$C_{\min out} = \frac{I_{O(\max)}}{0.01\times U_O \times f} = \frac{0.5}{0.01\times 5\times 300\text{K}} = 33\mu\text{F}\,. \tag{9}$$

In a word, when the output protected capacitor is between 33μF and 498.6uF, the circuit is the intrinsic safety. Generally, the real capacitance value is the 2-4 times of the computed minimum capacitance value, namely C_{out} is 66～132μF, here C_{out} is 100μF.

The designed node with intrinsic safety power is shown in figure 5. It consists of CC2430 SOC (system-on-a-chip), power circuit, reset circuit, ID position circuit, external interface, and LED pilot lamp.CC2430 SOC is the main computing and communication unit of the node, power circuit is charge of supplying energy for the other component of the node, reset circuit is charge of resetting the value of the internal components of the node, ID position circuit is charge of positioning the miner, external interface is charge of communicating with the external parts, for example the environment sensors, computers and so on, LED pilot lamp is charge of displaying the work state of the node.

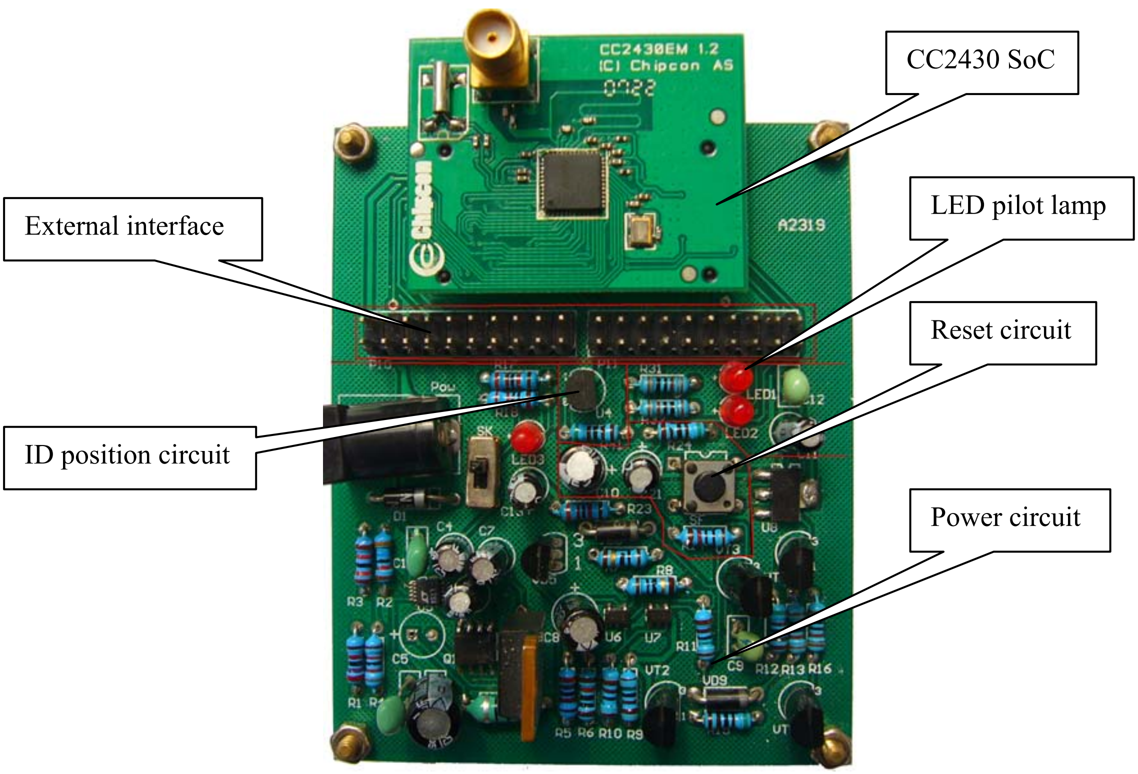

Fig.5. The intrinsic safety node

5. Analysis on the discharge properties of the intrinsic safety power

5.1 Analysis on the maximum discharge energy

It is very difficult to describe the energy release process of the circuit accurately. Korafeuqincoke presented a discharge current linear attenuation model, which can simulate the process of the discharge well[12].

Definition 7. When the discharge current decays from a steady value to zero in the discharge time, the real discharge current

$$i(t) = I \cdot (1 - \frac{t}{T}), \qquad (10)$$

where I is the current in the circuit, t is the real discharge time , T is the idea discharge time. In general, when the discharge process ends, current is not zero, but the real discharge time is little difference with the idea discharge time, and current is regarded to be zero.

Definition 8. The voltage of the electrode is:

$$U(\mathrm{t}) = \frac{E}{T} \cdot (t + \frac{L}{R}), \qquad (11)$$

where E is the voltage of power supply, L is the inductance, R is the equivalent resistance.

Definition 9. The discharge energy of the power

$$W = \int_0^T U(t) \cdot i(t) dt = \frac{EIT}{6} + \frac{1}{2} LI^2, \qquad (12)$$

where $EIT/6$ is the energy supplied by power, $LI_2/2$ is the energy deposited by the inductance.

From equation 12, we can see that when the power voltage is larger and the inductance is smaller, the energy of discharge of power is mainly $EIT/6$;while the power voltage is smaller and the inductance is larger, the energy of discharge of power is $LI_2/2$.

Definition 10. The discharge time in the low-energy inductive circuit[13]

$$T = \frac{LI}{(39 + 13L) \cdot I - E} \cdot \ln \frac{U_{arc\min} + (39 + 13L) \cdot I}{V_{arc\min}}, \qquad (13)$$

where V_{arcmin} is the minimum voltage arc, generally V_{arcmin} is 16V.

Because the designed intrinsic safety power is low-energy inductive circuit, the discharge time of circuit meets equation 13. At the same time, the inductive is the danger point when circuit failures, then the circuit discharge energy is defined the following:

Definition 11.

$$W = \frac{ELI^2}{(234 + 78L) \cdot I - 6E} \cdot \ln \frac{V_{arc\min} + (39 + 13L) \cdot I}{V_{arc\min}} + \frac{1}{2} LI^2. \qquad (14)$$

According to the standards of the intrinsic safety circuit, there is

Definition 12.

$$W < \frac{1}{\eta} \cdot W_{\max}, \qquad (15)$$

where η is the safety factor, generally η = 2-3, W_{max} is the maximum discharge energy of the intrinsic safety circuit.

In the designed intrinsic safety power circuit, E is 3V, L is 10μH, I is 1.9A, V_{arcmin} is 16V, η is 3, W_{max} is 0.28, therefore

$$W = \frac{ELI^2}{(234 + 78L) \cdot I - 6E} \cdot \ln \frac{V_{arc\min} + (39 + 13L) \cdot I}{V_{arc\min}} + \frac{1}{2} LI^2$$

$$W = \frac{3 \times 10 \times 1.9^2}{(234 + 78 \times 10) \times 1.9 - 6 \times 2} \cdot \ln \frac{16 + (39 + 13 \times 10) \times 1.9}{16} + \frac{1}{2} \times 10 \times 1.9^2$$

=0.0185mJ.

For $W = 0.0185\text{mJ} < \frac{1}{\eta} \cdot W_{\min} = \frac{1}{3} \times 0.28 = 0.093\text{mJ}$, the circuit is the intrinsic safety circuit.

5.2 Analysis on the maximum discharge power

Definition 13. The largest discharge power of circuit[14]

$$P_{\max} = \frac{EI}{4} \cdot \left(\frac{E + V_{arc\min}}{E}\right)^2, \qquad (16)$$

where V_{arcmin} is the minimal voltaic arc building value. Equation 16 may be transformed into the following:

$$P_{\max} = \frac{EI}{4} \cdot \left(\frac{E + V_{arc\min}}{E}\right)^2 = \alpha \frac{W}{\tau}, \qquad (17)$$

where α is the ratio coefficient, and $\alpha = \frac{1}{2}\left(\frac{E + V_{arc\min}}{E}\right)^2 \cdot \frac{3V_{arc\min}}{E + 3V_{arc\min}}$, τ is the time constant, and $\tau = \frac{L}{R}$.

Therefore, the largest discharge power of the intrinsic safety circuit should meet：

Definition 14.

$$P_{\max} < \frac{1}{\eta} \cdot \alpha \frac{W_{\min}}{\tau}. \qquad (18)$$

In the designed intrinsic safety power circuit, R is the equivalent resistance of the whole intrinsic safety protection circuit. Because the resistance of integrated chip ZXCT1010 is very low, the equivalent parallel resistance is attained through the parallel connection of R_{25} and R_{26} according to the Thevenin's theorem, and then R is 6.875k.. The value of E, L, I and V_{arcmin} are the same with which in the section 5.1, then there are following:

$$P_{\max} = \frac{EI}{4} \cdot \left(\frac{E + V_{arc\min}}{E}\right)^2 = \frac{3 \times 1.9}{4} \cdot \left(\frac{3+16}{3}\right)^2 = 57.16\text{W};$$

$$\alpha = \frac{1}{2}\left(\frac{E + V_{arc\min}}{E}\right)^2 \cdot \frac{3V_{arc\min}}{E + 3V_{arc\min}} = \frac{1}{2}\left(\frac{3+16}{3}\right)^2 \cdot \frac{3 \times 16}{3 + 3 \times 16} = 18.876;$$

$$\tau = \frac{L}{R} = \frac{10 \times 10^{-6}}{6.875 \times 10^{3}} = 1.455 \times 10^{-9}\text{s}.$$

For $P_{\max} = 57.16\text{W} < \frac{1}{\eta} \cdot \alpha \frac{W_{\min}}{\tau} = \frac{1}{3} \times 18.876 \times \frac{0.28 \times 10^{-3}}{1.455 \times 10^{-9}} = 1.21 \times 10^{6}\text{W}$, the power circuit is intrinsic safety.

5.3 The simulation test of discharge process of the intrinsic safety power

We simulate the processes of discharge energy and discharge power of the intrinsic safety power. The processes of discharge energy and discharge power are showed in figure 6 and figure 7 respectively.

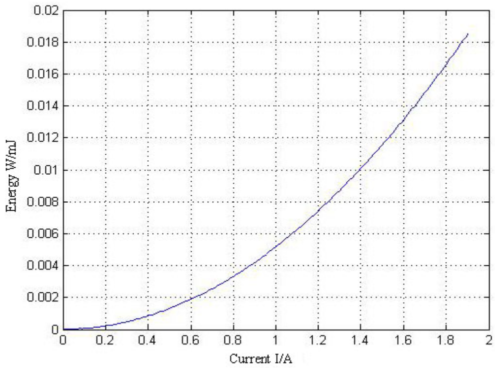

Fig.6. The process of discharge energy

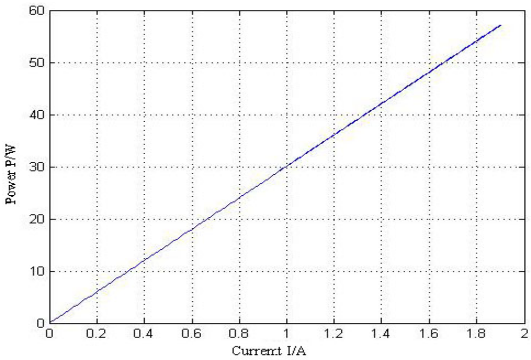

Fig.7. The process of discharge power

From figure 6, the discharge energy is the nonlinear proportion of the current, the discharge energy increases with the current increasing, and the maxim discharge energy is less than 0.02mJ. From figure 7, the discharge power is the linear proportion of current, the discharge power increases with the current increasing, and the maxim discharge power is less than 60W. From figure 6 and figure 7, the discharge energy and discharge power of the intrinsic safety power is within the permissible intrinsic safety standard; therefore the power is the intrinsic safety from the test view.

6. Conclusions

In order to apply wireless sensor networks into the explosive environment like coal mine, the nodes must be intrinsic safety, namely the instantaneous EDM is less than 0.28mJ in the situation of short-circuit and open circuit. The methods of intrinsic safety for the power of node is the following: (1)in the power supply circuits, an over-voltage protection circuit was integrated into the power control chips LTC1871; (2) The intrinsic safety protection circuit mainly consists of an integrated chip ZXCT1010 which has over-current and over-voltage protections, which makes up double over-voltage and over-current protection. According to the design schemes of the intrinsic safety power circuit, we discuss the processes of discharge energy and discharge power of the analysis from the theory view and test, the results of theory and test testify the designed circuit is intrinsic safety.

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