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Temperature Characteristic Analysis of the Output Intrinsically Safe Buck Converter and Its Design Consideration

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Abstract: Aiming at the unreliability resulting from ignoring the temperature effect and randomness of switching frequency in the traditional design method of an intrinsically safe Buck converter, a reliable design method based on the minimum frequency and considering the temperature characteristic is proposed. The theoretical design range of capacitance is deduced according to the maximum output ripple voltage and output intrinsic safety performance requirements. Considering the temperature characteristics of the capacitor, the actual maximum and minimum capacitances are obtained corresponding to the theoretical design capacitance within a given temperature range. It is pointed out that the actual minimum capacitance increases with the decrease of switching frequency, while the actual maximum capacitance is independent of frequency. Therefore, it can be deduced that there exists a minimum frequency which can meet the requirements of both output ripple voltage and intrinsically safe performance. When the actual maximum capacitance equals the actual minimum capacitance, the analytic expression of the minimum frequency is obtained. Assuming a capacitance adjustment, the actual working frequency of the converter corresponding to the minimum frequency is deduced. The design flow of an intrinsically safe Buck converter based on the minimum switching frequency considering the temperature characteristic is presented. The correctness of the theoretical analysis and the feasibility of the proposed design method are verified by experimental results. This design method can also be applied to other types of intrinsically safe converters.

Keywords: buck converter; output intrinsically safe; the minimum frequency; temperature characteristic

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1. Introduction

The switching power supply used in coal mines, petrochemical plants and other hazardous environments must meet anti-explosive requirements [1,2]. An intrinsically safe anti-explosive power supply guarantees compliance with the anti-explosive requirements because of the electrical parameters of the circuit [3]. Because there is no bulky explosion-proof shell, the safe power supply has the remarkable advantages of small size, light weight, high safety performance, low cost, simple manufacturing process and easy maintenance. Because of this, the anti-explosive power supply should be designed as intrinsically safe as possible [4]. The Buck converter is one of the most commonly used topologies of the switching power supply, and it contains inductor and capacitor. When the inductor is broken or the capacitor is short-circuited, the fault energy of the converter may ignite the specified explosive gas resulting in fire and explosion [5]. Therefore, it is very important to study the intrinsic safety performance of the converter. Generally, large capacitors are selected to meet the output ripple voltage index. However, there is always the possibility that the converter will ignite flammable and explosive gas due to an output short-circuit. Therefore, the intrinsic output safety characteristic corresponding to the output short-circuit discharge in a Buck converter must be considered.

When designing the converter, it is contradictory to choose both the energy storage element to satisfy the output ripple voltage index and the intrinsic safety requirement. That is, the inductance and capacitance required to meet the intrinsic safety performance should be as small as possible. In order to meet the output ripple voltage index, the inductance and capacitance should be as large as possible. This contradiction makes the parameter design of an intrinsically safe converter more complicated [4–6].

At present, according to the output ripple voltage index and the output intrinsic safety requirements, the parameter design range of the converter is obtained under ideal conditions [7,8]. Because the converter is a multi-objective and multi-parameter nonlinear system, some scholars use a genetic algorithm and particle swarm optimization algorithm to optimize the parameters of the converter [9–12]. In addition, in the design of an intrinsically safe switching converter, the maximum intrinsically safe output power under the given parameters is specified to avoid the problem of blindly proposing the intrinsically safe output power [13,14]. The design method of the intrinsically safe converter based on the maximum intrinsically safe output power is proposed [15]. References [16–19] analyzed the performance and reliability of the converter by capacitor and illustrated the effect of temperature on capacitor life. However, the influence of temperature on capacitance, electrical performance and intrinsic safety requirements of the converter was not analyzed.

Although the design methods mentioned above solve some practical problems, the existing design methods usually select the operating frequency randomly according to experience. The design range of inductor and capacitor is obtained according to the electrical performance index and intrinsic safety requirements of the converter. Due to the arbitrary choice of switching frequency, the value range of inductor and capacitor parameters may not exist because the frequency is too small or the switching loss of the circuit may too large due to the high frequency, which reduces the efficiency of the converter. In addition, the capacitance at the output of the converter will change with the temperature. Even if the switching frequency is constant, with the change of temperature, the actual capacitance may be larger than the nominal value, leading to the converter not meeting the requirements of output intrinsic safety. Likewise, the actual capacitance may be smaller than the nominal value, which makes the converter not meet the requirements of output ripple voltage index. However, the existing design method does not consider the influence of temperature. As a result, the range of the designed capacitance is unreliable.

In order to solve this problem, a design method based on the minimum frequency and considering the temperature characteristic is proposed. The main contributions of this paper are as follows.

The reliable actual capacitance value range, considering the temperature characteristics corresponding to the theoretical maximum and minimum capacitance is deduced based on the requirements of the output intrinsic safety and maximum output ripple voltage index This can solve the unreliability issue. The minimum switching frequency is defined, and its expression is derived, which can avoid the blind selection problem of operating frequency in parameter design. The capacitance adjustment is introduced, which can avoid the unreasonable problem of the capacitance design range.

2. Theoretical Parameter Design of the Capacitor

The composition circuit diagram of a Buck converter is shown in Figure 1.

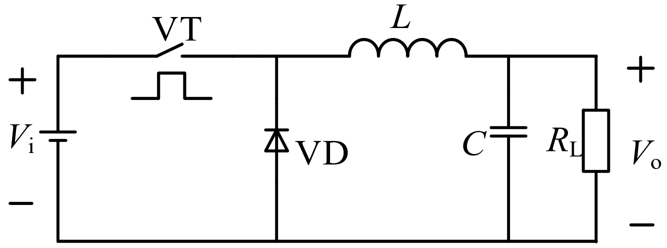

Figure 1. Schematic diagram of a Buck converter.

From Figure 1, V_i and V_o are the input and output voltages, respectively. VT and VD are the switching tube and current-continuing diode of the converter, respectively. L and C are the inductor and capacitor of the converter, respectively. R_L is the load resistance.

For the output intrinsically safe switching converters, it is necessary to meet both the specified electrical performance index and the output intrinsic safety requirements [20–22]. Through analyzing the electrical characteristics of the converter, the minimum theoretical capacitance C_min can be obtained, and the maximum theoretical capacitance C_max can be generated by analyzing the output intrinsic safety requirements.

2.1. Minimum Theoretical Capacitance

The output ripple voltage of the switching converter is not only relevant to the inductor and capacitor, but also to the operating mode of the converter. In the dynamic operating range, when the designed converter works in CCM, the output ripple voltage V_pp can be expressed as shown in Equation (1) [8,23].

$$V_\mathrm{PP} = \frac{V_\mathrm{o}(V_\mathrm{i} - V_\mathrm{o})}{8LCf^2V_\mathrm{i}} \tag{1}$$

where f is the switching frequency.

In Equation (1), the maximum output ripple voltage is obtained when the inductor L is the minimum value. If the Buck converter works in CCM, the inductor L needs to meet [23]

$$L \geq L_\mathrm{C} = \frac{R_\mathrm{L}(V_\mathrm{i} - V_\mathrm{o})}{2fV_\mathrm{i}} \tag{2}$$

where L_C is the critical inductance of the Buck converter working in CCM and DCM. When $L = L_\mathrm{C}$, the maximum output ripple voltage $V_\mathrm{pp,max}$ is

$$V_\mathrm{PP,max} = \frac{V_\mathrm{o}}{4fCR_{L,\mathrm{min}}} \tag{3}$$

It can be seen from Equation (3) that the maximum output ripple voltage of the Buck converter increases with decreasing the capacitance C. It is noted that there must be a minimum capacitance to satisfy the maximum output ripple voltage index. According to Equation (3), the minimum theoretical capacitance C_min can be obtained as

$$C_\mathrm{min} = \frac{1}{4mfR_{L,\mathrm{min}}} \tag{4}$$

where m is $V_\mathrm{pp,max}/V_\mathrm{o}$.

2.2. Maximum Theoretical Capacitance

Since the output short-circuit discharge energy of the converter is related to inductors [6,23–26], capacitors, the switching states and the operating mode of the converter, the intrinsic safety criterion of simple capacitor circuit cannot be directly used to judge the intrinsic safety performance of the converter. However, by analyzing the maximum output short-circuit discharge energy of the converter and using the energy equivalence principle, the Buck converter can be equivalent to a simple capacitor circuit, and then the output intrinsic safety criterion of the converter is obtained according to the critical ignition voltage curve of the simple capacitor circuit.

The output short test circuit of the Buck converter is shown in Figure 2.

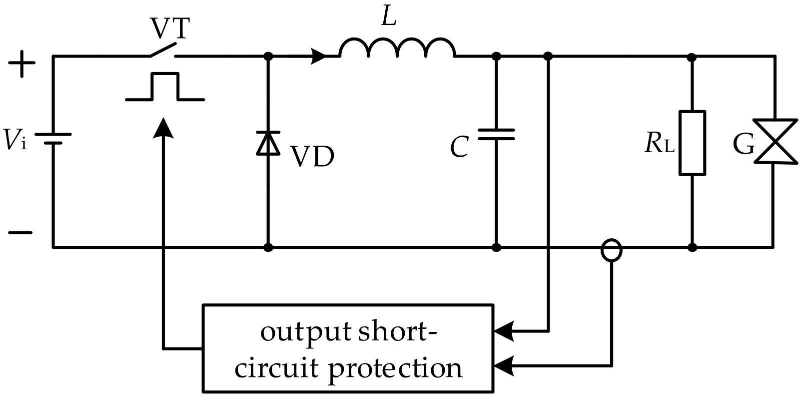

Figure 2. Output short test circuit of the Buck converter.

From Figure 2, G is the safety spark test device. When the two electrodes of G contact, the output is short-circuited.

Assuming that the load changes from $R_{\mathrm{L,min}}$ to $R_{\mathrm{L,max}}$, the input voltage changes from $V_{\mathrm{i,min}}$ to $V_{\mathrm{i,max}}$, the maximum output short-circuit discharge energy [8] of the Buck converter is

$$W_{\max} = \frac{V_{i,\max}^2 V_o^2 \Delta t^2 (V_{i,\max} - V_o)}{2L\left[V_{i,\max} f V_H^2 T_C - V_o^2 (V_{i,\max} - V_o)\right]} + \frac{V_{i,\max}^2 \Delta t^2}{L} + \frac{CV_o^2}{2} = W'_{\max} + \frac{CV_o^2}{2} \quad (5)$$

where Δt is the response time of the output short-circuit protection circuit. T_{C} is the output short-circuit spark discharge time. V_{H} is the average value of the spark discharge voltage. $W'_{\max}$ is the equivalent energy in addition to the energy released by the capacitor. So, $W'_{\max}$ is

$$W'_{\max} = \frac{V_{i,\max}^2 V_o^2 \Delta t^2 (V_{i,\max} - V_o)}{2L\left[V_{i,\max} f V_H^2 T_C - V_o^2 (V_{i,\max} - V_o)\right]} + \frac{V_{i,\max}^2 \Delta t^2}{L} \quad (6)$$

According to the energy equivalence principle, the Buck converter is equivalent to a simple capacitor circuit (as shown in Figure 3), the equivalent capacitance C_{e} can be obtained as

$$C_{\mathrm{e}} = \frac{2W_{\max}}{V_o^2} = C + \frac{2W'_{\max}}{V_o^2} = C + C'_{\mathrm{e}} \quad (7)$$

where C'_{e} is the equivalent capacitance corresponding to the effective energy transferred from the input power supply and inductor to the output short-circuit point, that is $C'_{\mathrm{e}} = \frac{2W'_{\max}}{V_o^2}$.

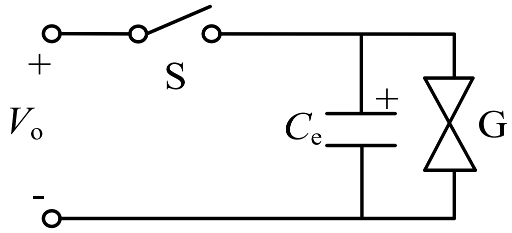

Figure 3. Equivalent simple capacitor circuit.

From Figure 3, S is the equivalent switch of a simple capacitor circuit. When the two electrodes of G are disconnected and S is closed, C_{e} is charged. When the two electrodes of G are closed and S is disconnected, C_{e} is discharged.

The non-explosive intrinsic safety criterion to meet the output intrinsic safety requirements is

$$C_{\mathrm{e}} < C_{\mathrm{B}} \quad (8)$$

where, C_B is the critical ignition capacitance corresponding to the output voltage V_o. It can be found from the critical ignition voltage curve of a simple capacitor circuit. When the equivalent capacitance C_e is less than the critical ignition capacitance C_B, the Buck converter satisfies the requirement of output intrinsic safety. Therefore, the maximum equivalent capacitance $C_{e,\max}$ of the Buck Converter is C_B. Substituting Equations (5) and (6) into Equation (7), the maximum theoretical capacitance $C_{\max}$ of the output intrinsically safe Buck converter is

$$C_{\max} = C_B - C'_e = C_B - \frac{2V_{i,\max}^2 \Delta t^2}{LV_o^2} - \frac{V_{i,\max}^2 \Delta t^2 (V_{i,\max} - V_o)}{L\left[V_{i,\max} f V_H^2 T_C - V_o^2 (V_{i,\max} - V_o)\right]} \tag{9}$$

At present, the output power of the intrinsically safe switching converter is not too high; V_i and V_o are relatively low. It makes C_B corresponding to V_o relatively large (for example, assuming that V_o is 18 V, the corresponding C_B is 50 μF), and in the practical application [4], Δt is 1–2 μs. Here, f is from a few hundred kilohertz to several megahertz; L is tens of microseconds; T_C is tens of microseconds; V_H is 8–9 V. According to the above parameters, C'_e is at least one order of magnitude smaller than C_B. Therefore. $C_{\max}$ can be expressed as

$$C_{\max} \approx C_B \tag{10}$$

From Equation (10), it can be seen that the maximum theoretical capacitance $C_{\max}$ of the output intrinsically safe Buck converter is only determined by the output intrinsic safety requirements C_B, which is independent on the switching frequency f.

Combined with Equation (4) and Equation (10), it can be concluded that the theoretical range of capacitance C satisfying both output ripple voltage and intrinsic safety requirements is

$$\frac{1}{4mfR_{L,\min}} \le C \le C_B \tag{11}$$

According to Equation (11), the maximum and minimum capacitance can be determined. In addition, the maximum capacitance is independent of switching frequency, while the minimum capacitance is inversely proportional to switching frequency.

2.3. Actual Value Range of Capacitance Considering Temperature Characteristics

With the change of ambient temperature, the capacitance of the switching converter also changes. If the capacitance exceeds the upper limit $C_{\max}$, the converter cannot meet the requirements of output intrinsic safety. Similarly, if the capacitance is less than the lower limit $C_{\min}$, the converter cannot meet the requirements of output ripple voltage. Therefore, the range of theoretical capacitance is not reliable. The temperature characteristics of capacitance must be considered, and the practical capacitance value range can be obtained based on the theoretical value range of capacitance.

Supposing that in Equation (11), the capacitance at room temperature (25 °C) is C. The actual capacitance at a certain temperature is C'. The maximum and minimum values of the ratio C' to C is defined as A_T and B_T, respectively. Therefore, the maximum and minimum values of the actual capacitance considering the temperature characteristics can be expressed as $A_T C$ and $B_T C$, respectively.

In order to ensure that the minimum capacitance within the given temperature range can still meet the requirements of output ripple voltage index, the minimum value of actual capacitance $B_T C$ should be greater than Equation (11), the lower limit $C_{\min}$. Similarly, the maximum capacitance must satisfy the requirements of output intrinsic safety, the maximum value of actual capacitance $A_T C$ should be less than Equation (11), the upper limit $C_{\max}$. According to Equation (11), the actual value range of capacitance considering temperature characteristics is

$$\frac{1}{4B_T mfR_{L,\min}} \le C \le \frac{C_B}{A_T} \tag{12}$$

From Equation (12), the maximum and minimum values of the actual capacitance considering the temperature characteristics can be expressed as follows, respectively.

$$\begin{aligned} C_{\mathrm{T,max}} &= \tfrac{C_B}{A_T} \\ C_{\mathrm{T,min}} &= \tfrac{1}{4B_T m f R_{L,\mathrm{min}}} \end{aligned} \tag{13}$$

It can be seen that the minimum value $C_{\mathrm{T,min}}$ considering temperature characteristics of an intrinsic safe Buck converter increases with the decrease of switching frequency f, while the maximum value $C_{\mathrm{T,max}}$ is independent of f.

3. Design of Minimum Switching Frequency

Since the maximum capacitance $C_{\mathrm{T,max}}$ is independent of f considering temperature characteristics, while the minimum capacitance $C_{\mathrm{T,min}}$ increases with the decrease of f, it is pointed out that there must be a minimum switching frequency to make the capacitance range effective. When $C_{\mathrm{T,min}}$ equals to $C_{\mathrm{T,max}}$, the minimum switching frequency f_{min} is obtained as

$$f_{\mathrm{min}} = \frac{A_T}{4B_T m C_B R_{L,\mathrm{min}}} \tag{14}$$

The actual switching frequency f of the converter must be greater than f_{min}.

Assuming that the expected value of capacitance C range from $C'_{\mathrm{T,min}}$ to $C_{\mathrm{T,max}}$, where $C'_{\mathrm{T,min}}$ is the minimum value of the actual capacitance; ΔC is the differential capacitance value of $C_{\mathrm{T,max}}$ and $C'_{\mathrm{T,min}}$. Then, the actual value range of C can be expressed as

$$\frac{C_B}{A_T} - \Delta C \le C \le \frac{C_B}{A_T} \tag{15}$$

When $C'_{\mathrm{T,min}} = C_{\mathrm{T,min}}$, the actual operating frequency f of the converter can be expressed as

$$f = \frac{C_{\mathrm{B}} f_{\mathrm{min}}}{C_{\mathrm{B}} - A_T \Delta C} \tag{16}$$

In Equation (16), it can be seen that the actual switching frequency f of the Buck converter is related to the temperature coefficient A_{T}, the minimum switching frequency f_{min} and the differential capacitance value ΔC. The actual switching frequency f is increases with the increase of ΔC.

4. Optimization Design Method and Design Example

4.1. Optimization Design Method

An optimal design method of output for an intrinsically safe Buck converter based on minimum switching frequency and considering temperature characteristics is proposed. The specific design process is shown in Figure 4.

First of all, the critical ignition capacitor C_{B} corresponding to the output voltage V_{o} can be determined according to the critical ignition curve of the simple capacitor circuit. A_{T} and B_{T} are obtained according to the temperature characteristic curve of the capacitor.

Then, the minimum switching frequency of the converter is calculated according to Equation (14). Based on the expected capacitance variation ΔC, the range of the actual capacitance C is determined according to Equation (15). The actual operating frequency is calculated according to Equation (16).

Finally, the value of inductance is determined according to the output ripple voltage index.

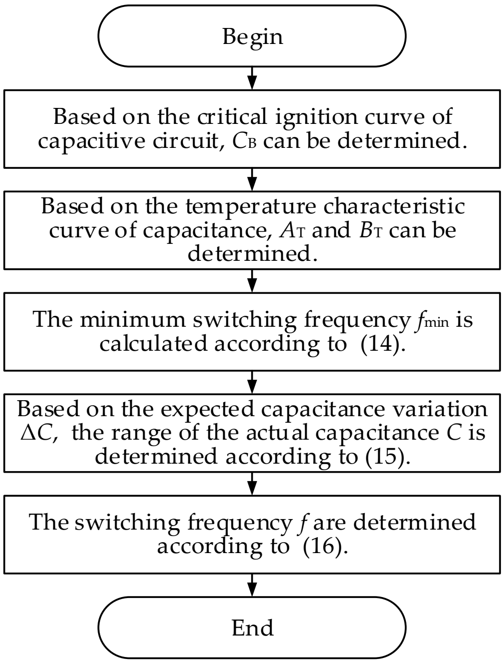

Figure 4. Proposed design method of an intrinsically safe Buck converter.

4.2. Design Examples

An output intrinsically safe Buck converter prototype was designed to verify the correctness of the above theoretical analysis and the proposed design method. We suppose that the specific indexes of the prototype are V_i = 20–24 V, V_o = 18 V, $V_{pp,max}$ = 1%V_o, R_L = 9–60 Ω. The ambient temperature ranges from −25 °C to 85 °C.

In order to verify the feasibility of the proposed design method, three groups of different parameters are set for experiments. According to the design process shown in Figure 4, the specific parameters are designed as follows:

(1) Determining the values of C_B, A_T and B_T.

When V_o = 18 V, the corresponding critical ignition capacitance C_B is 50 μF according to the critical ignition curve of a simple capacitor circuit.

Aluminum electrolytic capacitance is selected as the output filter capacitor. The temperature characteristics curve [27] is shown in Figure 5.

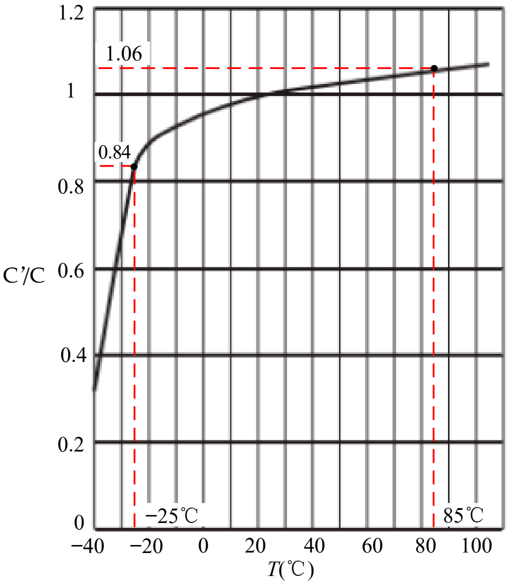

Figure 5. Temperature characteristics of aluminum electrolytic capacitor.

It can be seen from Figure 5 that A_T and B_T are about 1.055 and 0.84, respectively, within the temperature variation range (−25 °C to 85 °C).

(2) Solving the minimum switching frequency f_{min}.

According to Equation (13), the maximum capacitance $C_{\text{T,max}}$ is 47.4 µF. The fitting curve of the minimum actual capacitance $C_{\text{T,min}}$ versus frequency is shown in Figure 6.

Figure 6 shows that the minimum actual capacitance increases with the decrease of switching frequency. When the minimum actual capacitance is equal to the maximum actual capacitance, the minimum switching frequency considering the temperature characteristics is obtained. Substituting $R_{\text{L,min}} = 9\ \Omega$, $m = 0.01$, $A_T = 1.055$, $B_T = 0.84$ and $C_B = 50$ µF into Equation (14), the minimum switching frequency f_{min} is 69.8 kHz.

(3) Determining the value range of the actual capacitance C and the switching frequency f.

We set the three different groups of ΔC as 5 µF, 20 µF and 30 µF, respectively. According to Equation (15), the calculated and actual values of capacitance C are shown in Table 1.

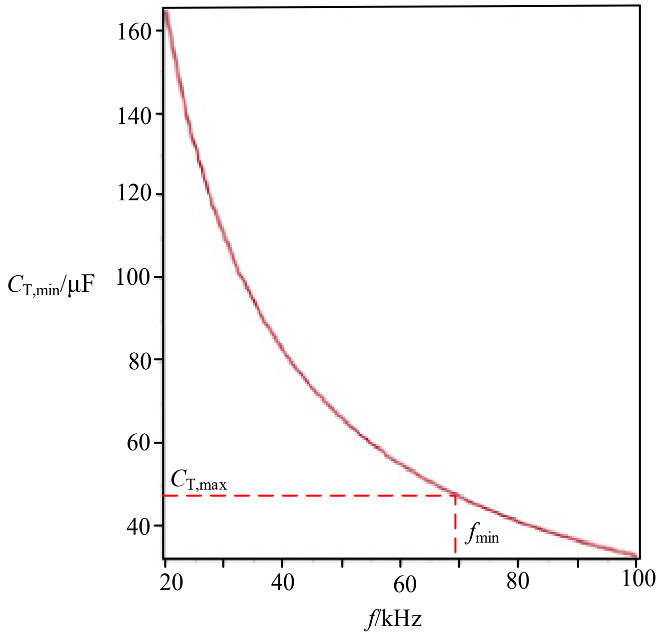

Figure 6. Fitting curve of the minimum actual capacitance versus frequency.

According to Equation (16), the calculated and actual values of the switching frequencies f are shown in Table 1, respectively.

Table 1. Calculated and actual values of the prototype.

Experimental Group	ΔC (µF)	Parameter	Calculated Value (Value Range)	Actual Value (Value Range)
Group 1	5	C (µF)	(42.4, 47.4)	(43, 47)
		f (kHz)	78	80
		L (µH)	14.1	15
Group 2	20	C (µF)	(27.4, 47.4)	(28, 47)
		f (kHz)	120.7	120
		L (µH)	9.4	10
Group 3	30	C (µF)	(17.4, 47.4)	(18, 47)
		f (kHz)	190.1	190
		L (µH)	5.9	7

(4) Determining the actual lower limit of inductance L.

When f is 80 kHz, 120 kHz and 190 kHz, the minimum values of the inductance L_{min} can be obtained as 14.1 µH, 9.4 µH and 5.9 µH.

It can be seen from Table 1 that the larger the capacitance variation range ΔC is, the larger the range of capacitance C is, the higher the switching frequency f is, and the smaller the required inductance L is. However, too large a frequency will lead to large switching loss and reduced efficiency. Therefore, it is not recommended to use excessively large ΔC in practical application.

(3) Analysis of experimental results. In order to verify the correctness of the above parameters, the output ripple voltage and safety spark experimental tests were carried out on the prototype, as shown in Figure 7.

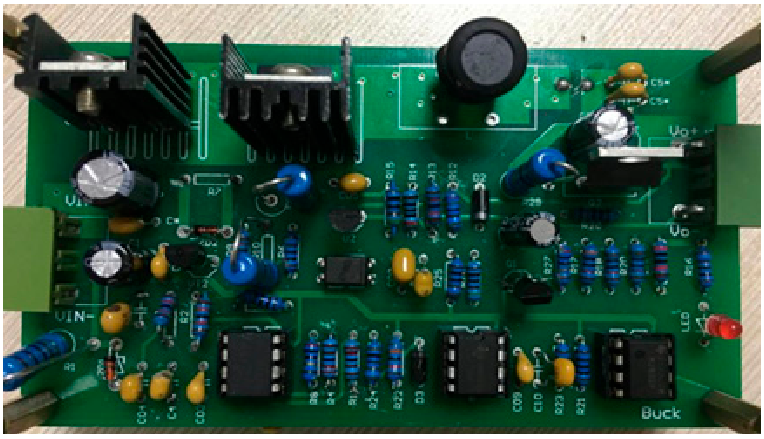

Figure 7. The experimental prototype.

(1) Verification of output ripple voltage index.

At room temperature, the lower limits of the capacitor design range in Table 1 is taken as the filter capacitors of the converter. When the temperature drops to the lower limit of the given range (−25 °C), the peak-to-peak values of the output ripple voltage corresponding to the above three conditions are 173 mV, 159 mV and 152 mV, respectively. When the temperature rises to 85 °C, the output ripple voltage still meets the specified index requirements. The output ripple voltages under different temperatures are shown in Table 2 (considering temperature characteristics method) for the three groups.

Table 2. Output ripple voltage of the prototype.

Design Method	**Parameter**		**Vpp/mV**		
			−25 °C	**25 °C**	**85 °C**
Considering temperature characteristics	Group 1	f = 80 kHz C = 43 µF L = 15 µH	173	150	112
	Group 2	f = 120 kHz C = 28 µF L = 10 µH	159	142	108
	Group 3	f = 190 kHz C = 18 µF L = 7 µH	152	138	106
Without considering Temperature characteristics	Group 4	f = 80 kHz C = 35 µF L = 16 µH	191	172	166
	Group 5	f = 80 kHz C = 48 µF L = 16 µH	158	131	122

It can be seen from Table 2 that the output ripple voltage of the Buck converter increases with the decrease of temperature, when the lowest temperature is −25 °C, the output ripple voltage is the maximum value, and it is less than the given index. It indicates that even for the lower limit of capacitance value, the output ripple voltage still meets the design requirements when the lowest temperature is taken. With the increase of the capacitance or the temperature, the output ripple voltage of the converter is less than the limit value of the maximum output ripple voltage.

(2) Safety spark test and verification of intrinsic safety performance.

The intrinsically safe spark test device is shown in Figure 8.

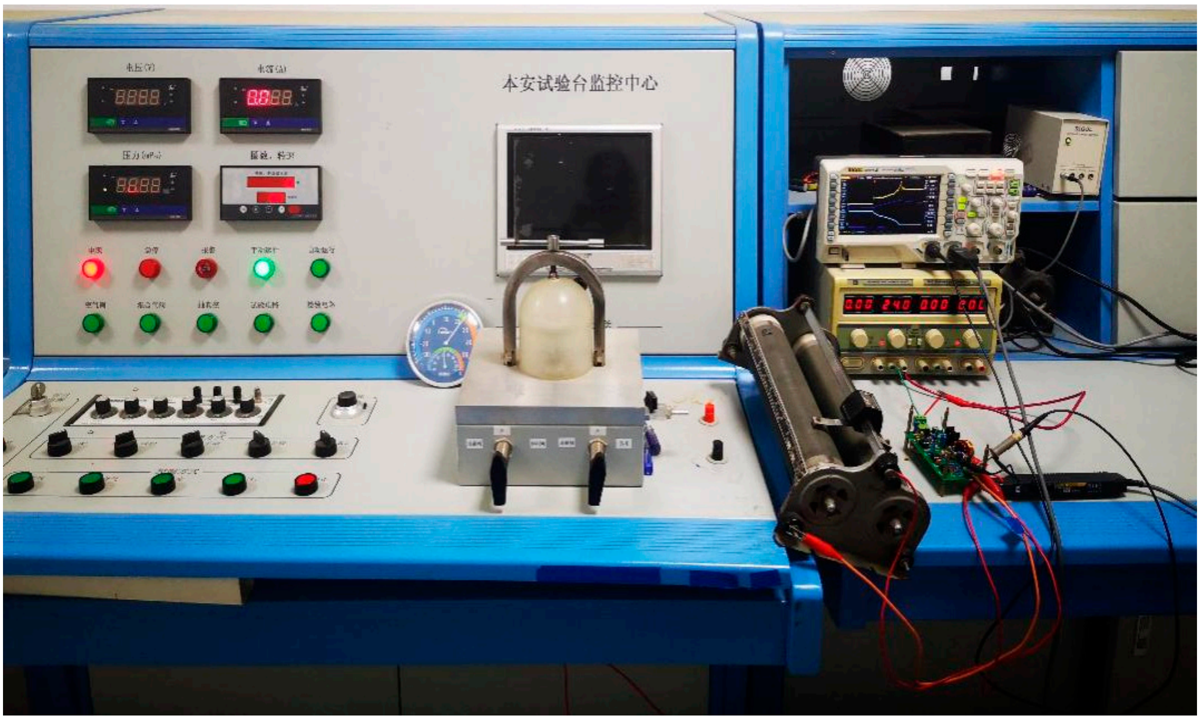

Figure 8. Intrinsically safe spark test device.

According to the curve of capacitance change rate shown in Figure 5, it is found that the capacitance increases gradually with the increase of temperature. Therefore, the upper limit of the capacitance design range at room temperature is taken as the filter of the converter considering the most dangerous situation. The prototype was placed in a humidifier to adjust its temperature to 85°C, and the safety spark test was carried out on the safety spark test device based on IEC standard.

The experimental results show that the specified explosive gas was not ignited. It indicates that the designed prototype of the Buck converter can meet the intrinsically safe requirements even at the specified highest temperature when the maximum capacitance is taken. Therefore, any capacitor in the range of capacitance value considering temperature characteristics obtained from Equation (15) can make the converter meet the output intrinsic safety requirements under a given temperature condition. The corresponding safety spark test results at different temperatures are shown in Table 3 (considering temperature characteristics method).

Table 3. Safety spark test results of the prototype.

Design Method	**Parameter**		**Safety Spark Test**		
			−25 °C	**25 °C**	**85 °C**
Considering temperature characteristics	Group 1	f = 80 kHz C = 47 µF L = 15 µH	safe	safe	safe
	Group 2	f = 120 kHz C = 47 µF L = 10 µH			
	Group 3	f = 190 kHz C = 47 µF L = 7 µH			
Without considering temperature characteristics	Group 4	f = 80 kHz C = 35 µF L = 16 µH	safe	safe	safe
	Group 5	f = 80 kHz C = 48 µF L = 16 µH	safe	safe	unsafe

(3) Comparative analysis and discussion.

In order to compare and analyze the influence of temperature on the electrical performance and intrinsic safety requirements of the converter, two groups of different parameters were set to test the Buck converter without considering the temperature characteristics of the capacitor. According to (11), the value range of capacitance is (34.7 µF, 50 µF) when f is 80 kHz. The minimum inductance L_{min} is 14 µH. The values of inductance, capacitance and their experimental results are shown in Table 3 (without considering temperature characteristics).

It can be seen from Tables 2 and 3 (without considering temperature characteristics) that the selected capacitance of Group 4 is close to the minimum value, and the capacitance of Group 5 is close to the maximum value. When the temperature is reduced to −25 °C, the output ripple voltage of Group 4 is greater than the specified requirement. However, when the temperature rises to 85 °C, Group 5 does not meet the output intrinsic safety requirements. It indicates that the value range of capacitance without considering the temperature characteristics is not reliable in a certain temperature range.

Therefore, in order to obtain a reliable converter parameter design range that meets the requirements of the specified output intrinsic safety and output ripple voltage indexes, the temperature characteristics of the capacitor must be considered within a given range of temperature when designing the intrinsically safe Buck converter.

5. Conclusions

A reliable design method of an output intrinsic safety Buck converter considering the temperature characteristics is proposed. The conclusions are as follows.

(1) The actual capacitance design range satisfying the output ripple voltage and output intrinsic safety requirement was obtained in a certain temperature variation range. It was concluded that the maximum actual capacitance allowed by the output intrinsic safety requirement is independent of operating frequency, and the minimum actual capacitance meeting output voltage ripple requirement increases with the decrease of operating frequency.

(2) It is pointed out that there must be a minimum switching frequency, which makes the converter meet both the output voltage ripple and output intrinsic safety requirement. The expression of a minimum switching frequency was derived through letting the minimum actual capacitance equal the maximum actual capacitance. Considering the influence of temperature on both the output voltage ripple and output intrinsic safety requirement, the actual operating frequency can be obtained.

(3) An optimal design method of an output intrinsically safe Buck converter considering temperature characteristics was proposed in a given temperature variation range.

This design method can also be applied to other switching converters. It plays an important role in the development and application of intrinsically safe converters.

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