Research Article

Optimal Design Method for Inner-Intrinsically Safe Buck-Boost Converters Based on Ignition Capability

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Intrinsically safe switching converters are the best choice for low-voltage DC power supplies in explosive environments (such as coal mine). To obtain the optimal design method of the inner-intrinsically safe buck-boost converter (IISBBC), the equivalent circuits for various switching states and operating conditions of the buck-boost converter are studied, and the most dangerous inductor-disconnected discharge (IDD) condition of the buck-boost converter is obtained. Based on this condition, the IDD behavior of the IISBBC is studied. According to the minimum ignition curves (MICs) of the resistive circuit and the simple inductive circuit, the expressions describing the IDD ignition capability of the IISBBC in terms of the critical ignition power and the critical ignition energy are derived. The IDD has the strongest ignition capability based on power when the IISBBC is working at its maximum input voltage and minimum load resistance, and it has the strongest ignition capability based on energy when the IISBBC is working at its minimum input voltage and minimum load resistance. The converter is inner-intrinsically safe only when the maximum arc power is less than the critical ignition power and the inductive energy is less than its critical value. By incorporating the proposed criterion, the optimal design method for IISBBCs that meets the demands of electric and inner-intrinsic safety performance is obtained. Based on this method, the design range of the inductance and capacitance and the optimal inductance to give the IISBBC the best inner-intrinsic safety performance are obtained. The feasibility and reliability of the proposed optimal design method are demonstrated by an explosion test.

1. Introduction

Electrical equipment working in explosive environments must meet explosion-proof requirements, and the intrinsically safe type is the best type of explosion-proofing [1, 2]. With the development of modern industrial control systems for integration and low power consumption, buck-boost converters are the best choice for intrinsically safe power supply because of their advantages of boost or buck output, small size, light weight, and high conversion efficiency.

The inner-intrinsically safe buck-boost converter (IISBBC) must not ignite explosive gases when an inductor-disconnected discharge (IDD) occurs [3–5]. Intrinsic safety is achieved by limiting the ignition capability of components in the IISBBC [6–10]. Therefore, research on the design and optimization of the IISBBC is needed.

The design principle of the IISBBC is to meet the demands of both inner-intrinsic safety and electric performance [11]. The optimal topology design methods for the buck-boost converter have been researched [12–14], and the control strategies for the buck-boost converter have also been studied [15, 16]. However, the intrinsically safe performance of buck-boost converters has not been considered.

Presently, ignition capability can be evaluated by non-explosive and explosive evaluation methods. The explosive evaluation method is accurate and reliable, but it cannot guide the design of an IISBBC. The nonexplosive evaluation method is more suitable for the analysis and design of an IISBBC. At present, the IDD ignition capability is largely described in terms of the minimum ignition energy [17–20] and the average discharge power [21]. However, the minimum ignition energy cannot explain why an IDD with a longer discharge time has a weaker ignition capability. The

ignition capability evaluation according to the average discharge power is affected by the energy loss factor, which reduces the reliability of the evaluation result. Moreover, the above studies cannot be applied to time-varying nonlinear circuits such as buck-boost converters [22]. Thus, the most dangerous output short-circuit discharge conditions and the design methods of output intrinsically safe buck-boost converters have been studied [23]. However, inner-intrinsic safety was not considered, which means that output intrinsic safety converters must be equipped with an explosion-proof enclosure, which causes them to lose the advantages of intrinsic safety. The design method for intrinsically safe buck-boost converters was based on minimum ignition curves (MICs) [24]. However, this method is complicated, and large errors may arise.

To obtain a reliable and feasible optimal design method for the IISBBC, equivalent circuits in different switching states and operating modes of buck-boost converters were analyzed. The most dangerous IDD conditions were obtained. The relationship between the IDD characteristics and converter parameters was then analyzed in depth. Based on the MIC of a resistive circuit and a simple inductive circuit, expressions describing the IDD ignition capability of the buck-boost converter will be derived. Then, the design method for an IISBBC meeting the demands of both inner-intrinsic safety and electric performance will be obtained. Based on the principle of the maximum safety margin of the inner-intrinsic safety, the optimal method will be obtained. The feasibility and reliability of the proposed optimal design method will be evaluated by the explosion criterion based on the International Electrotechnical Commission (IEC) spark test apparatus.

2. Design Consideration Based on Electric Performance Demand

2.1. Operating Modes of Buck-Boost Converters. The buck-boost converter schematic is shown in Figure 1, where U_i represents the input voltage, U_o represents the output voltage, I_o represents the output current, S represents the switch, L represents the inductance, VD represents the diode, C represents the capacitance, R_L represents the load resistance, and f represents the switching frequency.

$$L_C = \frac{R_L(1-d)^2}{2f} = \frac{R_L U_i^2}{2f(U_i + U_o)^2}, \quad (1)$$

If the inductance current i_L drops to zero during a switching cycle, the buck-boost converter operates in the discontinuous conduction mode (DCM); otherwise, it operates in the continuous conduction mode (CCM). The critical inductance of the CCM and DCM, L_C is given by [24], where d represents the switching duty cycle. If $L > L_C$, the converter works in the CCM; if $L < L_C$, it works in the DCM. The inductance peak current I_{LP} of the converter in the CCM and DCM are given by [24].

FIGURE 1: The schematic diagram of the buck-boost converter.

$$I_{LPCCM} = \frac{U_o(U_i + U_o)}{R_L U_i} + \frac{U_o U_i}{2Lf(U_i + U_o)}, \quad (2)$$

$$I_{LPDCM} = U_o \sqrt{\frac{2}{LfR_L}}, \quad (3)$$

where I_{LPCCM} represents the inductance peak current in the CCM and I_{LPDCM} represents the inductance peak current in the DCM. From equations (2) and (3), I_{LPCCM} decreases with increasing U_i , L , and R_L in the CCM; I_{LPDCM} is independent of U_i and decreases with increasing R_L and L in the DCM.

The laws governing the change in I_{LP} with L in different operating modes according to equations (2)–(3) are shown in Figure 2.

If the inductance valley current I_{LV} is always larger than the output current I_o in a switching cycle, the buck-boost converter operates in the complete inductance supply mode (CISM); otherwise, it operates in the incomplete inductance supply mode (IISM). The critical inductance L_K of the CISM and IISM [24] is given by the following:

$$L_K = \frac{R_L(1-d)^2}{2fd} = \frac{R_L U_i^2}{2fU_o(U_i + U_o)}, \quad (4)$$

when $L > L_K$, the converter works in the CISM; when $L < L_K$, it works in the IISM. Substituting equation (1) into (4), it is obvious that L_C is always smaller than L_K ; therefore, the operating modes of the buck-boost converter according to L are shown in Figure 3.

As shown in Figure 3, the buck-boost converter has three operating modes: CCM-CISM, CCM-IISM, and DCM-IISM. The output ripple voltages U_{PP} of the buck-boost converter in these three operating modes are given by [23]:

$$U_{PP,CCM-CISM} = \frac{U_o^2}{R_L C f (U_o + U_i)}, \quad (5)$$

$$U_{PP,CCM-IISM} = \frac{LU_o}{2CR_L} \left[\frac{U_o}{U_i} + \frac{R_L U_i}{2Lf(U_o + U_i)} \right]^2, \quad (6)$$

$$U_{PP,DCM-IISM} = \frac{U_o}{fCR_L} \left(1 - \sqrt{\frac{2Lf}{R_L}} + \frac{Lf}{2R_L} \right). \quad (7)$$

The laws governing the change in U_{PP} with L in different operating modes according to equations (5)–(7) are shown in Figure 4.

FIGURE 2: I_{LP} vs. L in different operating modes. FIGURE 3: Operating modes vs. L . FIGURE 4: U_{pp} vs. L in different operating modes.

According to Figure 4, U_{pp} decreases with increasing L in the IISM and U_{pp} is independent of L in the CISM.

2.2. Inductance Design Based on Electric Performance Demands. According to Figure 3, L affects the operating modes in which the buck-boost converter works. Assuming that the range of U_i is $[U_{i\min}, U_{i\max}]$ and the range of R_L is $[R_{L\min}, R_{L\max}]$, the laws of the changes in the operating modes with L, U_i , and R_L are shown in Figure 5.

In Figure 5, $L_1 > L_2 > L_3 > L_4$, and the shaded area indicates that the converter is working in the CCM, and in the other areas, it works in the DCM. The larger the inductance L is, the larger the area in which the converter operates in the CCM. For each figure, the inductance

FIGURE 5: Operating modes vs. L, U_i and R_L .

valley current I_{LV} decreases as R_L and U_i increase, and after it drops to zero completely, the converter's operating mode changes from the CCM to the DCM. According to equations (2)–(3) and Figure 4, I_{LP} and the current stress of the switch will be too large if the converter always works in the DCM in the assumed $U_i - R_L$ area. Moreover, I_{LP} increases with increasing I_o . Therefore, to ensure that I_{LP} will not be too large when I_o is large, the converter is better designed to work in the CCM at least when the output current I_o reaches the maximum. In this case, the operating mode within the assumed $U_i - R_L$ working area is shown in Figure 6.

Thus, the minimum inductance that meets the electric performance demands $L_{E\min}$ is L_C when the converter works at $U_{i\max}$ and $R_{L\min}$. According to equation (1), $L_{E\min}$ is given by the following:

$$L_{E\min} = \frac{R_{L\min} U_{i\max}^2}{2f(U_{i\max} + U_o)^2}. \quad (8)$$

2.3. Capacitance Design Based on Electric Performance Demands. After the inductance is determined, the capacitance should be determined based on the maximum output ripple voltage $U_{pp\max}$ in the assumed $U_i - R_L$ working area to meet the electric performance demand. If the converter works in the CCM when the output power is large (such as in the case of L_3 in Figure 5), the maximum output ripple voltage $U_{pp\max}$ is obtained when the converter works at $U_{i\max}$ and $R_{L\min}$ in the CCM-IISM. Thus, the minimum capacitance $C_{E\min}$ that can meet the electric performance demand is given by [25]:

$$C_{E\min} = \frac{L}{2mR_{L\min}^2} \left[\frac{U_o}{U_{i\min}} + \frac{R_{L\min} U_{i\min}}{2Lf(U_{i\min} + U_o)} \right]^2, \quad (9)$$

where $m = U_{pp\max}/U_o$. The change laws for $C_{E\min}$ according to L and m are shown in Figure 7.

According to Figure 7, the larger $U_{pp\max}$ is, the lower $C_{E\min}$ is. $C_{E\min}$ decreases first and then increases with increasing L .

FIGURE 6: Operating mode to meet electric performance.

FIGURE 7: C_{Emin} vs. L and m .

3. Design Consideration Based on the Inner-Intrinsic Safety Demand

The buck-boost converter is a time-varying and nonlinear circuit with multiple operating modes. Therefore, it is necessary to analyze its operating characteristics to obtain the most dangerous IDD condition and the IDD characteristics in this condition.

3.1. The Most Dangerous Condition of the Inductor-Disconnected Discharge. The buck-boost converter has two equivalent circuits according to the switching state, as shown in Figure 8.

Figure 8 shows that the arc energy W_{arc} is provided by the power source and the inductance in the switch-on state; thus, the switch-on state arc energy $W_{arc.on}$ is as follows:

$$W_{arc.on} = W_{U_i} + W_L, \quad (10)$$

where W_{U_i} represents the arc energy provided by the power supply and W_L represents the inductive energy.

In the switch-off state, W_L supplies the arc, C , and R_L . Thus, the switch-off state arc energy $W_{arc.off}$ is given as follows:

$$W_{arc.off} = W_L - W_{RC}, \quad (11)$$

where W_{RC} represents the energy consumed by C and R_L .

Comparing equations (10) and (11), it can be seen that when the IDD occurs completely in the switch-on state, W_{arc} is maximized, and the inductive energy W_L is entirely supplied to the arc. W_L can be expressed as follows:

$$W_L = \frac{1}{2} L i_L^2, \quad (12)$$

where i_L represents the inductance current. According to equation (12), if i_L is equal to I_{LP} , W_{arc} is equal to the maximum arc energy $W_{arc.max}$. Therefore, the most dangerous IDD condition of the buck-boost converter is that IDD occurs when i_L is equal to I_{LP} , and the switch remains in the switch-on state.

3.2. Maximum Inductor-Disconnected Discharge Characteristics. Based on the above analysis, the most dangerous IDD condition of the buck-boost converter is obtained. The IDD ignition capability is strongest in the most dangerous IDD condition. Therefore, research on IDD behavior in the most dangerous condition is necessary.

In the most dangerous IDD condition, the buck-boost converter is equivalent to a simple inductive circuit with wire resistance. The typical arc voltage u_{arc} and arc current i_{arc} waveforms of the simple inductive circuit based on the IEC spark test apparatus are shown in Figure 9.

In Figure 9, T represents the arc discharge time, $u_{arc.max}$ represents the maximum arc voltage, $i_{arc.max}$ represents the maximum arc current, and $u_{arc.min}$ represents the minimum arc voltage, which is mainly determined by the electrode material and is approximately 10 V in the IDD based on the IEC spark test apparatus. According to the change trend of u_{arc} , the IDD can be divided into three stages:

- (I) Arc-building stage: the electrode begins to break, the voltage at the breaking point rises rapidly from zero to the minimum arcing voltage, and the arc is formed.
- (II) Arc-discharging stage: at this stage, u_{arc} rises to $u_{arc.max}$, and i_{arc} drops to approximately zero. The process is mainly affected by the circuit parameters.
- (III) Glow-discharging stage: the arc is basically extinguished, and the remaining energy (if any) oscillates back and forth between the equivalent capacitance between the inductance and the

FIGURE 8: Equivalent circuits of the buck-boost converter. (a) Switch on. (b) Switch off.

FIGURE 9: Typical IDD volt-amp waveform. (a) Arc voltage. (b) Arc current.

breaking electrode and is eventually consumed in the circuit resistance.

Since i_{arc} is approximately zero in stage III, the release of arc energy and the generation of Joule heat mainly occur in stages I and II. In these two stages, u_{arc} increases from zero to $u_{\text{arc,max}}$ and finally equals U_i , whereas i_{arc} decreases from $i_{\text{arc,max}}$ to zero. Therefore, $u_{\text{arc,max}}$ and $i_{\text{arc,max}}$ of the buck-boost converter in the most dangerous IDD condition are given by the following:

$$u_{\text{arc,max}} = \max\{U_i + |U_L|\} = \max\left\{U_i + \left|L \frac{di_{\text{arc}}}{dt}\right|\right\}, \quad (13)$$

$$i_{\text{arc,max}} = I_{LP}, \quad (14)$$

where U_L represents the IDD inductor voltage. However, $u_{\text{arc,max}}$ is random. Based on the linear attenuation model, it can be assumed that i_{arc} decreases linearly from I_{LP} to zero within the discharge time T ; thus, equation (13) can be simplified as follows:

$$u_{\text{arc,max}} = U_i + L \frac{I_{LP}}{T}. \quad (15)$$

According to equations (14) and (15), the maximum arc power $P_{\text{arc,max}}$ is given by the following:

$$P_{\text{arc,max}} = u_{\text{arc,max}} i_{\text{arc,max}} = U_i I_{LP} + L \frac{I_{LP}^2}{T}. \quad (16)$$

3.3. Critical Ignition Power of the Inductor-Disconnected Discharge. The maximum arc power $P_{\text{arc,max}}$ of the buck-boost converter is obtained. Although the arc power P_{arc} used in the test is random, it will never be greater than $P_{\text{arc,max}}$. If $P_{\text{arc,max}}$ has the capability to ignite explosive gases, P_{arc} used in the test will also have a chance of igniting explosive gases. Therefore, the inner-intrinsic safety performance of the buck-boost converter can be judged according to whether $P_{\text{arc,max}}$ has the capability to ignite explosive gases.

The change laws for the minimum ignition current I_{MIC} for U_i can be obtained from the Type I MIC of the resistive circuit [26]. Based on power function regression analysis, the relationship between I_{MIC} and U_i is approximately given by the following:

$$I_{MIC} = 22.35 (V_i - 14)^{-1.24}. \quad (17)$$

Comparing I_{MIC} obtained by equation (17) and the Type I MIC of the resistive circuit under different U_i , the results are shown in Table 1.

According to Table 1, the relative errors of I_{MIC} obtained by equation (17) and the Type I MIC of the resistive circuit are less than $\pm 5\%$, which proves the feasibility and accuracy of equation (17). According to equation (17), the critical ignition power P_{CI} of the resistive circuit is given by the following:

$$P_{CI} = U_i I_{MIC} = (12.25 I_{MIC}^{(25/31)} + 14) I_{MIC}. \quad (18)$$

According to Figure 8(a) and equation (13), the buck-boost converter in the most dangerous IDD condition can be taken as the equivalent to the resistive circuit consisting of the input voltage source U_i , the controlled voltage source $U_L = L di_{arc}/dt$, and the wire resistance R_{wire} shown in Figure 10.

In Figure 10, G is the discharge electrode. Based on the proposed equivalent circuit, if $P_{arc,max}$ is greater than P_{CI} , the IDD of the buck-boost converter will have the capability to ignite methane-air mixtures. Combining equations (15) and (18), the following can be derived:

$$U_i I_{LP} + L \frac{I_{LP}^2}{T} = P_{arc,max} \leq P_{CI} = (12.25 I_{LP}^{-(25/31)} + 14) I_{LP}. \quad (19)$$

If equation (19) holds, then the buck-boost converter is inner-intrinsically safe based on the arc power; otherwise, it is dangerous. To explore the influence of the converter parameters on the ignition capability based on the arc power, the change laws of $P_{arc,max}$ and P_{CI} in terms of U_i , R_L , and L are shown in Figure 11.

When $P_{arc,max} < P_{CI}$, the buck-boost converter is an inner-intrinsically safe converter; when $P_{arc,max} \geq P_{CI}$, the converter will have the capability to ignite methane-air mixtures, and the greater the difference is between $P_{arc,max}$ and P_{CI} , the stronger the ignition capability.

According to Figure 11, P_{CI} decreases with increasing L and R_L , is independent of U_i in the DCM, and decreases with increasing U_i in the CCM.

$P_{arc,max}$ decreases with increasing R_L , increases with increasing U_i when L is small, decreases with increasing U_i when L is large, and first decreases and then increases with increasing L . Therefore, the IDD ignition capability is

TABLE 1: Errors of I_{MIC} between regression expression and MIC.

U_i (V)	I_{MIC} by equation (17) (A)	I_{MIC} by MIC (A)	Relative error (%)
20	2.423	2.35	3.11
30	0.718	0.74	-2.97
40	0.393	0.41	-4.14
50	0.263	0.26	1.15
60	0.194	0.185	4.86
70	0.152	0.145	4.83
80	0.124	0.12	3.33
90	0.104	0.105	-0.95
100	0.089	0.088	1.14
200	0.034	0.033	3.03

FIGURE 10: Equivalent resistive circuit of the buck-boost converter in the most dangerous IDD condition.

strongest when the converter operates at $U_{i,max}$ and $R_{L,min}$ based on the arc power.

3.4. Critical Ignition Energy of the Inductor-Disconnected Discharge. For the IDD of the buck-boost converter, the effect of the arc energy on the ignition capability should also be analyzed.

According to equation (12), W_L is affected by L and i_L . The minimum ignition current I_{MIC} with different values of inductance L can be obtained from the Type I MIC of the simple inductive circuit [26]. Suppose W_{arc} is equal to the critical ignition energy W_{CI} ; then, according to equations (10) and (12), the critical inductive energy W_{LCI} is given by the following:

$$W_{LCI} = \frac{1}{2} L I_{MIC}^2 = W_{CI} - W_{U_i}. \quad (20)$$

According to the Type I MIC of the simple inductive circuit, when $I_{LP} < 0.4$ A, the energy provided by the power source W_{U_i} is negligible; thus, W_{arc} is mainly provided by L , so W_{LCI} is approximately constant at $525 \mu J$; when $I_{LP} \geq 0.4$ A, W_{LCI} is not constant. In this condition, W_{LCI} decreases with increasing U_i when $U_i < 18$ V, and W_{LCI} is independent of U_i when $U_i \geq 18$ V. Therefore, based on the power function regression analysis, the change laws of W_{LCI} with U_i and I_{LP} are given by the following:

FIGURE 11: $P_{\text{arc.max}}$ and P_{CI} vs. L . (a) Different U_i ($T = 200 \mu\text{s}$, $U_o = 18 \text{ V}$, $R_L = 36 \Omega$, and $f = 200 \text{ kHz}$). (b) Different R_L ($T = 200 \mu\text{s}$, $U_o = 18 \text{ V}$, $U_i = 20 \text{ V}$, and $f = 200 \text{ kHz}$).

$$W_{\text{LCI}} = \begin{cases} 525 \times 10^{-6}, & (I_{LP} < 0.4 \text{ A}), \\ 3.28 I_{LP}^2 (2.5 I_{LP})^{-1.596 - 0.012 \exp(0.187 U_i)} \times 10^{-3}, & (I_{LP} \geq 0.4 \text{ A}, U_i < 18 \text{ V}), \\ 0.55 I_{LP}^{0.05} \times 10^{-3}, & (I_{LP} \geq 0.4 \text{ A}, U_i \geq 18 \text{ V}). \end{cases} \quad (21)$$

Comparing W_{LCI} obtained by equation (21) and the Type I MIC of the simple inductive circuit under different U_i and I_{LP} , the results are shown in Table 2.

According to Table 2, the relative errors of W_{LCI} obtained by equation (21) and the Type I MIC of the simple inductive circuit are less than $\pm 5\%$, which proves the feasibility and accuracy of equation (21). Equation (21) shows that if $W_L < W_{\text{LCI}}$, the buck-boost converter will be inner-intrinsically safe based on the arc energy.

To investigate the influence of the converter parameters on the ignition capability based on the arc energy, the change laws of W_L and W_{LCI} with U_i , R_L , and L are shown in Figure 12.

According to Figure 12, W_{LCI} and W_L decrease with increasing U_i and R_L ; W_{LCI} decreases and tends to be stable with increasing L ; W_L increases with increasing L and I_{LP} and decreasing U_i . Therefore, the IDD ignition capability is strongest when the converter operates at $U_{i\min}$ and $R_{L\min}$ based on the arc energy. It can also be concluded that in low-voltage and large-current conditions, W_{LCI} is not constant but changes with U_i and I_{LP} only when $I_{LP} < 0.4 \text{ A}$ is W_{LCI} equal to $525 \mu\text{J}$. This is consistent with the conclusions regarding the Type I MIC of the simple inductive circuit.

3.5. Inductance Design Based on Inner-Intrinsic Safety Demands. According to Figure 11, there is a maximum

inductance $L_{P\max}$ and a minimum inductance $L_{P\min}$ based on power, which are shown in Figure 13.

If $L > L_{P\max}$ or $L < L_{P\min}$, $P_{\text{arc.max}}$ will be greater than P_{CI} , and the IDD of the converter will have the capability to ignite methane-air mixtures in both conditions. According to Figure 13, the inductance design range based on power L_p is given by the following:

$$L_p \in [L_{P\min}, L_{P\max}]. \quad (22)$$

As shown in Figure 11, $L_{P\max}$ decreases as U_i increases and R_L decreases; $L_{P\min}$ increases as U_i increases and R_L decreases. Therefore, the values of $L_{P\max}$ and $L_{P\min}$ when the converter is operating in the $U_{i\max}$ and $R_{L\min}$ conditions should be considered in the design.

According to Figure 12, there is a maximum inductance based on the energy $L_{W\max}$, which is shown in Figure 14. If $L > L_{W\max}$, W_L will be greater than W_{LCI} . Thus, the converter IDD will have the capability to ignite methane-air mixtures.

By incorporating Figure 14, the inductance design range based on the energy L_W is given by the following:

$$L_W \in [0, L_{W\max}]. \quad (23)$$

From Figure 12, $L_{W\max}$ decreases as U_i and R_L increase. Therefore, the value of $L_{W\max}$ when the converter is operating in the $U_{i\min}$ and $R_{L\min}$ conditions should be considered in the design.

TABLE 2: Error of W_{LCI} between regression expression and MIC.

U_i (V)	I_{LP} (A)	W_{LCI} by equation (21) (μJ)	W_{LCI} by MIC (μJ)	Relative error (%)
8	0.3	525	517	1.55
8	1	771.44	750	2.86
8	3	1224.33	1215	0.77
12	0.5	568.5	587.5	3.18
12	1	730.44	700	4.35
12	3	1085.78	1057.5	2.67
18	0.5	539.82	537.5	0.43
18	1	589.27	575	2.48
18	3	677.09	652.5	3.77

FIGURE 12: W_{LCI} and W_L vs. L and U_i . (a) Different U_i ($T = 200 \mu s$, $U_o U_o = 18 V$, $R_L = 36 \Omega$, and $f = 200 kHz$). (b) Different R_L ($T = 200 \mu s$, $U_o = 18 V$, $U_i = 20 V$, and $f = 200 kHz$). FIGURE 13: The inductance design range based on power ($T = 200 \mu s$, $U_o = 18 V$, $R_L = 36 \Omega$, and $f = 200 kHz$).

FIGURE 14: The inductance design range based on energy ($T = 200 \mu s$, $U_o = 18 V$, $R_L = 36 \Omega$, and $f = 200 kHz$).

3.6. Inductance Optimization Based on Inner-Intrinsic Safety Demands. According to Figure 13, there is an optimal

$$\begin{aligned} & \frac{4.94U_iU_o}{L^2f(U_i+U_o)}I_{LPCCM}^{-(25/31)} + \frac{U_i^2U_o}{2L^2f(U_i+U_o)} + \frac{I_{LPCCM}U_iU_o}{LTf(U_i+U_o)} - \frac{I_{LPCCM}^2}{T(L)} \\ & + \frac{I_{LPCCM}U_iU_o}{T(L)Lf(U_i+U_o)} + \frac{I_{LPCCM}^2L[T(L)]'}{[T(L)]^2} - \frac{U_iU_o(12.25I_{LPCCM}^{-(25/31)} + 14)}{2Lf(U_i+U_o)} = 0, \end{aligned} \quad (25)$$

where $T(L)$ represents the discharge time T affected by the inductance L . The root of equation (25) is the optimal inductance L_{opt} that maximizes the power difference P_Δ .

To investigate the influence of U_i on the design and optimization of inductance, the laws governing the change

inductance L_{opt} that maximizes the power difference P_Δ between P_{CI} and $P_{arc,max}$ when the converter operates in the $U_{i,max}$ and $R_{L,min}$ conditions. Thus, this inductance will cause the buck-boost converter to have the maximum safety margin of the inner-intrinsic safety performance based on power.

Since $L > L_{E,min}$, the converter works in the CCM when $R_L = R_{L,min}$. According to equation (19), the power difference P_Δ can be obtained by the following:

$$P_\Delta = \left(12.25I_{LPCCM}^{-(25/31)} - U_{i,max} - L \frac{I_{LPCCM}}{T} + 14 \right) I_{LPCCM}. \quad (24)$$

For the first derivative of equation (24) is equal to zero, we can obtain

in L_P , L_W , $L_{E,min}$, and L_{opt} with U_i are shown in Figure 15. The discharge time T can be determined from the IDD time model based on the IEC spark test apparatus [27], which is given by

$$T(L) = (2.98 + 1.66 \times 10^3 L + 221.37 I_{LP} - 119.38 I_{LP}^2 - 25.67 I_{LP}^3 + 24.1 I_{LP}^4) \times 10^{-6}. \quad (26)$$

In Figure 15, the shaded area is the design range in which the inductance L meets the demands of inner-intrinsic safety and electric performance. To ensure that the IISBBC has the best inner-intrinsic safety performance in the most dangerous condition, the inductance L should be as close to L_{opt} as possible.

4. Experimental Verification

4.1. Design of the Inner-Intrinsically Safe Buck-Boost Converter. Two groups of the main system and component parameters of the IISBBC are shown in Table 3.

According to Figure 15 and Table 3, in these parameters, when U_i is higher than 24 V, L will have no value to meet the electrical performance and inner-intrinsic safety demands. Therefore, considering the working demands and voltage fluctuations, U_i of the IISBBC is set to 14–22 V and divided into two groups of low-input voltage (Group 1) and high-input voltage (Group 2). Taking Group 1 as an example, the design steps are as follows:

- (1) According to the above parameters and equation (8), the inductance L must be greater than $L_{E,min}$, which is given by the following:

FIGURE 15: L_p , L_W , L_{Emin} , and L_{opt} vs. U_i ($U_o = 18$ V, $R_L = 36$ Ω , and $f = 200$ kHz).

TABLE 3: Main system and component parameters.

Variables	Group 1	Group 2
U_i	14–18 V	18–22 V
U_o	18 V	18 V
R_L	36–90 Ω	36–90 Ω
f	200 kHz	200 kHz
U_{pp}	1% U_o	1% U_o

$$L \geq L_{Emin} = \frac{R_{Lmin} U_{i max}^2}{2f(U_{i max} + U_o)^2} = 22.5 \mu H. \quad (27)$$

- (2) The inductance L must ensure that there is no IDD ignition capability when the converter operates at $U_{i max}$ and R_{Lmin} based on the arc power. Since $L > L_{Emin}$, the converter works in the CCM when $R_L = R_{Lmin}$. Combining equations (2) and (19), the maximum inductance L_{Pmax} and the minimum inductance L_{Pmin} based on the arc power can be obtained by

$$U_{i max} I_{LPCCM} + L \frac{I_{LPCCM}^2}{T} = (12.25 I_{LPCCM}^{-(25/31)} + 14) I_{LPCCM}. \quad (28)$$

Solving equation (28), we obtain the following:

$$\begin{cases} L_{Pmin} = 7.51 \mu H, \\ L_{Pmax} = 813.92 \mu H. \end{cases} \quad (29)$$

According to equation (22), the inductance design range based on power L_p is given by the following:

$$7.51 \leq L_p \leq 813.92 \mu H. \quad (30)$$

- (3) The inductance L must ensure that there is no IDD ignition capability when the converter operates at $U_{i min}$ and R_{Lmin} based on the arc energy. Since the expression of W_{LCI} is different according to U_i and I_{LP} , the minimum inductance peak current I_{LPmin} needs to be determined. According to equation (2), I_{LP} decreases to I_{LPmin} when L is infinite, which is given by the following:

$$I_{LPmin} = \frac{U_o(U_{i min} + U_o)}{R_{Lmin} U_{i min}} = 1.14 \text{ A} > 0.4 \text{ A}. \quad (31)$$

Combining equations (12) and (21) and substituting the parameters, the maximum inductance based on the energy L_{Wmax} can be obtained by

$$L_{Wmax} = 3.28 I_{LPCCM}^2 (2.5 I_{LPCCM})^{-1.596 - 0.012 \exp(0.187 U_i)} \times 10^{-3}. \quad (32)$$

Solving equation (32), we obtain

$$L_{Wmax} = 1003.11 \mu H. \quad (33)$$

According to equation (23), the inductance design range based on the energy L_W is given by the following:

$$0 \leq L_W \leq 1003.11 \mu H. \quad (34)$$

- (4) According to equations (25) and (26), the optimal inductance L_{opt} is as follows:

$$L_{opt} = 74.05 L \mu H. \quad (35)$$

To ensure that the IISBBC has the the best inner-intrinsic safety performance, the inductance L is taken as L_{opt} .

- (5) According to equation (9), C_{Emin} is 9.437 μF . Thus, we can set C equal to 22 μF to meet the electric performance demand.

Similarly, the inductance design range of Group 2 can be obtained. The inductance design ranges of these two groups of IISBBC are shown in Table 4.

The design ranges of inductance and capacitance obtained by the proposed method and design method based on the MIC [24] are compared in Table 5.

The design method based on the MIC takes L_{Emin} as the initial value, iterates by querying the MIC after considering the safety margin λ ($\lambda = 1.5$ in Table 5), and obtains the maximum inductance that meets the inner-intrinsically safe performance demands. However, this method is more complicated, and reading errors may accumulate by querying the MIC multiple times; thus, the accuracy of the method is reduced. Moreover, according to Group 2 in Table 5, when U_i is large, there is a case where the critical ignition current I_{MIC} corresponding to L_{Emin} fails to meet the intrinsic safety demand, and the iteration cannot be performed. Thus, the applicability of the method is also reduced.

TABLE 4: Inductance design range of IISBBC.

Variables	Group 1 (μH)	Group 2 (μH)
$L_{E\min}$	22.5	28.225
$L_{P\min}$	7.51	38.29
$L_{P\max}$	813.92	508.98
$L_{W\max}$	1003.11	1100.11
L_{opt}	74.05	137.78

TABLE 5: Comparison of the inductance and capacitance design ranges.

	Variables	Proposed method	Method based on the MIC
Group 1	L	$22.5 \leq L \leq 813.92 \mu\text{H}$	$22.5 \leq L \leq 349.88 \mu\text{H}$
	L_{opt}	74.05 μH	None
	C (if $L = L_{\text{opt}}$)	$9.437 \mu\text{F} \leq C$	$9.437 \mu\text{F} \leq C$
Group 2	L	$38.29 \leq L \leq 508.98 \mu\text{H}$	
	L_{opt}	137.78 μH	N/A
	C (if $L = L_{\text{opt}}$)	$9.355 \mu\text{F} \leq C$	

The proposed design method considers the effect of the critical ignition power and energy on the IDD ignition capability. According to the analysis of the critical ignition power, if L is too large or too small, the IDD can ignite methane-air mixtures, which contradicts the idea of the design method based on the MIC that L meets the intrinsically safe performance demand and should be as small as possible. Moreover, based on the principle that the converter has the largest safety margin of IDD, the optimal inductance L_{opt} is obtained. Thus, the inductance design method is clearer. According to the analysis of the critical ignition energy, W_{LCI} is affected by L , I_{LP} , and U_i . Therefore, the critical ignition energy W_{CI} is generally not considered to be constant. The main difference between these two methods is the design consideration based on the inner-intrinsic safety performance. However, the design considerations based on the electrical performance are basically identical, so the two methods have consistent $L_{E\min}$ and $C_{E\min}$.

4.2. Explosive Test Based on the IEC Spark Test Apparatus. The IISBBCs were tested by the IEC spark test apparatus. The IEC spark test apparatus [28] and its structure are shown in Figure 16, where the tungsten wire and the cadmium disk are the disconnected electrodes.

The disconnected points of the tested circuit are connected with these two electrodes. The disconnected electrodes are contacted and disconnected through the transmission gear rotates so that the circuit is turned on and off [29, 30].

The steps of the explosive test are as follows:

- (1) Prepare a gas mixture corresponding to an explosive environment. The Type I environment is a methane-air mixture with a concentration ratio of 8–8.6%. Clean the electrodes.
- (2) Calibrate the sensitivity of the apparatus. The calibration circuit is a simple inductive circuit with parameters of supply voltage $E = 24 \text{ V}$, inductance

$L = 95 \text{ mH}$, and current $I = 110 \text{ mA}$. If an explosion occurs within 400 revolutions of the transmission gear, the sensitivity calibration of the apparatus is qualified. The explosive evaluation of the tested circuit can be carried out only after the apparatus sensitivity has been calibrated three times.

- (3) The IISBBC is connected to the resistive load and the IEC spark test apparatus for the explosive tests. If an explosion occurs within 400 revolutions of the transmission gear, the tested circuit has ignition capability; otherwise, it is intrinsically safe.

To verify the effectiveness of inductance optimization, the theoretical and experimental values of the difference P_{Δ} between the critical ignition power P_{CI} and the maximum arc power $P_{\text{arc,max}}$ under different L are shown in Figure 17.

According to Figure 17, the closer L is to L_{opt} , the larger P_{Δ} is, and the maximum P_{Δ} is reached when L is equal to L_{opt} . The inner-intrinsic safety performance of the IISBBC has the maximum safety margin based on the arc power, which proves the effectiveness of the inductance optimization.

However, it can be found that the margin of the test value is smaller than the theoretical value. This is due to the parasitic parameters of the converter, which makes the inductance peak current I_{LP} greater than the theoretical value, which reduces the safety margin. However, the safety margin of L_{opt} is still the largest.

To verify the feasibility and reliability of the proposed design method, explosive tests were performed on buck-boost converters with different inductances. The test results are shown in Table 6.

According to Table 5, when L is within the design range that meets the inner-intrinsic safety performance demands, IDD will not have the ignition capability, which verifies the feasibility of the proposed design method.

Moreover, if L is near the boundary between the inner-intrinsic safety and dangerous range, it still does not have ignition capability. This is because the proposed method

FIGURE 16: IEC spark test apparatus. (a) Prototype appearance. (b) Structural schematic.

FIGURE 17: P_A vs. L of the IISBBC in the explosive test ($U_i = 22$ V, $U_o = 18$ V, $C = 22$ μ F, $R_L = 36$ Ω , and $f = 200$ kHz).

TABLE 6: Explosive test results ($U_i = 22$ V, $U_o = 18$ V, $C = 22$ μ F, $R_L = 36$ Ω , and $f = 200$ kHz).

Design range	Critical value	Inductance (μ H)	Results
Unsafe		20	Exploded
		35	Unexploded
Inner-intrinsically safe	$L_{P \min}$	38.29	Unexploded
		50	Unexploded
	L_{opt}	137.78	Unexploded
		300	Unexploded
Unsafe	$L_{P \max}$	508.98	Unexploded
		520	Unexploded
		900	Exploded
		1095.11	Exploded
		1500	Exploded

considers the most dangerous condition, and the actual IDD ignition capability is weaker than this condition, so it has a safety margin, which verifies the reliability of the proposed design method.

However, the proposed design method does not consider the output intrinsic safety performance of the converter, so further research on this is needed.

5. Conclusion

- (1) The most dangerous IDD condition of the buck-boost converter is that IDD occurs when i_L is equal to I_{LP} and the switch remains on. In this condition, a resistive circuit model with a controlled voltage source is proposed to represent the buck-boost converter.
- (2) Expressions describing the IDD ignition capability of the buck-boost converter in terms of the critical ignition power and energy were derived. P_{CI} decreases with increasing R_L and L , is independent of U_i in the DCM, and decreases with increasing U_i in the CCM. $P_{arc,max}$ decreases with increasing R_L , increases with increasing U_i when L is small, decreases with increasing U_i when L is large, and first decreases and then increases with increasing L . W_{LCI} and W_L decrease with increasing U_i and R_L ; W_{LCI} decreases and tends to be stable with increasing L ; W_L increases with increasing L and I_{LP} and decreasing U_i . Therefore, the IDD has the strongest ignition capability based on power when the buck-boost converter operates in the $U_{i,max}$ and $R_{L,min}$ conditions and has the strongest ignition capability based on energy when the converter operates in the $U_{i,min}$ and $R_{L,min}$ conditions. When $P_{arc,max} \geq P_{CI}$ or $W_L \geq W_{LCI}$, the IDD of the buck-boost converter will have the capability to ignite methane-air mixtures; thus, the converter is inner-intrinsically safe only when $P_{arc,max} < P_{CI}$ and $W_L < W_{LCI}$.
- (3) The optimal method for designing an IISBBC to meet the demands of electric and inner-intrinsic safety performance was obtained. Based on this method,

the ranges of L , C , and L_{opt} to design an IISBBC with the best inner-intrinsic safety performance can be obtained. The increased applicability of the proposed optimal design method compared with the design method based on querying the MIC was shown; the accuracy, feasibility, and reliability of the proposed optimal design method were demonstrated by comparison in explosion tests based on the IEC spark test apparatus.

Data Availability

The data used to support the findings of this study are included within this article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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