

Design of quasi-resonant flyback secondary intrinsically safe power supply

SHENGNAN LU¹, BIN WANG²

¹Xi'an Shiyou Universtiy, China

²State grid Corporation of China, China
e-mail: lushengnan@xsyu.edu.cn

(Received: 02.05.2018, revised: 17.09.2018)

Abstract: In order to improve the efficiency and ensure the security of power supply used in a mine, this paper mainly studies the quasi-resonant flyback secondary power supply and analyzes its operational principles based on the requirements of soft-switching technology. In accordance with the maximum energy of a short-circuit and the request of maximum output voltage ripple, this paper calculates the spectrum value of the output filter capacitor and provides its design and procedures to determine the parameters of the main circuit of power supply. The correctness and availability of this theory are eventually validated by experiments.

Key words: intrinsic safety, secondary power supply, quasi-resonant technology

1. Introduction

Presently, in the coal industry, there exist various kinds of power and electrical equipment with different voltage levels, which makes the issue of the power supply system very complicated. To solve this problem, different power architectures are adopted. The power architecture can be divided into three types: central centralized power architecture, distributed power architecture and intermediate bus architecture [1]. The distributed power architecture has the first switching converter to provide a bus voltage (typically 48 V or 24 V), and then a secondary switching converter is used to convert the bus voltage to the desired voltage level according to different load requirements. The structure of an intrinsically safe [2–5] power supply system is shown in Fig. 1.

Here the secondary switching converter is called a secondary power supply. At present, an increasing number of secondary intrinsically safe power supplies [6] have come into underground use. At the same time, with the advancement in switching power supply technology, more and more new technologies have been applied to the design of intrinsically safe power supply. The quasi-resonant technique [7, 8], as a simple and effective one which could reduce the switching losses and electromagnetic interference (EMI), is available in many LED solutions and power

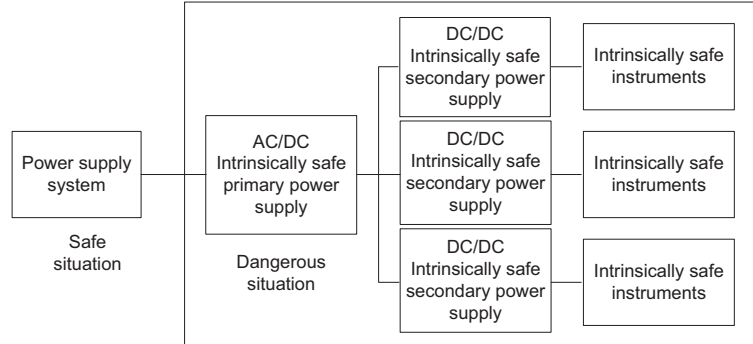


Fig. 1. Structure of intrinsically safe power supply system

adapter solutions [9]. However, its application in intrinsically safe power supply application is rare. This study designs a secondary converter intrinsically safe power supply [10] based on the output intrinsically safe theory in order to improve its efficiency, thereby increasing the load efficiency of the first-stage intrinsically safe power supply.

2. Operating principles of quasi-resonant flyback converter

The schematic diagram of a quasi-resonant flyback converter is shown in Fig. 2.

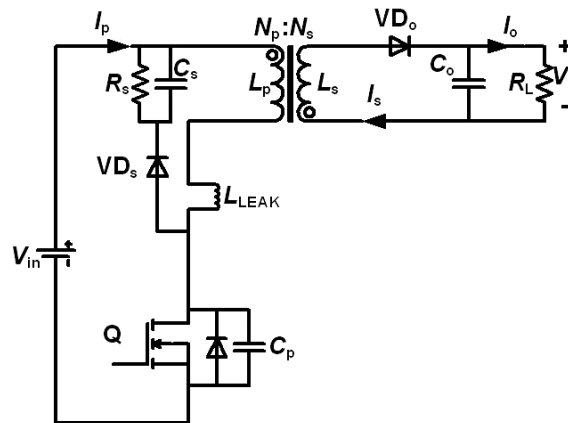


Fig. 2. Schematic diagram of quasi-resonant flyback converter

V_{in} is the input voltage, i_p is the primary instantaneous current, i_s is the secondary instantaneous current, L_p is the primary winding inductance, L_s is the secondary winding inductance, L_{LEAK} is the primary winding leakage inductance, Q is the power switch, C_p is the resonant capacitor, N_p and N_s , respectively, refer to the turns of the primary and secondary winding coil, VD_o is

the freewheeling diode, C_o is the output filter capacitor, V_o is the output voltage, R_L is the load resistance.

When the power switch Q is on, the reverse biased voltage borne by the freewheeling diode VD_o is off, the current i_p flowing through the inductor L_p shows a linear increase, and the inductor L_p converts the electrical energy to magnetic energy and stores it in the inductor L_p . At this time, the output filter capacitor C_o achieves power supply for the load; when the power switch Q is off, the resonance occurs between the parasitic capacitance C_p and parasitic leakage inductance L_{LEAK} , and then the primary inductance L_p of transformer degausses. After degaussing, the resonance occurs between C_p and L_p so that the drain voltage of the power switch Q shows a variation with damped oscillation, and the system will choose one from various valleys of the resonant drain voltage waveform of the power switch Q to start a new switching cycle.

3. Analysis of energy in secondary side

To achieve the effect of opening the metal-oxide semiconductor field-effect transistor (MOS-FET) at the valley, the quasi-resonant flyback converter can only work in DCM mode. The secondary inductor current and the waveform of a capacitor voltage at both ends are shown in Fig. 3.

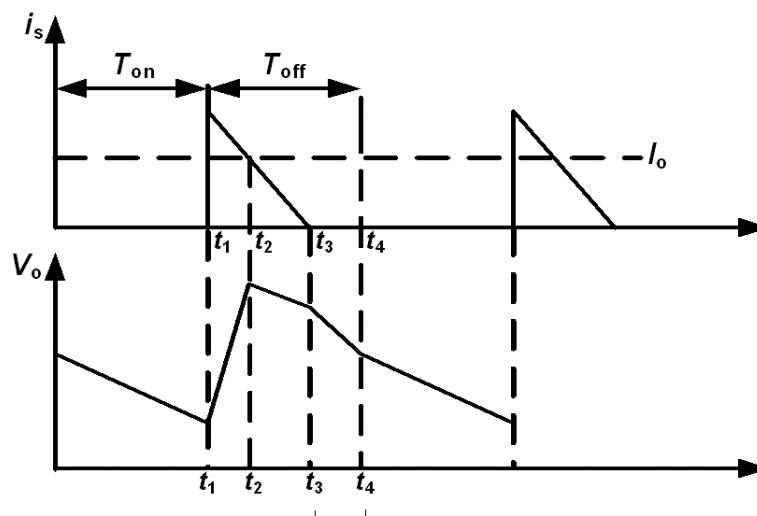


Fig. 3. Waveform of inductor current and the capacitor voltage of converter in DCM mode

The energy conversion process of a quasi-resonant flyback converter can be divided into three stages after the disconnection at the time of t_1 :

Stage 1, energy supplied by inductors ($t_1 \sim t_2$), as shown in Fig. 4(a). The secondary inductance L_s charges the capacitor. As the current i_s of the secondary inductor is greater than the output current I_o , the secondary inductance L_s has to provide energy for capacitance and load

simultaneously, so that the capacitor voltage rises. This process continues until the secondary inductor current falls to the level $i_s = I_o$ at the time of t_2 .

Stage 2, energy supplied by inductors and the capacitor ($t_2 \sim t_3$). When the inductor current $i_s < I_o$, this stage begins and the inductor L_s and the capacitor energy provide energy for the load at the same time with its equivalent circuit as shown in Fig. 4(b). The capacitor voltage begins to drop until the secondary inductor current i_s is reduced to 0.

Stage 3, energy supplied by the capacitor ($t_3 \sim t_4$). At this time, the diode VD_o is off, as the next cycle has not yet arrived, so that the capacitor has to provide energy for the load and the voltage of the capacitor continues to drop with its equivalent circuit as shown in Fig. 4(c). This stage maintains until a new switching cycle begins and the secondary inductor current i_s rises again from 0.

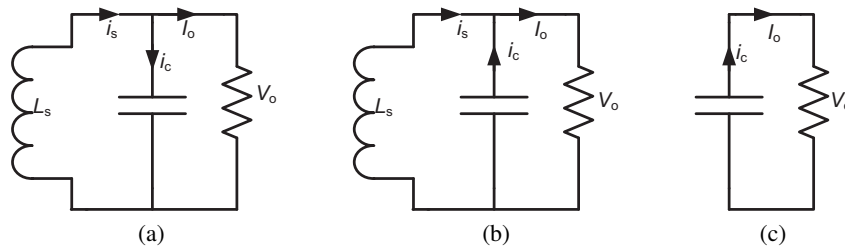


Fig. 4. The equivalent circuit diagram of converter at different stages: energy supplied by inductor (a); energy supplied by inductor and capacitor (b); energy supplied by capacitor (c)

4. Design of quasi-resonant flyback converter

A quasi-resonant flyback converter adopts the frequency converting control method, therefore, the minimum operation frequency coping with the converter should be restricted. Taking into account the fact that the upper limit of sound frequency that a human ear can hear is 20 kHz, the lowest operating frequency of the converter is greater than 20 kHz. While due to EMI noise, the switching frequency is preferably not more than 150 kHz. To make the converter always operate in the DCM mode, the corresponding critical inductance value should be selected based on the minimum input voltage and maximum output power:

$$L_c = \frac{R_{L.\min} \cdot \gamma^2 \cdot V_{in.\min}^2}{2 \cdot f_{\min} (\gamma \cdot V_{in.\min} + V_o)^2} \quad (1)$$

In the equation, $R_{L.\min}$ is the minimum load value, γ represents the transformer turn ratio, $V_{in.\min}$ refers to the minimum input voltage, f_{\min} stands for the lowest operating frequency, and V_o expresses the output voltage.

When the secondary inductance $L_s > L_c$, the flyback converter runs in CCM mode. However, when the secondary inductance $L_s < L_c$, the flyback converter runs in DCM mode.

According to the formula of the inductance of a quasi-resonant flyback converter, the following equation can be obtained:

$$L_p = \frac{2 \cdot P_o}{\eta \cdot I_{pp}^2 \cdot f_{\min}} \quad (2)$$

In the equation, P_o is the output power, η refers to the efficiency of the converter, and I_{pp} stands for the peak current of the primary inductor.

According to the turn ratio, it is possible to verify whether the converter meets the quasi-resonant working status. The turn ratio of the transformer is shown as follows:

$$\gamma = \frac{N_s}{N_p} = \frac{k_c \cdot (V_o + V_f)}{V_{\text{clamp}}} . \quad (3)$$

In the equation

$$V_{\text{clamp}} = V_{\text{dss}} \cdot k_D - V_{\text{in, max}} - V_{\text{OR}} ,$$

V_{dss} stands for the avalanche voltage of a metal-oxide-semiconductor (MOS) transistor, and k_D represents the margin coefficient (generally taken 0.8 ~ 0.85); V_{clamp} refers to the clamping voltage, V_{OR} denotes the refraction voltage, and $k_c = V_{\text{clamp}}/V_{\text{OR}}$, which represents a ratio between the clamp resistor loss and conduction losses of a MOSFET, generally between 1.0 to 1.5.

The number of primary turns is:

$$N_p = \frac{V_{\text{in, min}} \cdot D_{\text{max}}}{\Delta B \cdot A_e \cdot f_{\text{min}}} . \quad (4)$$

The number of secondary turns is:

$$N_s = \gamma \cdot N_p . \quad (5)$$

In the equation, ΔB is the maximum flux density, and A_e refers to the effective cross-sectional area of the magnetic core.

In accordance with the design conditions, the design parameters are worked out. The sandwich winding is used to reduce the leakage inductance of the transformer. The desired primary inductance value is obtained by adjusting the air gap. The above formulas help get the main transformer parameters. On the other hand, based on the premise of meeting the electrical performance, according to the standard IEC 60079-11-2011 [11] provisions, use methods of adding a shielding layer between the windings, winding retaining the wall around both sides of the transformer, and increasing the creep-age distance to meet the essential safety requirements of a quasi-resonant flyback transformer with high frequency.

5. Capacitor design of the output filter of intrinsically safe quasi-resonant flyback converter

The intrinsic safety technology has requirements for the size of a safe storage inductor and filter capacitor, which will inevitably affect the ripple voltage of the converter. Moreover, according to the output ripple voltage standard, there are different indicators for different levels. Therefore, it is necessary to analyze the output ripple voltage in order to meet requirements of output the intrinsically safe switching converter.

Based on the premise that the quasi-resonant flyback converter could meet the electrical performance and the safety requirements, the changes in the inductance value of the transformer

are identified. Then the value ranges of filter capacitor design can be obtained according to the requirements of the output ripple safety requirements. Furthermore, the following equation can be obtained under the conditions of the maximum inductor:

$$C_{\min} = \frac{V_o(\gamma V_{\text{in.min}} + 2V_o)^2}{4f_{\min} V_{\text{pp.max}} R_{L.\min}(\gamma V_{\text{in.min}} + V_o)^2}. \quad (6)$$

In the equation, $V_{\text{pp.max}}$ refers to the peak value of the maximum peak of the ripple voltage.

The analysis of the second part of this paper shows that the energy of the quasi-resonant flyback capacitor is mainly stored in the inductor, thus there must be maximum energy storage when the circuit is in different working conditions. If the output short circuit occurs during the off period of the Q switch, the main switch Q is disconnected, thereby isolating the energy pathway between grid points and short circuit contact. It can be inferred that the energy stored in the circuit is equal to the sum of the energy storage inductor L_s in a short circuit time and the energy storage of the filter capacitor. However, when the switch Q is in the ON state, the diode VD is cut off, blocking the power input energy, so the maximum energy of the output circuit is only provided by the output filter capacitor. Therefore, the instantaneous energy reaches the greatest when the switch shifts from the ON state to the OFF.

The maximum storage of the secondary inductance (L_s) is

$$W_{L_s.\max} = \frac{1}{2} L_s I_{LSP}^2,$$

where I_{LSP} is the peak current of the inductor L_s . The maximum stored energy of the output ripple capacitor is

$$W_{C.\max} = \frac{1}{2} C V_o^2 \approx \frac{1}{2} C V_o^2.$$

Here, the energy generated by the ripple voltage is ignored. Within the duration period of spark discharge, the energy consumed by the load at this time is

$$W_{RL} = \frac{V_H^2 T_C}{R_L},$$

where T_C is the spark discharge duration, and V_H is the arc voltage. Therefore, the maximum energy discharged by the spark of the output short circuit is

$$W_{\max} = W_{C.\max} + W_{L_s.\max} - W_{RL} = \frac{1}{2} (C V_o^2 + L_s I_{LSP}^2) - \frac{V_H^2 T_C}{R_L}. \quad (7)$$

The maximum discharge energy of the output circuit of the converter is transformed to the equivalent of a simple capacitor circuit. The minimum ignition voltage curve of the capacitive circuit can be used to judge the output intrinsic safety of the converter after the equivalent transformation. According to the standard IEC 60079-11-2011, it is necessary to take into account on the voltage the safety factor K (a fault, safety factor of 1.5), and then for the converter with the output voltage of V_o , the corresponding capacitance of $K V_o$ is C_B found in the minimum ignition voltage curve, while the output intrinsic safety of the converter is based on the following:

$$C_e < C_B. \quad (8)$$

The lower limit of the output filter can be obtained according to the energy analysis of the output short circuit, as the maximum energy value of the output short circuit may work in two conditions, which is obtained in the maximum load and minimum load as follows:

$$C_{1\max} = C_B + \frac{2V_H^2 T_C}{R_{L.\max} V_o} - \frac{2}{f_{\max} R_{L.\max}}, \quad (9)$$

$$C_{2\max} = C_B + \frac{2V_H^2 T_C}{R_{L.\min} V_o} - \frac{2}{f_{\min} R_{L.\min}}, \quad (10)$$

$$C_{\max} = \min\{C_{1\max}, C_{2\max}\}. \quad (11)$$

According to the above method, the output filter capacitor meeting the safety requirements and electrical indicators, which is used in the quasi-resonant flyback converter, can be selected. It should be between C_{\min} and C_{\max} .

6. Design examples and experimental results

To verify the correctness of the theory, this paper adopts the NCP1380 as the control chip of a converter to design a quasi-resonant flyback converter applied in the Class-I work environment. There are two operating modes of NCP1380: the quasi-resonant current mode with a bottom lock function which could be used to eliminate noise; the VCO mode used to improve efficiency at light loads. The VCO mode can improve the minimum operating frequency of a quasi-resonant flyback converter, and it could reduce the size of the transformer as well as the inductance value from the point of view of the safety performance. Meanwhile, it also can effectively reduce the output ripple so that the output filter capacitor value may decrease, thus improving the safety performance.

The design parameters are shown as follows:

- input voltage is 24 V \pm 20%;
- output voltage is 12 V;
- ripple voltage is 250 mV;
- output current is 2 A;
- minimum output resistance is 6 Ω ;
- maximum output resistance is 60 Ω .

The following values can be calculated:

- transformer turns ratio $\gamma = 0.748$;
- primary inductance value $L_p = 35 \mu\text{H}$;
- primary-order and secondary-order turns $N_p = 19$, $N_s = 14$;
- output capacitance $C_{\min} = 88 \mu\text{F}$, $C_{1\max} = 102 \mu\text{F}$, $C_{2\max} = 116 \mu\text{F}$,

so the output capacitor should be in the range of 88 μF \sim 102 μF . The design uses two 47 μF electrolytic capacitors with low ESR in parallel to be used as the output filter capacitor of the converter.

Fig. 5 shows the DS terminal voltage of a quasi-resonant flyback power MOSFET and its current waveforms under full load conditions. It can be seen that under full load conditions, the

quasi-resonant flyback voltage power MOS experiences a small shock at the rising edge due to the leakage inductance. However, the RCD clamp overshoot the energy of the leakage inductance, the MOSFET achieved breakover at the first valley to realize the zero voltage breakover, and the switching loss reaches its minimum value at this time. However, there is still a small spike of the power tube current at that moment, which is due to the parasitic capacitor of the transformer is charged by the input voltage. It can be further improved to minimize the switching losses.

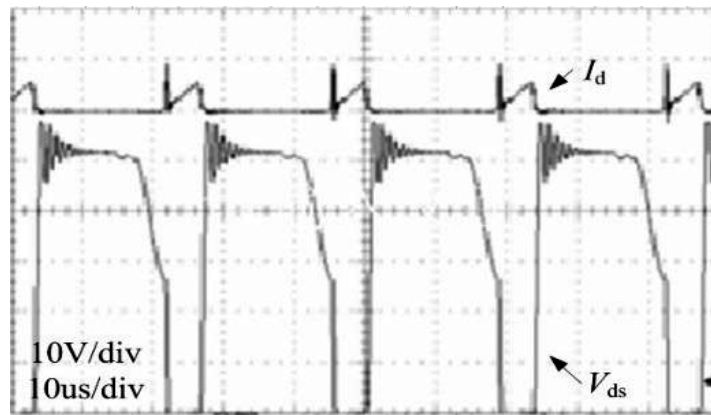


Fig. 5. V_{ds} of power MOSFET under full load conditions and its current waveforms

Fig. 6 shows the waveform of the output ripple voltage of the converter operating at full load conditions. At this time, the maximum value of the ripple is about 200 mV, less than the expected design value 250 mV.

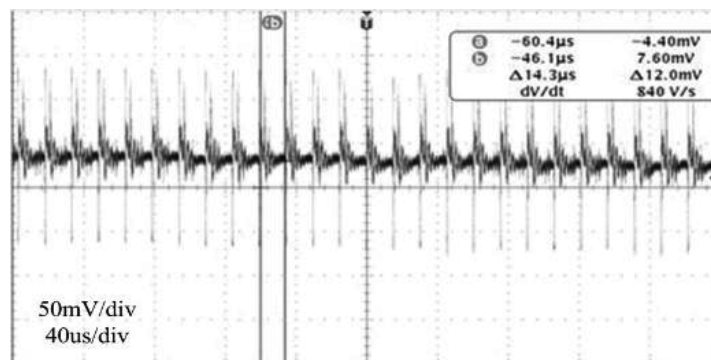


Fig. 6. Output ripple voltage under full load conditions

Table 1 shows the efficiency test of the converter at low input, standard voltage input and high case input. It can be seen from the table that the efficiency of converter is about 85%, which is a relatively ideal value at lower input voltage.

Table 1. Converter efficiency

Input voltage / V	Input power / W	Output power / W	Efficiency
19.8	28.33	24	84.7%
24.0	28.17	24	85.2%
26.4	27.94	24	85.9%

7. Conclusion

Based on the operating principle of a quasi-resonant flyback converter, this paper analyzes its working mode in the DCM mode and then studies the maximum dissipated energy of the output short circuit of the quasi-resonant flyback converter to determine its main parameters. This intrinsically safe secondary power could make the switch be on in the case of nearly zero voltage, which improves the power efficiency. At the same time, the intrinsic safety could be ensured and the ripple could be controlled in an acceptable range.

References

- [1] Blaabjerg F., Chen Z., Kjaer S.B., *Power electronics as efficient interface in dispersed power generation systems*, IEEE Transactions on Power Electronics, vol. 19, no. 5, pp. 1184–1194 (2004).
- [2] Yu Y.S., Xie D.Y., Wu X.J., *Research on the Characteristics of Intrinsically Safe Systems and Intrinsically Safe Power Supply Structure and Its Classification*, Journal of Convergence Information Technology, vol. 7, no. 8, pp. 27–33 (2012).
- [3] Meng H.Z., Zhang H.J., Jin B.Q., *Design and Performance Research of Intrinsically Safe Switching Power Supply in Coal Mine*, Coal Technology, vol. 19, no. 3, pp. 28–36 (2015).
- [4] Lee B., *Single-Switch ZVZCS Quasi-Resonant CLL Isolated DC-DC Converter for 32" LCD TV*, Journal of Electrical Engineering and Technology, vol. 10, no. 4, pp. 1646–1654 (2015).
- [5] Wang C.M., *A novel ZCS-PWM flyback converter with a simple ZCS-PWM communication cell*, Transactions on Industrial Electronics, vol. 55, no. 2, pp. 749–757 (2008).
- [6] Hsieh Y.C., Chen M.R., Cheng H.L., *An interleaved flyback converter featured with zero voltage transition*, IEEE Transactions on Power Electronics, vol. 26, no. 1, pp. 79–84 (2011).
- [7] Kwon J.M., Choi W.Y., Kwon B.H., *Single switch quasi-resonant converter*, Transactions on Industrial Electronics, vol. 56, no. 4, pp. 1158–1163 (2009).
- [8] Cho S.H., Kim C.S., Han S.K., *High efficiency and low-cost tightly regulated dual-output LLC resonant converter*, IEEE Transactions on Industrial Electronics, vol. 59, no. 7, pp. 2982–2991 (2012).
- [9] Ridley R.B., Lee F.C., *Multi-loop control for quasiresonant converters*, IEEE Transactions on Power Electronics, vol. 6, no. 1, pp. 28–38 (1991).
- [10] Guo J., Ma H., *Design of Quasi-resonant Flyback Power Supply with Wide Input Voltage Range*, Power Electronics, vol. 11, pp. 23–25 (2011).
- [11] Cui J.M., Yu X.F., Wu L., Xu W.J., Qin H.B., Shao L.H., *The control-loop design of quasi-resonant flyback converter for HI-bright LED driver*, 2011 International Conference on Proceedings of the Electrical and Control Engineering (ICECE), pp. 16–18 (2011).