Research in Improving the Conversion Efficiency of LED Power Supply

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***Abstract*—Since LED street lamps are mostly located in outdoor environments with complex environment, more efficient and reliable power supply is needed, whose core index is conversion efficiency. Taking FLYBACK AC/DC converter as an example, the calculation formula of conversion efficiency is analyzed. For LED power supply, MOSFET loss is one of the main factors of energy loss, including conduction loss and switching loss, which reduces the conversion efficiency. Zero Voltage Switch Quasi-Resonant Circuit of soft switch technology is used to reduce the switching loss of MOSFET. The prototype is made and tested, which shows the power conversion efficiency can be improved up to 94.4%.**

Keywords- LED; power supply; conversion efficiency; soft-switching; quasi resonance

I. INTRODUCTION

Street lamps widely use LED as a new way of lighting, with energy saving, long life, no mercury pollution and other significant advantages, broad prospects for development. However, due to the poor environment, inconvenient to replace and maintain, and high energy consumption of street lamps, more efficient and reliable LED power supply is needed.

The core index of the power supply is conversion efficiency, that is, the ratio of high-voltage AC input power to low-voltage DC output power[1]. The higher the conversion efficiency, the higher the power utilization rate, and the lower the heat and radiation dissipated, the better the power performance. Obviously, the greater the loss of the power circuit and the smaller the output power, the lower the conversion efficiency.

There are many factors causing circuit loss, such as transformer, MOSFET, sampling resistor, rectifier diode, filter capacitor and so on. They not only reduce conversion efficiency, but also increase harmful thermal energy and radiation, especially transformers and MOSFET [2-4].

II. CONVERSION EFFICIENCY ANALYSIS

At present, the common topology of LED power supply mainly includes Flyback, Boost-LLC half bridge, Boost-Flyback. Flyback topology is suitable for a low cost and simple power supply. The advantage of Flyback topology is simple circuit, low-cost and conversion efficiency of around 88%, but the disadvantage is that the maximum power is only up to 70W. Boost-LLC half bridge topology is suitable for high-end power supply. It has the advantages of large power supply, high conversion efficiency over to 95%. The disadvantages are complex circuit, high cost, tedious processing, and low reliability. Usually, the Boost-Flyback topology is the best choice, which typically falls somewhere in between.

Taking Flyback AC/DC converter as an example, the topology diagram is shown in Figure 1. AC Input voltage is range for AC 85~264V, applicable to the global national market power standards. *D*1~*D*4 constitute the full-bridge rectifier. The HIGH-voltage DC V_{bus}, namely the bus voltage, can be obtained through *C*1 filtering. As the medium of the Input end and Output end, the transformer T1 converts the Input high voltage into any parameter electric energy of the Output through electromagnetic and magnetoelectric conversion, and realizes the isolation between the Input end and the Output end at the same time. The transformer T1 has three windings, the primary winding *N*p is used for receiving input electric energy, the secondary winding *N*s is used for output converted electric energy, and the auxiliary winding *N*a is used for power supply and feedback signal detection of converter control circuit. Diode *D*6 is used for output rectification of the secondary winding, and *D*5 is used for rectifier of the auxiliary winding to the converter power supply circuit.

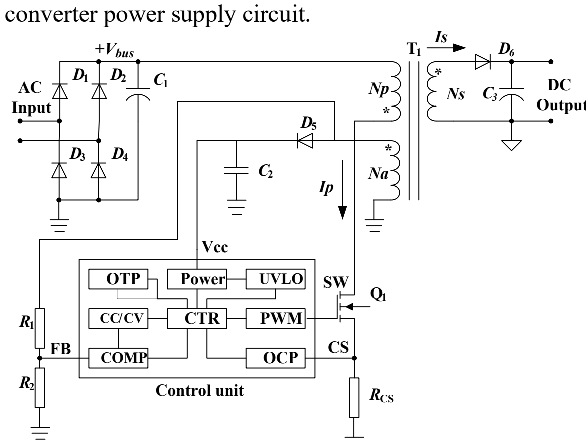

Figure 1. Diagram of Flyback AC/DC converter.

The Control Unit of flyback converter consists of eight units: Power, power supply unit; CTR, central processing unit; COMP, feedback comparator; CC/CV, constant pressure/constant current unit; PWM, pulse width modulation unit; OCP, overcurrent protection unit; UVLO, under-voltage locking unit; OTP, overtemperature protection unit. The Control Unit can be set to work in

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constant voltage mode (CV) or constant current mode (CC). The LED power supply works in constant current mode.

In constant current mode (CC), when MOSFET Q1 on (T_{on}), the current I_P of primary winding Np rises, while the current I_S of secondary winding Ns has no output. When Q1 off (T_{off}), the energy of the primary winding Np is transferred to the secondary winding Ns, and the secondary peak current I_{sk} and the primary peak current I_{pk} are respectively:

$$I_{SK} = I_{\mathrm{PK}} \times \frac{Np}{Ns} \tag{1}$$

$$I_{PK} = \frac{V_{cs}}{R_{cs}} \tag{2}$$

Vcs is the sampling voltage of the primary winding and Rcs is the sampling resistance.

The secondary output current Is is:

$$I_S = \frac{I_{\mathrm{SK}}}{2} \times \frac{T_{\mathrm{off}}}{T_{\mathrm{on}}+T_{\mathrm{off}}} \tag{3}$$

Substitute the formulas (1-2) and (1-3) into the formula (1-4) and get Is:

$$I_S = \frac{1}{2} \times \frac{V_{cs}}{R_{cs}} \times \frac{Np}{Ns} \times \frac{T_{\mathrm{off}}}{T_{\mathrm{on}}+T_{\mathrm{off}}} \tag{4}$$

When the ratio between T_{off} and T_{on} is constant, any constant current value Is can be set by circuit parameters Vcs, Rcs, Np and Ns.

The converter monitors and feedback the output power through the auxiliary winding Na, and constructs a complete two-loop feedback logic control with the least devices to realize the constant current mode (CC) of the AC/DC converter. Compared with the traditional feedback circuit, it can save the isolated optocoupler and secondary reference voltage, reduce the cost and improve the reliability of the circuit.

In the converter, the transformer T1 is the device for energy storage, release and conversion. The transformer converts the input electrical energy into magnetic energy which is stored in the excitation inductance and then released to the output end in the form of electrical energy.

According to the calculation formula of transformer core energy storage J:

$$J = \frac{1}{2} \times L_P \times I_{PK}^2 \tag{5}$$

L_P is the inductance of the primary winding.

Then, the calculation formula of transformer output power P_{out} is:

$$P_{out} = \frac{1}{2} \times L_P \times I_{PK}^2 \times f_{SW} \tag{6}$$

The peak I_{pk} of primary winding current I_P is:

$$L_P < \frac{(V_{bus} \times D)^2}{2 \times f_{SW} \times P_{in}} \tag{7}$$

$$I_{PK} = \frac{V_{bus} \times D}{L_P \times f_{SW}} \tag{8}$$

V_{bus} is the bus voltage, D is duty ratio, f_{SW} is switching frequency, P_{in} is transformer input power.

The output power of transformer P_{out} can also be calculated as follows:

$$P_{out} = \frac{1}{2} \times V_{bus} \times I_{PK} \times D \tag{9}$$

Obviously, the main parameters of the converter can be calculated by formula (1) ~ (9).

The conversion efficiency η can be calculated as follows:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{in} - P_S}{P_{in}} \leq 100\% \tag{10}$$

P_{in} is the input power, P_{out} is the output power, and P_S is the loss power. η represents how much of the input power is converted to output power, and all the energy that is not converted to output power is converted to heat or electromagnetic radiation. Obviously, as η close to 100%, the performance of power supply is better, and it can save energy, reduce the generation of heat or electromagnetic radiation; improve product life and electromagnetic compatibility.

III. THE LOSS OF MOSFET

MOSFET is a high-frequency switching tube. During the conduction process, internal resistance will bring about the conduction loss, which will be brought about at the moment of on-off switch [5].

A. Conduction Loss

MOSFET, as an electronic switch, has two states of disconnection and conduction. Under the ideal model, when MOSFET off, internal resistance $R_{ds}=+\infty$; internal resistance $R_{ds}=0$ when MOSFET on. But actual situation: when MOSFET off, internal resistance $R_{ds} \approx 1\mathrm{M\Omega} \sim 10\mathrm{M\Omega}$; when MOSFET on, internal resistance $R_{ds} \approx 0.1\Omega \sim 10\Omega$.

Figure 2 is the R_{ds} parameter table of a MOSFET. With the rising of the temperature of the MOSFET, internal resistance R_{ds} increased from 1.5Ω to 5Ω, when the current through the resistance R_{ds} will produce power consumption.

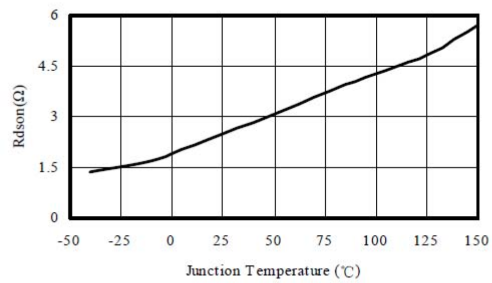

Figure 2. Internal resistance curve of MOSFET.

When MOSFET conducted, the primary current Ip flows through MOSFET, and its effective value is I_{PAV}:

$$I_{PAV} = \frac{P_{\mathrm{out}}}{D \times \eta \times V_{\mathrm{bus}}} \tag{11}$$

I_{PAV} flowing through MOSFET produces conduction loss P_{Rds}:

$$P_{Rds} = I_{PAV}^2 \times R_{ds} = \left(\frac{P_{\mathrm{out}}}{D \times \eta \times V_{\mathrm{bus}}}\right)^2 \times R_{ds} \tag{12}$$

If the input is 220V and the output is 5V/2A, V_{bus} =310V and duty cycle D=0.4, P_{out}=10W and conversion efficiency η =80%. According to the figure 2 at 50 ℃, substitute R_{ds}=3Ω into formula (2-5) and get:

$$P_{Rds} = \left(\frac{10}{0.4 \times 0.8 \times 310}\right)^2 \times 3 = 0.03\mathrm{W} \tag{13}$$

It can be seen that the conduction loss of 0.03w, accounting for 0.3% of the total output power of 10W, has little influence on the conversion efficiency. Conduction loss is converted into heat, which increases MOSFET temperature and internal resistance, further increases conduction loss, resulting in more heat generation and positive feedback. Obviously, the MOSFET with low internal resistance should be selected, but the MOSFET with low internal resistance is more costly, and the selection should take both performance and cost into consideration.

B. Switching Loss

The power converter adopts pulse width modulation, which enables MOSFET to carry out high frequency switching, thus generating high frequency energy storage and release process in voltage generator, and realizing primary to secondary energy conversion. There are parasitic parameters in MOSFET, leading to a certain delay in the switching state, resulting in switching loss. Its waveform is shown in Figure 3.

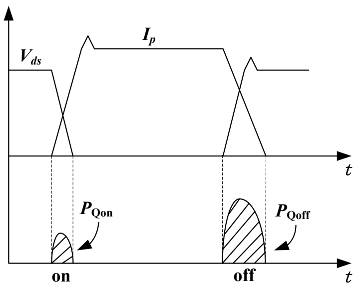

Figure 3. Schematic diagram of MOSFET switch waveform.

When MOSFET is turned on, voltage V_{ds} needs a certain period of time to drop to 0. During this period, the primary current I_P gradually rises to the peak I_{PK}, resulting in the opening loss P_{Qon}:

$$P_{Qon} = \frac{2}{3} \times f_{SW} \times C_{Q1} \times V_{bus}^2 \quad (14)$$

f_{SW} is the switching frequency, C_{Q1} is the parasitic capacitance of MOSFET, and V_{bus} is the bus voltage.

Similarly, when MOSFET is turned off, the primary current I_P needs a certain period of time to drop to 0. During this period, the voltage V_{ds} gradually increases, resulting in the cutoff loss P_{Qoff}:

$$P_{Qoff} = \frac{1}{2} \times f_{SW} \times V_{bus} \times I_{PK} \times t_r \quad (15)$$

t_r is the rise time of V_{ds}.

In general, the cutoff loss is much higher than the opening loss, which is the main loss of MOSFET.

In the case that the above parameters cannot be improved, the switching mode of MOSFET should be improved to reduce the loss and improve the conversion efficiency.

IV. Conversion Efficiency Improvement Method

A. Soft Switching Technology

As mentioned above, the parasitic capacitance of the circuit causes the MOSFET switch not to jump between the off and on state, resulting in switching loss. This kind of switch is called hard switch, although its circuit is simple, but turn off voltage and turn on current peak big, electromagnetic interference is serious. With the increase of switching frequency, switching loss becomes an important factor to limit the conversion efficiency.

By controlling the MOSFET's switching process, soft switching technology eliminates the overlap time between voltage V_{ds} and current I_P, thereby reducing switching loss, improving electromagnetic compatibility and high-frequency performance, and improving conversion efficiency and power density [6]. Soft switching technology includes zero voltage switch (ZVS) and zero current switch (ZCS), that is, in the MOSFET switching process, the voltage V_{ds} or current I_P is zero, thus eliminating switching loss.

Using the circuit parasitic resonant inductance Lr (mainly determined by primary excitation inductance L_m) and resonant capacitor Cr (mainly determined by MOSFET parasitic capacitor C_{Q1}), the resonant principle is adopted to control MOSFET switching under the condition of ZVS or ZCS [7].

Resonant converters include load resonant converter (LRC), multi-resonant converter (MRC), quasi square wave resonant converter (QSC) and quasi resonant converter (QRC), most of which adopt pulse frequency modulation (PFM).

B. Quasi Resonant Converter

Quasi resonant converter (QRC) is usually adopted, including zero voltage switch quasi resonant converter (ZVS-QRC) and zero current switch quasi resonant converter (ZCS-QRC). The topology structure is shown in Figure 4.

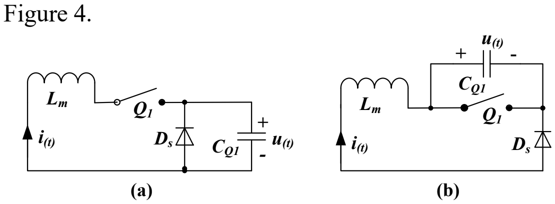

Figure 4. Diagrams of QRC: (a) ZCS-QRC; (b) ZVS-QRC.

Figure 5 is the topology diagram of the ZVS-QRC-Flyback converter. L_m is the primary side excitation inductor, Q_1 is the MOSFET switching tube, C_{Q1} is the MOSFET parasitic capacitance, D_S is the continuing current diode. The equivalent parameters refracting from the secondary output winding to the primary input winding are C_f, L_f and R_f.

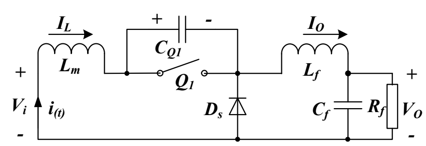

Figure 5. Diagram of ZVS-QRC-Flyback converter.

A MOSFET switching cycle is divided into four stages, including inductive charging stage, LC resonance stage, capacitor charging stage and continuous current stage.

When MOSFET is on, V_{ds}=0 and the transformer stores energy. When MOSFET is turned off, the transformer releases the stored energy to the secondary, while leakage L_k and parasitic capacitor C_{Q1} oscillate. When the primary energy storage is released, the excitation inductor L_m and parasitic capacitor C_{Q1} oscillate. If the quasi-resonant frequency is 350KHz and the oscillation period is 45 μ s, 16 quasi-resonant oscillations are required during one switch period. Just at the moment V_{ds} reaches the lowest value, MOSFET is turned on again, and the switching loss is the minimum.

In the quasi-resonant mode, zero voltage switch (ZVS) is realized by monitoring the zero voltage state of V_{ds} and conducting MOSFET when V_{ds} drops to 0, thus reducing the switching loss of MOSFET, improving the power conversion efficiency and the electromagnetic compatibility.

V. The Prototype Test

The prototype is made based on quasi - resonant mode. PC40 magnetic core of TDK and 5+5PIN skeleton of PQ3220 are used for transformer. Double-sided FR4 plate with Dual Inline Package (DIP) devices installed on top and chip devices installed on the bottom. The shell is made of aluminum, which is conducive to heat dissipation. The prototype is shown in Figure 6.

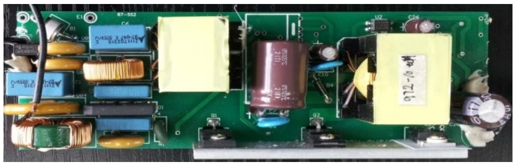

Figure 6. The prototype.

The test scheme diagram is shown in Figure 6. The input voltage V_{in} is 160~270VAC, the output power P_o is about 150W, the output voltage V_o fluctuates around 33V, the output current I_o is set at 4.5A, the input power is P_{in} , the conversion efficiency is η and the ambient temperature is 25℃.

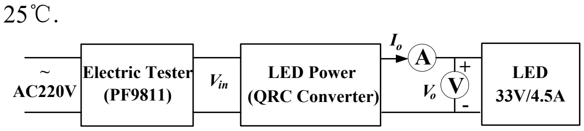

Figure 7. Schematic diagram of the prototype test.

The test data are shown in Table I. The output current fluctuation of the prototype is within 0.5%, with good constant current characteristic, which is lower than the current fluctuation value of the same specification power supply by 2%. Conversion efficiency is up to 94.4%, significantly higher than the same specification power efficiency of 90%.

TABLE I. Test Data

V_{in} (V)	I_o (A)	V_o (V)	P_{in} (W)	P_o (W)	η (%)
160	4.51	33.03	157.66	148.83	94.4
190	4.51	33.03	157.97	148.97	94.3
220	4.52	33.09	158.78	149.57	94.2
250	4.53	33.15	160.10	150.17	93.8
270	4.53	33.26	161.25	150.67	93.4

VI. Conclusions

In order to improve the conversion efficiency of LED power supply, it is necessary to understand the topology structure of power supply circuit and analyze its working principle and conversion efficiency. When the power loss increases, the output power decreases, resulting in the reduction of conversion efficiency. There are many factors causing power loss, the main factors are MOSFET and transformer. MOSFET loss includes conduction loss and switching loss. Zero voltage quasi-resonance (ZVS-QRC) soft switching technology can reduce the MOSFET switching loss and improve the power conversion efficiency. In the future, transformer technology can be improved to reduce leakage loss and thus improve conversion efficiency.

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References

[1] H. Xuefeng, G. Benbao, H. Yuanyuan, C. Hao, “Novel single switch DC-DC converter for high Step-Up conversion ratio,” Journal of Power Electronics, vol. 18, pp. 662-671, May 2018.

[2] W. Weida, H. Lijin, X. Changle, M. Yue, L. Hui, “Efficiency-based optimization for the power distribution of power-split hybrid electric vehicles,” Chinese Journal of Mechanical Engineering, Vol.27, pp. 58-68, Jan 2014.

[3] L. Fangcheng, G. Yunxiang, L. Peng, “Calculation and correction method for leakage inductance of high-power medium-frequency transformer,” High Voltage Engineering, Vol. 42, pp. P1702 1707, Jun 2016.

律方成, 郭云翔, 李鹏. 大功率中频变压器漏感计算及其校正方法[J]. 高电压技术, 2016, (46):1702-1707.

[4] H.Yi, P. Ke, W. Wenchao, C. Lian, D. Mi, S. Tian, L. Jiahao, “Loss analysis and thermal control of power transformers with high power and high voltage,” Journal of Central South University(Science and Technology), Vol. 50, pp. 1089-1097, May 2019.

黄毅, 彭可, 王文潮, 陈练, 董密, 邵添, 雷佳豪. 大功率高压开关电源变压器的损耗分析及散热控制[J].中南大学学报(自然科学版), 2019, 50(05):1089-1097.

[5] C. Zongxiang, S. Lin, L. Yanfei, G. Lusheng, “Analysis of MOSFET loss model based on current source driver,” Electric power automation equipment, Vol 30, pp. 50-53, Oct 2010.

陈宗祥, 束林, 刘雁飞, 葛芦生. 基于电流源驱动的 MOSFET 管损耗模型及分析[J]. 电力自动化设备, 2010, 30(10):50-53.

[6] M. R. Yazadani, M. P. Dust, P. Hemmati, “A new family of Non-Isolated Zero-Current transition PWM converters,” Journal of Power Electronics, Vol. 16,pp. 1669-1677, Sep 2016.

[7] H. Yangqiang, X. Jianping, Y.Gang, M. Hongbo, “Quasi-Resonant Soft-Switched Two-Switch flyback converter,” Transactions of China Electrotechnical Society, Vol. 33, pp. 4313-4322, Sep 2018.

黄阳强, 许建平, 殷刚, 马红波. 准谐振软开关双管反激变换器[J]. 电工技术学报, 2018, 33(18):4313-4322.