

High Voltage Transformer design based on Flyback Switching Power Supply

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Abstract. The single source generator could change the frequency and duty cycle of the pulse to control the voltage of output in flyback switching power supply. A variety of methods and calculations could be used to design high voltage transformer, such as A_p method that will be used in this transformer, k_g method and K_{RP} method. In this paper, the process of how to select the magnetic core and the other parameters of the transformer will be discussed step by step. At first, the voltage of output will be over two thousand and five hundred voltage. The single source generator changing the frequency and duty cycle, the voltage of output will stay stability on five hundred voltage. The seize of the transformer is smaller than that has been used, so it will be beneficial for the circuit integrated.

1. Introduction

DC-DC devices are widespread used to electronic equipment ^[1]. Comparing to tradition liner regulated power supply, switching power supply with the advantages of high efficiency, lower seize, low cost. In the history of switch power supply, lots of topological structures have been created, like forward, flyback, full bridge, half bridge, APEC and other topologies ^[2]. By changing some parameters of transformer could control the voltage of output in flyback switching power supply. For example, magnetic core, the voltage of input, the frequency of pulse, the number of windings, air gap, the diameter of enameled wire. Because there are so many parameters could influence the voltage of output, that it will be difficult for power supply engineers to have a comprehensive thought when design their own transformer. If some parameters could not be selected well, that the temperature of magnetic core will be very high because of leakage inductance and the power efficiency will not reach an ideal stage. The efficiency of most flyback switching power supply will be over 80% when all parameters could be well calculated. The transformer can work on CCM mode and DCM mode, the design formula of transformer about those two modes will be very different ^[3-4]. In this paper, there will be a smaller transformer be designed to replace the same function transformer with bigger volume.

The rest of this paper will be organized as follows. First, the basic working principles on flyback switching power supply will be shown in Section 2. Second, some important parameters will be introduced in Section 3. Next, there be given a brief introduction on some protection circuits and control



circuits in Section 4. After theory analysis, the calculation will be given step by step in Section 5. At the end of this paper, there will be a conclusion and acknowledgement in Section 6 and Section 7.

2. Basic working principles

All transformers are based on the principle of electromagnetic induction. If the power of the transformer is lower than 100W, the flyback topology will be one suitable choice for design high voltage transformer in nowadays. And the power supply of this transformer will be designed below 10W, so it is suitable. During the process of designing the transformer, The MOS tube, triode, could be used as the switch. The description of the basic principles will be easily understood in Figure 1. When the switch is turn on, the rectifier diode is in the situation of reverse bias, so the energy only could be stored in this transformer. Next, when the switch is off, the rectifier diode is conductive, the energy that has been stored will be released to the capacitor and the load ^[5].

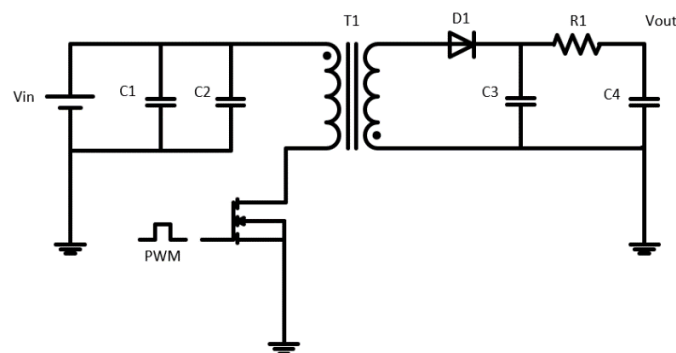


Figure 1. The basic framework of flyback switching power supply

2.1 Two basic working modes

There are two basic modes about flyback switching power supply, DCM mode and CCM mode. In Figure 2 and in Figure 3, there will be a brief description about those two modes. Sometimes, some books and journals will introduce the third mode, BCM mode which is the boundary between DCM mode and CCM mode. The formula of those two modes on design transformer quite different, but some engineers had finished some papers to unify these two ways.

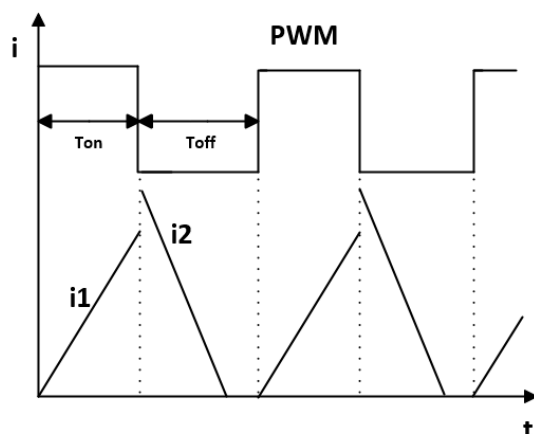


Figure 2. DCM mode

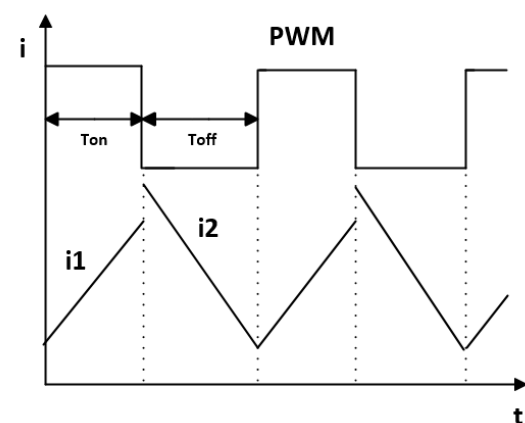


Figure 3. CCM mode

2.1.1 CCM mode

In figure 2, during the period of T_{on} , the switch is on, the current of primary windings is increased linearly. During the period of T_{off} , the switch is off, the current of secondary windings is decreased

linearly. It is obvious that the current will not reach the stage of zero from the Figure 2, so that not all power that has been stored in transformer will be conveyed to capacitor and the load.

2.1.2 DCM mode

In figure 3, DCM mode compared with CCM mode, the largest difference is that the current of secondary windings will run out to zero. After the current of secondary windings run out, the switch is still in the situation of off. During the next period, the current of the current of primary windings will start from zero current. BCM mode is the boundary between DCM mode and CCM mode in Figure 4, after the current of secondary windings reached zero, the switch will be in the situation of opening at once ^[6].

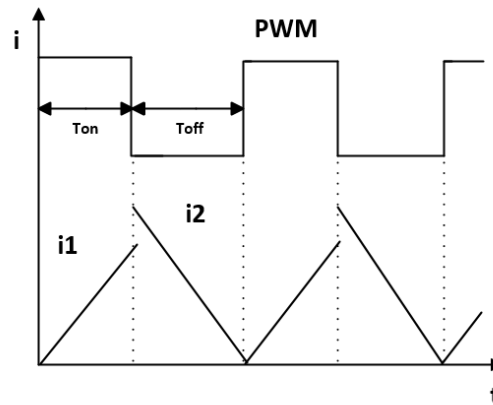


Figure 4. BCM mode

3. Several important parameters

To design one ideal transformer, several parameters must be thought carefully. For example, air gap, the magnetic core, the number of turns, and the frequency of pulse. In this chapter, the following will concentrate on those parameters.

3.1 Air gap

The gap of the magnetic core is vital for the power that will be stored in this transformer. From the formula of 1, the energy of the transformer could be calculated if some parameters could be known.

$$\Delta E = \frac{V_e}{\mu_e * \mu_o} * \Delta B * B_{DC} \quad (1)$$

As usual, engineers may select one bigger magnetic core or supply one higher voltage to supply more energy. In this paper, by narrow the gap of the air, the parameter of μ_e will decrease, so more energy could be stored in transformer. The formula between μ_e with the air gap in formula of 2.

$$\mu_e = \frac{\mu_m}{1 + \mu_m * \frac{\ell_g}{MPL}} \quad (2)$$

But the air gap should not beyond some extent, otherwise the leakage inductance around the transformer will increase obviously. The air gap usually be controlled between 0.1mm and 1.5mm in flyback switching power supply.

3.2 The modulating of pulse

Nowadays, the trend of the frequency of pulse applied into transformer becoming higher and higher. There are three basic modulates about switching power supply, including PWM, PFM, and PWM-PFM ^[7]. PWM mode will not change the time of one period, but the time of T_{off} will be changed. In PFM

module, the frequency will be changed, however the time of T_{on} will not be changed. PWM-PFM module is mixed with PWM and PFM, so it will bring more challenges when design the transformer.

During the experiment of testing the transformer, the output of voltage will not stay at the former stage along with the frequency decrease or increase. First, the modes of CCM and DCM may be different in the same transformer. For example, if the percentage of time T_{off} is very small, that there will not enough time for transformer to release the energy has been stored. Second, the efficiency of transformer will be influenced by the frequency of the pulse. In Figure 5, few peaks represent the high efficiency around the frequencies, the primary winding is 16 and the secondary winding is 160, source of power V_{in} is 6V. In this picture, one colorful line express one duty cycle, from 20% to 80%, and the average frequency from 20kHz to 158kHz.

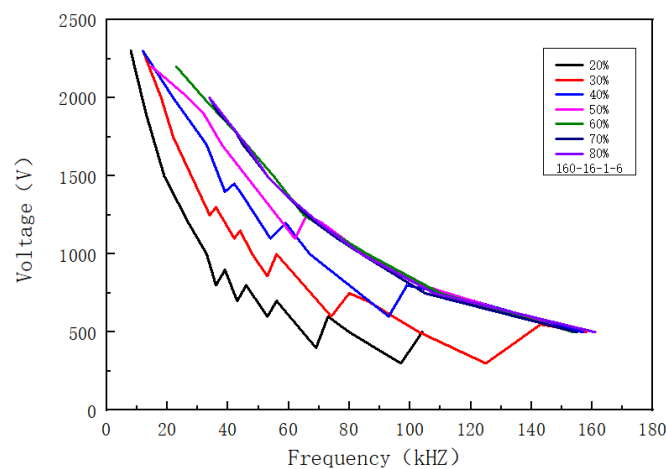


Figure 5. Experiment on frequencies and duty cycle

3.3 The magnetic core

There are so many kinds of magnetic core have been applied into engineering. Magnetic core is a kind of sintered magnetic metal oxide composed of various iron oxide mixtures. For example, Mn-Zn ferrite and Ni-Zn ferrite are typical core materials [8]. Ferrite cores are used in coils and transformers of various electronic equipment. Some magnetic cores are suitable for the occasion that high space height, such as PQ magnetic core. Even the magnetic cores with same shape are divided into several sizes to satisfy different energy convey. Just one magnetic core will include so many important when design the transformer, such as effective area A_e , the length of effective magnetic core ℓ_e , the effective volume V_e , and the average turn length MLT. When referred the important parameters about magnetic core, saturation flux density B_s and the inductance without air gap A_L must be introduced. During design the DC-DC converter, the number of saturation flux density usually be selected from 0.15 to 0.3. The formula of 3 about A_L will be used to figure out the air gap, the parameter also could be known from the technical data sheet.

$$A_L = \frac{\mu_e * \mu_o * A_e}{\ell_e} \quad (3)$$

4. Necessary circuits

According to the principle of flyback switching power supply, the framework of the power supply is not including too much component. To get one more precise and stable switching power supply, the protection circuits, the filter circuits, the voltage doubling rectifying circuits always be used into the circuits. In this paper, there will be a short introduction about the RCD circuit and the feedback circuit.

4.1 RCD circuits

Not all energy could be conveyed to the secondary winding from the primary winding, the leakage inductance of the transformer will create a high voltage on the D pole of the MOS tube. When the switch from on to off, there will be a very high peak voltage that the number is beyond $U_{IN} + U_{OR}$. Besides, there will be a delay when the rectifier diode from on to off, that the energy stored in the primary winding will create an instant high voltage. So, engineers must add an RCD circuit to prevent the damage caused by instant high voltage. The basic framework of RCD circuit in Figure 6^[9]. In reality, a fast recovery diode is necessary applied into the flyback switching power supply when design flyback switching power supply.

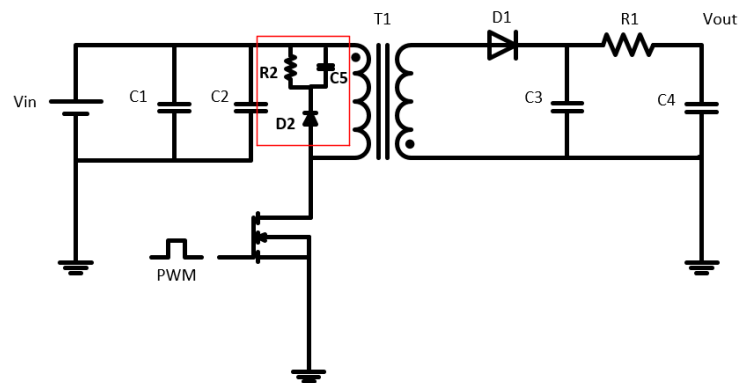


Figure 6. RCD circuits

4.2 Voltage doubling rectifying circuit

To get a very high voltage, in most framework the voltage doubling rectifying circuit will be included. The substance of the voltage doubling rectifying circuit is a charge pump, the voltage is stored in every capacitor, and the voltage with the same polar will be added by series connection^[10]. The disadvantage of this circuit is that there will be a limit on the circuit current and the seize of PCB will be occupied with several capacitor, so it is not easy to be integrated. In this paper, just make a brief introduction that the framework could be seen in Figure 7 and will not use this method.

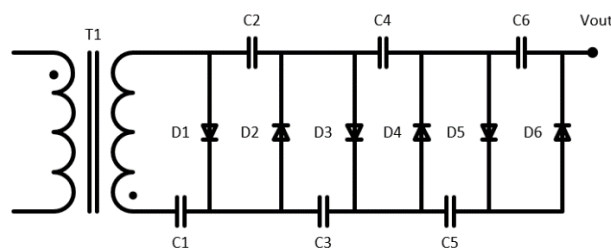


Figure 7. voltage doubling rectifying circuit

5. Calculations on the transformer

5.1 The basic specification

When design the transformer, all standards must be defined at first. The high voltage switching power supply offer 2500V just a for a second minute. After that a 500V voltage will last for a long time, and the current of output about 2.4 mA. In this chapter, *Ap* method is used to design the transformer. The maximum duty cycle is 50%, frequency of the pulse about 400kHz, the efficiency of this power supply is 80%.

5.1.1 Select the working point

The output power P_{out} is 1.2W, because $\eta = 0.8$, according the formula $P_{in} = \frac{P_{out}}{\eta}$, so the input power is 1.5W. According to the current of primary winding will not be changed and the principle of electromagnetic induction, the primary flyback voltage U_{or} and U_{in} has the relationship in the formula of 4. The result of U_{or} is 15V.

$$D_{max} = \frac{U_{or}}{U_{or} + U_{in}} \quad (4)$$

5.1.2 Select the magnetic core by Ap method

The relationship between the power the transformer could offer P_{out} , area product A_p core sectional area A_e and window area A_w in the formula of 5.

$$A_p = A_e * A_w = \frac{2 * P_o * D_{max}}{\eta * K_j * K_u * B_{max} * f} * 10^4 = \frac{2 * 1.2 * 0.5}{0.8 * 600 * 0.29 * 0.35 * 400000} * 10^4 = 0.000616 \text{ cm}^4 \quad (5)$$

In this paper, the A_p of TDK-PC44EPC-10 is $0.00647 \text{ cm}^4 > 0.000616 \text{ cm}^4$, so magnetic core EPC-10 is suitable for this transformer. On average, the current density K_j is about 600 A/cm^2 , B_{max} from 0.2 to 0.4T, window utilization coefficient of K_u typically is about 0.29.

5.2 Current related to primary winding

When design the transformer, all safe parameters must be considered, such as the current of primary turns. In this chapter, three current numbers will be introduced in formulas from 6-7. In the following formula of 8 will introduce the scale of primary turns.

5.2.1 Largest current of input

$$I_{in(max)} = \frac{P_{out}}{U_{in} * \eta} = \frac{1.2}{15 * 0.8} = 0.1 \text{ A} \quad (6)$$

5.2.2 Peak current of primary winding

$$I_{p(pk)} = \frac{2 * P_{out}}{U_{in} * \eta * D_{max}} = \frac{1.2 * 2}{15 * 0.8 * 0.5} = 0.4 \text{ A} \quad (7)$$

5.2.3 The scale of primary turns

$$L = \frac{U_{in}^2 * D_{max}^2 * \eta}{2 * P_o * f} = \frac{15^2 * 0.5^2 * 0.8}{2 * 1.2 * 400000} = 46.9 \mu\text{H} \quad (8)$$

5.3 The number of turns

The material of turns usually is enamelled wire. The formulas of 9-10 is the basic formulas to calculate the numbers of turns. The U_f is 0.7V.

5.3.1 The number of primary turns

$$N_p = \frac{10^4 * U_{in} * D_{max}}{f * B_{max} * A_e} = \frac{10^4 * 15 * 0.5}{400000 * 0.35 * 0.094} = 5.6 \quad (9)$$

5.3.2 The number of secondary turns

$$N_s = \frac{N_p * (U_o + U_f)(1 - D_{max})}{U_{in} * D_{max}} = \frac{5 * (500 + 0.7) * 0.5}{15 * 0.5} = 166.9 \quad (10)$$

Sometimes when select the number of turns, experience usually play a more important than theory. In this transformer, the number of primary turns is 5 and the number of secondary turns is 167.

5.4 The diameter of wire

When the number of turns has been calculated. According the current density, the diameters could be calculated by the formula of 12-13. In the next calculations, the current density is 500A/cm⁴.

5.4.1 The diameter of primary turns

$$D_p = 2 \sqrt{\frac{I}{\pi * K_j}} = 2 \sqrt{\frac{0.0024}{\pi * 500}} = 2.47 * 10^{-3} \text{cm} \quad (11)$$

5.4.2 The diameter of secondary turns

$$D_s = 2 \sqrt{\frac{I}{\pi * K_j}} = 2 \sqrt{\frac{0.1}{\pi * 500}} = 0.16 \text{mm} \quad (12)$$

Because the skin effect and current heat effect, the diameter of primary turns is 0.1mm, the diameter of secondary turns is 0.18mm in this paper.

5.5 The air gap

The last important must be calculated is air gap in the formula of 14. A_L is coefficient of self-inductance when the seize of air gap is zero.

$$\ell_e = 4\pi * A_e \left(\frac{N_p^2}{L * 10^3} - \frac{1}{A_L} \right) = 4\pi * 0.094 \left(\frac{5^2}{46.9 * 10^3} - \frac{1}{416 * 10^6} \right) = 0.063 \text{cm} \quad (13)$$

6. Conclusion

The principle of flyback switching power supply has been given a brief description in this paper. High voltage power supply is applied into industry for a long time. Some important circuits, like RCD circuit, voltage doubling rectifying circuit and other parameters has been introduced. The calculations of A_p is written step by step. The next work about flyback switching power supply will pay more attention on control methods and high efficiency. Now, with the development of DSP, FPGA, Single-Chip Microcomputer, more methods and the transformer based on piezoelectric ceramic has been used at present. Several chips of STM32G4 are aimed for designing switching power supply are widespread used into electronic devices.

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