Analysis and Design of the Flyback Transformer

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***Abstract*—A practical design method, which is based on the current shape, is presented to achieve the appropriate parameters of the flyback transformer. Through this method, a practical transformer is achieved, and its performance is verified by a step-up flyback converter, experimental waveforms and result are presented.**

***Index Terms*—Flyback Converter, Transformer, design methodology**

I. INTRODUCTION

Flyback converter has been long of appeal because of its relative simplicity and its excellent performance for multiple outputs when compared with other converters used in the lower power application.

In a flyback converter, the transformer operates more like an inductor with two (or more) windings than a typical transformer: the Primary winding is used to magnetize the core and store the energy on a cycle to cycle basis; the secondary winding demagnetizes the core and transfers the stored energy to the load.

So the transformer must have the capability to store the required energy, especially for the step-up application.

At present, the design methods of the flyback transformer proposed in existing papers have been concentrated on some parameters rather than all the tightly coupled parameters of the transformer and the electric parameters[1][2]. In fact, each of the above parameters is coupled with the others, and during the design of the transformer, the coupling relationship must be considered especially the main parameters affecting the operating performance.

In this paper, the relationship among the main parameters has been quantitatively analyzed, and a design process has been proposed. To verifying the proposed method, a practical experiment is presented.The result shows that the method is practical

Manuscript received October 9, 2001.

This work was supported in part by the Scientific Research Foundation of Harbin Institute of Technology under Project HIT. MD2002.12

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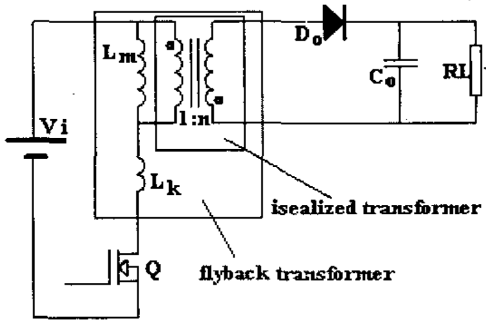

Fig.1 Equivalent circuit of the flyback converter

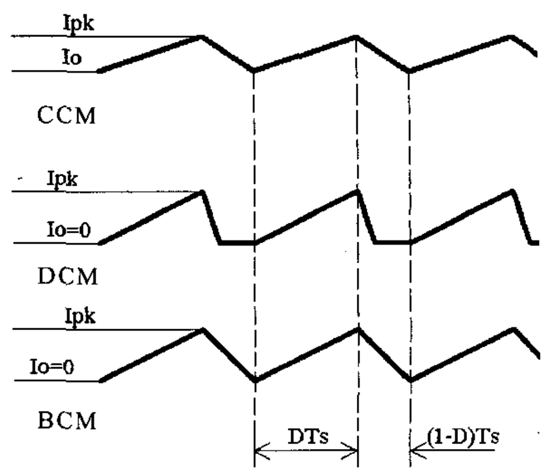

Fig.2 Primary inductor current of flyback converter

II. ANALYSIS AND DESIGN PROCESS

Fig.1 [5]shows the equivalent circuit of the common flyback converter, in which the transformer is substituted by a linkage inductor L_k, in series with the combined block consisted of an ideal transformer in parallel with an inductor L_m to store the energy. For the typical three conducting mode: CCM, DCM and BCM, the current through the L_m is shown in Fig.2, where I_0 is initial current in every cycle and its peak value is I_{pk}.

From Fig.1 and Fig.2, the current through leakage inductor will be equal to the primary during ON interval, it not only means the power loss but induce a voltage spike across the main switch, and damage the switch when the switch turn off[3][4].

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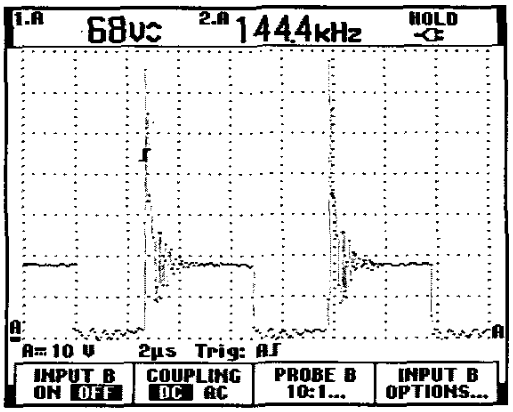
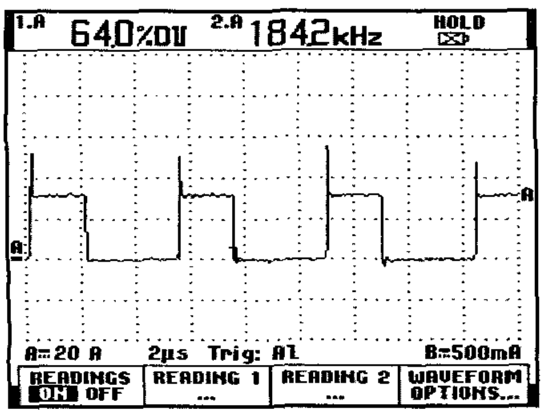
Though the leakage inductor is quite small, the snubber circuit is required. Fig.3 shows two different experiment results where the second is achieved by an excellent snubber circuit.

Besides the effect of the leakage inductor, analysis should be concentrated on the effect on the CCM operating performance by the consideration other parameters of the transformer.



a) 22W output power, 144.5KHz switching frequency with a poor absorb circuit



b) 40W output power, 184.2KHz switching frequency with the excellent absorb circuit

Fig.3 The voltage across the main switch

In CCM, the primary inductor current is increased from an initial value in linearity, that is:

$$I_{Lm}(t) = I_0 + \frac{V_i \cdot t}{L_m} \tag{1}$$

The peak value of the primary current I_{pk} can be achieved:

$$I_{pk} = \frac{V_i \cdot D \cdot T_S}{L_m} \tag{2}$$

Because the change of the energy stored in the inductor during the ON interval can be expressed as:

$$\Delta W = \frac{1}{2} L_m \left(I_{pk}^2 - I_0^2 \right) \tag{3}$$

This is the energy that will be dissipated in the load of the secondary side and it can be expressed as:

$$\Delta W = \frac{P \cdot T_S}{\eta} = \frac{V_o^2 T_S}{R \cdot \eta} \tag{4}$$

The energy stored in the core during the ON interval can be transferred to the load during the OFF interval. However, for the CCM mode, an non-zero initial energy will be kept in the core, that can be shown as:

$$W = \frac{1}{2} L_m I_0^2 \tag{5}$$

In CCM mode, I_0 will determine the operating point of the transformer and the residual magnetism Br, increase the magnitude of the peak current I_{pk} and worsen the operating condition.

From equation (2) and (3), I_{pk} and I_0 can be solved as equations (6), (7), (8) and (9):

$$I_{pk} = \frac{P}{\eta \cdot V_i \cdot D} + \frac{V_i \cdot D \cdot T_S}{2L_m} \tag{6}$$

$$I_0 = \frac{P}{\eta \cdot V_i \cdot D} - \frac{V_i \cdot D \cdot T_S}{2L_m} \tag{7}$$

$$I_{avg} = \frac{I_{pk} + I_0}{2} = \frac{P}{\eta \cdot V_i \cdot D} \tag{8}$$

$$\Delta I = I_{pk} - I_0 = \frac{V_i \cdot D \cdot T_S}{L_m} \tag{9}$$

Where ΔI is the incremental of the current flowing through the L_m in each cycle, I_{avg} is the average current of the primary inductor. However, the average current I_i from the source is not the same as I_{avg}, it can be expressed as:

$$I_i = \frac{P}{\eta \cdot V_i} = D \cdot I_{avg} \tag{10}$$

In CCM mode, the output voltage is a function of the duty ratio D shown as equation (11):

$$\frac{dI_{pk}}{dD} = -\frac{P}{\eta \cdot V_i \cdot D^2} + \frac{V_i \cdot T_s}{L_m} \tag{11}$$

$$P = \frac{V_o^2}{R_L} \tag{12}$$

From the above figures, if the rated power P, V_i, T_s, L_m and the load are given, with the increasing of the duty ratio D, both

I_{pk} and I_0 are all decreased .When D is less than a point, on which I_0 is equal to 0, the flyback is operating in BCM. This point can be achieved by the following:

$$\frac{dI_{pk}}{dD} = -\frac{P}{\eta \cdot V_i \cdot D^2} + \frac{V_i \cdot T_s}{2L_m} \tag{13}$$

$$D = D_{cr} = \sqrt{\frac{2 \cdot P \cdot L_m}{\eta \cdot V_i^2 \cdot T_s}} \tag{14}$$

$$I_{pk\_\min} = \sqrt{\frac{2 \cdot P \cdot T_s}{\eta \cdot L_m}} \tag{15}$$

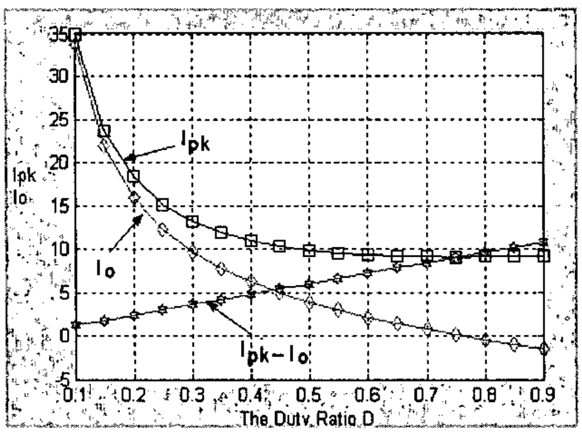


Fig.4 Relation between the primary current and the duty ratio

$$I_o = 0 \tag{16}$$

If D is increased continually, I_0 will still be

and I_{pk} will be increased and its value can be expressed by equation (17):

$$I_{pk} = \frac{V_i \cdot D \cdot T_S}{L_m} \tag{17}$$

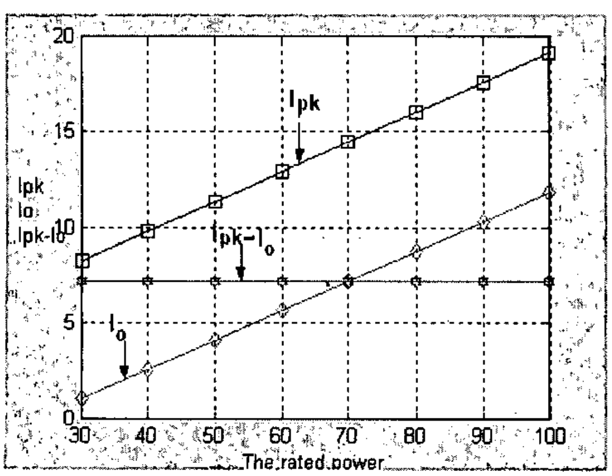


Fig.5. Relation between the primary current and the rated output power

But it should be noted that Fig.4 is induced with the fixed parameters, if the parameters can be changed, the duty ratio, that BCM and DCM would be occurred, can be any value.

The values of I_{pk}, I_0 and the difference between them are affected by the rated power P and the switching frequency f_s as shown in Fig.5. I_{pk} and I_0 will increase linearly when increasing the rated power, and the difference is a constant value. As the switch frequency is increased, I_{pk} and the difference will be increased, and I_0 will be decreased. This will decrease the current stress, which is helpful to avoid the magnetic core saturation, however the remanence in each cycle will be increased and a certain length of the air gap in the core must be required.

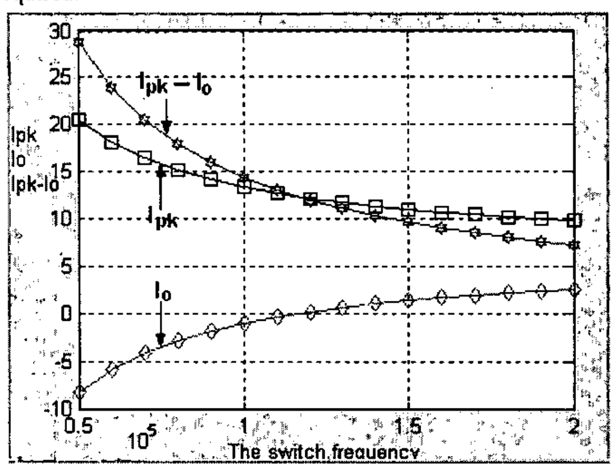


Fig.6 Relation between the primary current and the switching frequency

The turn ratio n in flyback transformer can be used to avoid the extreme duty ratio and achieve wider output voltage range, however, n is not a parameter which can be designed optionally. If it is too high, the adjustable duty ratio D would be limited to a very narrow value, which will lead to large I_{pk} and I_0 as shown in Fig.4 and Fig 6. Because there exist a relationship between D and n, which is expressed by (18):

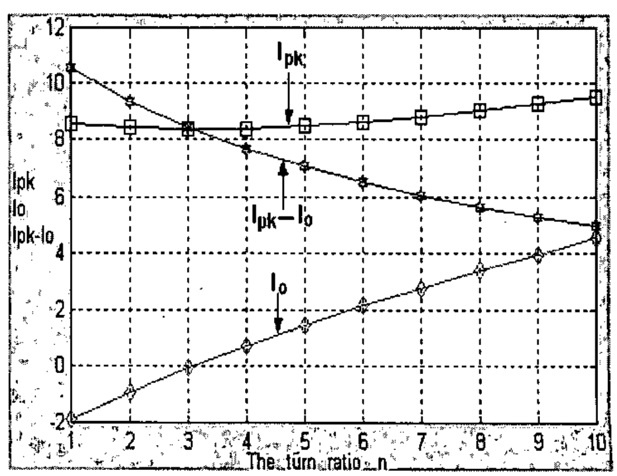


Fig.7 I_{pk} and I_0 at different turn ratio

$$D = \frac{V_o}{V_o + n \cdot V_i} \tag{18}$$

For flyback converter, the air gap is an important parameter, it should be sufficient to prevent core from saturation[1][2][5]. The energy stored in core can be expressed by (19):

$$W = \frac{1}{2}(\hat{H}_{Fe\,Fe} \cdot \hat{B}_{Fe} \cdot V_{Fe} + \hat{H}_{air} \cdot \hat{B}_{air} \cdot V_{\lg}) \tag{19}$$

Because

$$\hat{B}_{Fe} = \hat{B}_{air} = B$$
$$V_{Fe} = l_{Fe} \cdot A$$
$$V_{air} = \lg \cdot A$$
$$W = \frac{B^2}{2\mu_0}(\frac{l_{Fe}}{\mu_r} + \lg) \cdot A \tag{20}$$

μ_0 of ferrite is larger than that of the air so the later item in the bracket in (20) will play the main role, therefore, energy is mainly stored in the air gap. That is:

$$W = \frac{B^2}{2\mu_0} \cdot V_{air} \tag{21}$$

While the energy needed to stored by the core is determined by the peak current and its inductance value L_m:

$$W = \frac{1}{2} L_m I_{pk}^2 \tag{22}$$

The core material has its maximum magnetic flux density B_{max}, which common value is about 3000*Gs*, So the required minimum volume of the air gap should be[5]

$$V_{air} = A \cdot \lg \geq \frac{\mu_0 L_m \cdot I_{pk}^2}{B_{mav}^2} \tag{23}$$

In the flyback converter and its transformer, the primary inductor and the turn ratio are two key parameters and the later has been described, The primary inductor L_m directly determined the increment rate of the primary current. If the switch frequency and the duty ratio are fixed, the higher the inductance, the lower the difference betweenI I_{pk} and I_0. So it should be calculated through the expected current shape. Fig.7 is a procedure of designing the flyback transformer for voltage step-up application. Because adjusting the air gap is a usual method to adjust the value of the primary inductance. The length of the air gap should met the need of the required Lm-value as well as (23).

III. EXPERIMENTAL RESULT

The follow is an example using the proposed method for a step-up application. Giving the following parameters:

V_i=12V; T_s=5us; V_o=100V; P=40W

A high switching frequency about 180*kHz* is selected to achieve a shorter on-time for a given duty ratio *D*, the shorter the on-time, the smaller the peak current which is an advantage for the converter as long as it is not excessive high. Before designing, I_{pk} and I_0 must be given in an acceptable range. For example, I_{pk} is selected to 6-10*A* and I_0 is under 5*A*. The result of the design is:

D=0.6, L_m=5.2*uH*, and the turn ratio *n*=5.56 is obtained from *D*=0.6. The expected I_{pk}=9.02*A* and I_0=2*A*, for the RM8 core, the length of the air gap is 0.25*mm*.

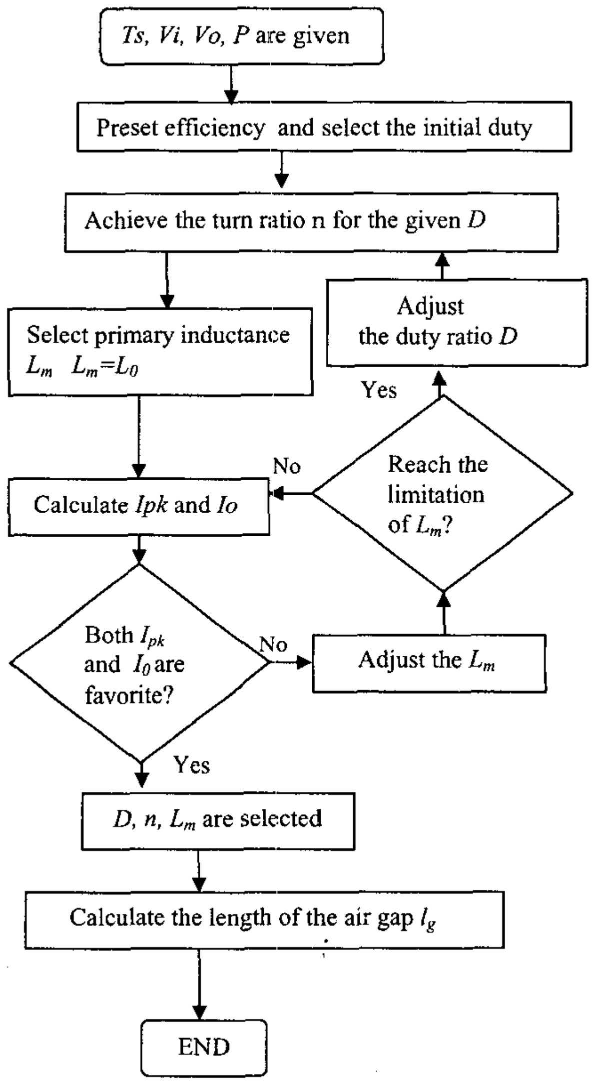
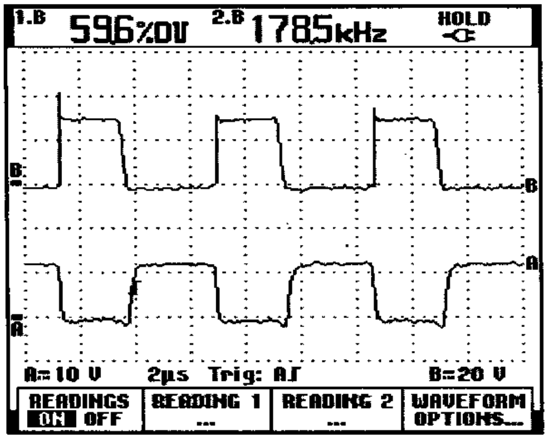


Fig.8 The design procedure of the flyback transformer

Build a flyback converter with the designed transformer, and a absorb circuit of the leakage inductor, the efficiency of the main converter is 85.36%, the driving control circuit, which power is about 2-3*W*, is supplied by the absorb circuit, the efficiency of the total system is about 90.2%. The power density of the whole device is about 28.5 $W/inch^3$,and that of the flyback stage is about 85.5 $W/inch^3$. The experiment waveform of the voltage across the main flyback switch is shown in Fig.9, the spike of the voltage across the main switch is disappeared.



A: The drive signal of the main switch
B: The voltage across the mian switch
Fig.9 Experiment waveform of the flyback

IV. CONCLUSION

The transformer in flyback converter plays the role of a transformer and rather a coupled inductor, so its parameters which may affect the performance of the converter, especially for the voltage step-up application, is the key issues in designing the converter. With this proposed method, according to the anticipant peak and the initial current shape, the duty ratio D, the primary inductor Lm, turn ratio n, and the air gap lg can be optimized. Refer to the method, a transformer is designed and is adopted in the experiment circuit. The result verified the transformer is well-done, and the design method can be used to design the flyback transformer.

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