A GENERALIZED DYNAMIC MODEL FOR FLYBACK SWITCHING CONVERTER BASED ON NONLINEAR FINITE ELEMENT ANALYSIS

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Abstract

This paper presents a generalized dynamic model for flyback switching AC-DC converters. Comparing with the current model in the published literatures, several important factors are taken into account, including the anomalous loss in magnetic cores, differential inductance and leakage inductance. In order to obtain accurate parameters, nonlinear finite element analysis method is used to calculate some key parameters of transformer: differential inductance and leakage inductance. Furthermore, a modified flyback transformer model is built. The systematic method to build the hybrid model - system switching state based on time sequence is also introduced. A simulation model in MATLAB/Simulink, in which all three operational modes are included, is built. The developed model is validated by executing the model on an existing converter, and several performances are obtained.

1 Introduction

Because of its simpler structure than other types of switching mode converters, the flyback converter is commonly used as small power converters. To predict, assess and optimize the performance of flyback converters, a generalized dynamic simulation model for the behavior of flyback converters would always be useful. As an accurate model with high practical value, it must have high efficiency and must be also easy to be used. This paper includes two parts of work.

One is the method to build the simulation model. There are three existing basic kinds of method: state-space averaging technique and linearization, linear circuit technique, and nonlinear design technique. Among them, the state-space averaging technique and linearization has more advantages of efficiency and accuracy, and with this technique, several simulation models were introduced in early literatures [1-3]. According to the state-space averaging technique and linearization, a method based on switching state-space to build MATLAB/Simulink model, which is likely similar to the method for designing numerical system based on time sequence, has been primarily introduced in [1]. In fact, the hybrid simulation model in MATLAB/Simulink can be seen as a time sequence system, the method for designing the numerical system based on time sequence is introduced in this paper systematically.

The other important work is to build the accurate system physical model. In the typical circuit of flyback switching AC-DC converter, as shown in Fig.1, much attention must be paid to the transformer model. As an accurate model, it should account for the nonlinear inductance and the effect of all kinds of magnetic core loss. A generalized dynamic ladder network circuit model of high frequency transformer, which has accounted for all kinds of magnetic core loss and nonlinear inductance, has been introduced in [4-5] and the circuit model with one level of ladder network is shown in Fig.2 (a). Based on the model in [4-5], and according to the special characteristic of flyback switching converters, a more suitable model for the transformer is introduced, as shown in Fig.2 (b). Due to the nonlinear magnetization property of soft magnetic cores, the differential inductance, L_m, varies with winding current. The current dependence of inductance can be obtained through nonlinear Finite Element Analysis (FEA) method. By implementing this developed model into Matlab/Simulink environment, the equivalent resistance of core loss, R_a, and a comprehensive performance of flyback switching converter could be dynamically obtained. Comparing with the models built in early literatures, the models obtained here can give more accurate analysis result, especially, that in operation with heavy load, because the influence on the differential inductance, L_m, caused by winding current will be most high.

2 Physical model for high frequency transformer in flyback converter

The typical circuit of flyback switching AC-DC converter is shown in Fig.1. Since the details of the principle of flyback switching AC-DC converters can be obtained from [6], this section mainly discusses the transformer model. The other circuit models of three parts of converters can be sorted as the follows: 1) Passive components (resistance, inductance and capacitance) can be seen as linear, time-invariant, frequency-independent and ideal; 2) Switching components (diode, power MOSFET): the power MOSFET in the ON state is modeled by a zero resistance and in the OFF state by an infinite resistance, e.g. R_{INF} =10^{20} Ω. The output capacitance and the inductance of the leading wires are considered as zero. The diode in the ON state is modeled by a constant voltage battery V_F plus a constant forward resistance R_F, and in the OFF state by an infinite resistance, e.g. R_{INF}=10^{20} Ω. During the charge-carrier's lifetime, the diode junction capacitance and leading wire inductance are zero. 3) Integrated chip (UC3842, TL431A and PC817B): As three kinds of control delay will be added in their corresponding run mode [1], their models just need to take into account their corresponding normal functions, the details of which can be obtained from the data sheet provided by the manufacturer.

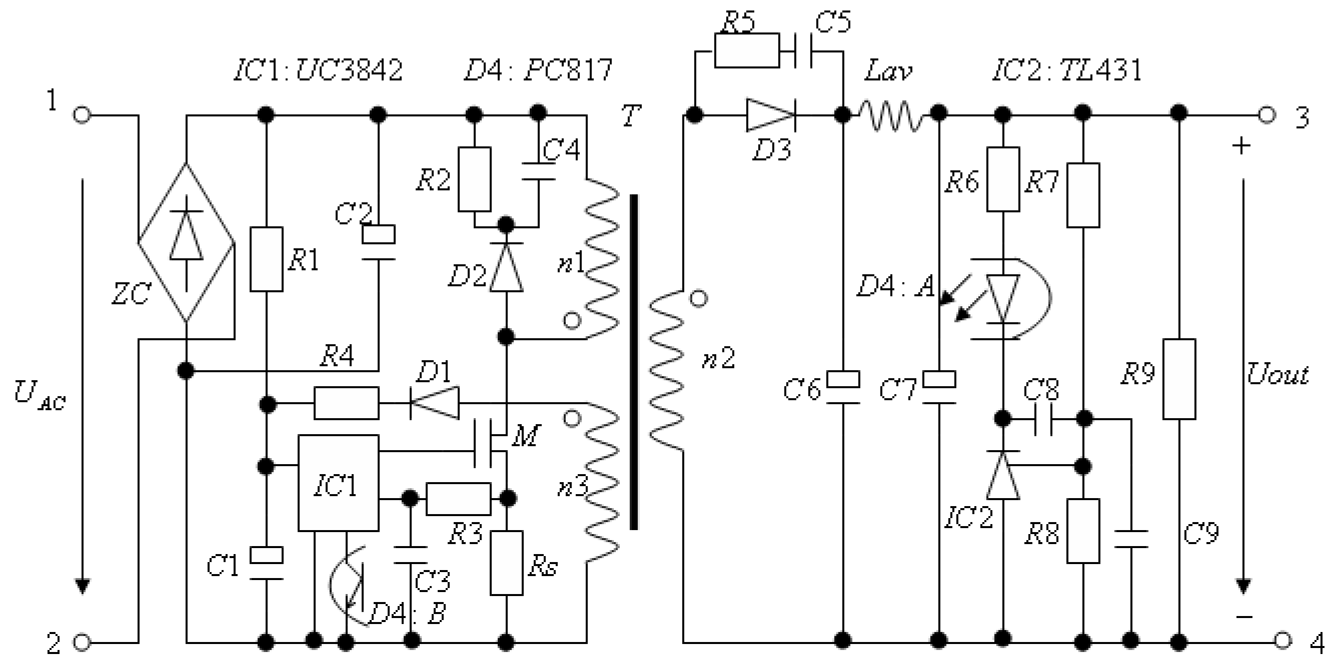

Fig.1: typical circuit topology of flyback AC-DC Converter.

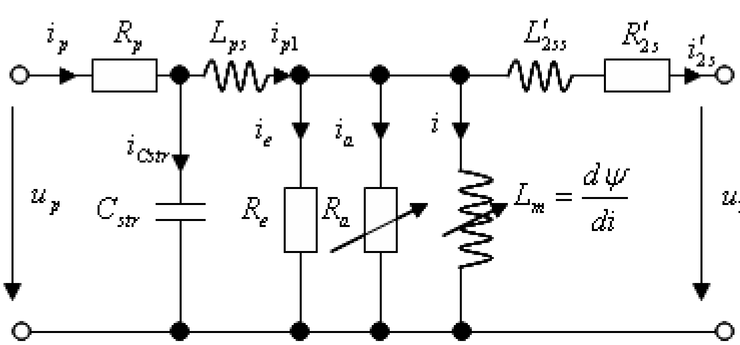

Fig.2 (a): dynamic circuit model of transformer.

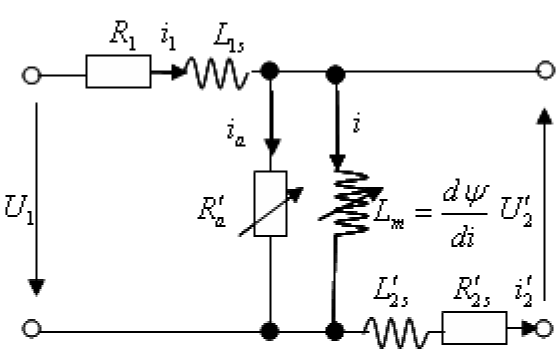

Fig.2 (b): modified dynamic circuit model of transformer.

2.1 Modified dynamic circuit model for transformer

The model shown in Fig.2 (a) has taken hysteresis loss, eddy current loss, anomalous loss and distributed capacitance into account, where R_a is the nonlinear equivalent resistance of anomalous loss, R_e the equivalent resistance of eddy current loss, L_m the nonlinear differential inductance which has accounted for the effect of hysteresis loss, R_P and L_{PS} the resistance and leakage inductance of the primary winding, R_{2s}' and L_{2ss}' the equivalent resistance and equivalent leakage inductance of the secondary winding, respectively. The stray capacitance, C_{str}, is the equivalent distributed capacity of transformer and can be obtained by experiment [5].

Since the soft magnetic cores used in flyback converters, such as TDK-PC40 and N27, have high electrical resistivity and narrow B-H hysteresis limiting loop, the skin effect, hysteresis loss and eddy current loss can be neglected. The major core loss is the anomalous loss, and the level number of ladder circuit can be reduced to one level. Considering that the RCD snubber circuit, consisting of R2, C4 and D2, has the similar function of the stray capacitance, and the output from the third winding is small, the modified dynamic circuit model of flyback switching converters is built as shown in Fig.2 (b).

2.2 Differential inductance and leakage inductance

As we know the behavior of the transformer equivalent electrical circuit is dominated by the differential inductance rather than the apparent inductance. In this paper, the winding differential inductances is calculated through the following two steps: (1) For a given winding current, i, conduct a non-linear field analysis to find the flux linkage of windings, ψ_m; (2) When the flux densities in two consecutive time steps are obtained, the differential inductances can be calculated by

$$L_m(i)=\frac{d\psi_m(k)}{di}=A*n_1*\frac{B_m(k)-B_m(k-1)}{i(k)-i(k-1)}, \tag{1}$$

where A is the cross-sectional area of transformer, n_1 the number of turns of the primary winding, and subscripts *(k)* and *(k-1)* refer to the *k*th and *(k-1)*th steps, respectively. Fig.3 shows the 2D magnetic force lines of an E25-transformer with air gap, and Fig.4 shows the differential inductance at different current of wingding. The leakage inductances, L_{1S} and L_{2S}' are constant.

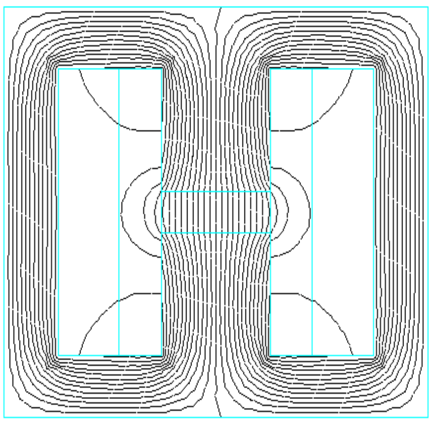

Fig.3: 2D magnetic force lines of E25-transformer.

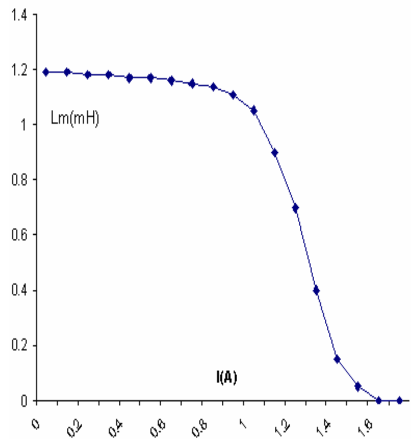

Fig.4: differential inductance at different current.

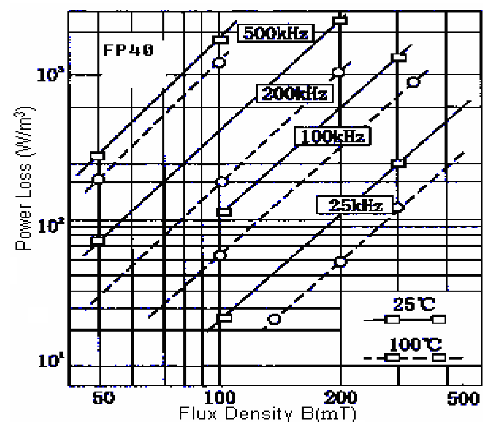

Fig.5: core loss curve of soft magnetic core, FP40.

2.3 Consideration of anomalous loss

It has been pointed out in [4] that the anomalous loss P_a (in W/Kg) of magnetic cores is given by

$$P_a=C_a\left|\frac{dB}{dt}\right|^{3/2} \tag{2}$$

where C_a is the coefficient of the anomalous loss and B is the magnetic flux density.

The core loss curve of soft magnetic cores is provided by material manufacturer and shown in Fig.5. Through the method of fitting the curve in Fig.5, C_a can be obtained.

According to Fig.2 (b), the equivalent core loss resistance of transformer is given by

$$R_a'=\frac{C_a}{U^2}w\left|\frac{dB}{dt}\right|^{3/2} \tag{3}$$

where U is the voltage across the differential inductance, L_m, w and B are the mass and magnetic flux density of magnetic core, respectively.

For a transformer with symmetrical structure, considering that the voltages across R_a and L_{1S} or R_{2s}' and L_{2s}' are very small comparing to U_1 and U_2', the following equations could be obtained:

$$R_a'\approx C_a w|U_1|^{-1/2}(An_1)^{3/2}; PWM=ON \tag{4}$$

$$R_a'\approx C_a w|U_2|^{-1/2}(An_1)^{3/2}; PWM=OFF \tag{5}$$

2.4 Physical model of transformer

The current variable model of transformer in flyback switching AC-DC converters is given as

$$U_1=(R_1 i_1+L_{1s}\frac{di_1}{dt})+L_m\frac{di}{dt}, \tag{6}$$

$$U_2'=-[(R_{2s}'i_1+L_{2s}'\frac{di_2'}{dt})+L_m\frac{di}{dt}] \tag{7}$$

$$i=i_1+i_2'-(L_m\frac{di}{dt})/R_a' \tag{8}$$

where the variables of L_{1s}, L_m and L_{2s}' are used as their conventional meanings and are obtained from the nonlinear FE solutions, in which the saturation effect is considered. The equivalent resistance of R_a', which relies on the voltage across the inductance, L_m, can be obtained from (2)-(5).

3 Dynamic Simulation Model for Flyback Switching AC-DC Converters

According to the circuit model obtained in section II, the hybrid dynamic simulation model for flyback switching AC-

DC converters is built by using the method for designing the numerical system based on time sequence in this section.

3.1 General principle for modeling a hybrid system

The flyback converter has both continuous circuit blocks and discontinuous blocks, so it is a hybrid system rather than a numerical system based on time sequence. However, many parts have the characteristic of two values, i.e. on/off states in converters, and their current states are decided by their former states and current input data. This property has some similarity to the numerical system based on time sequence. In fact, the flyback converter can be modeled by a digital system with two level structures: the top level is the digital system instituted by all the switching parts and some other pure parts with switching characteristic, and the second level is the continuous system instituted by all passive components. Then the design method for numerical system based on time sequence needs to be slightly modified, which can be used to design the simulation model for flyback converters. As several points in system need to be watched and many parameters can be modified, this system is multi-input and multi-output system.

The system state of the top level is described by

$$Q^n = (Q_1{}^n, Q_2{}^n, \ldots, Q_k{}^n) \quad , \qquad (9)$$

where Q^n is the current system state, and $Q_k{}^n$ the current state of the *kth* switching part. In order to consider the influence on performance caused by transferring delay, three kinds of delay are taken into account in this simulation model, including the delay, T_{dvc}, in the loop of normal output voltage control block (VCB), the delay, T_{doc}, in the loop of over current protection (OCP) block, and the delay, T_{duv}, in the loop of under voltage protection (UVP). As they have the characteristic of two values, they are also considered as switch parts.

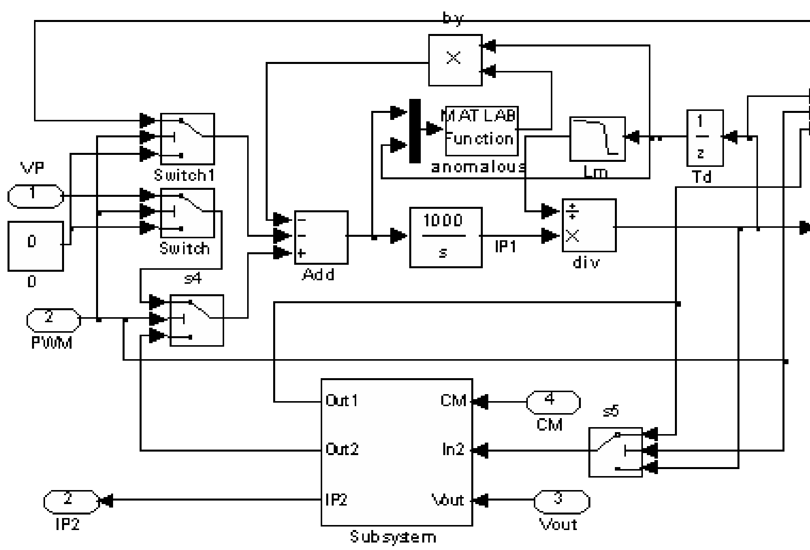

Fig.6 Simulation model of transformer considering differential inductance and anomalous loss

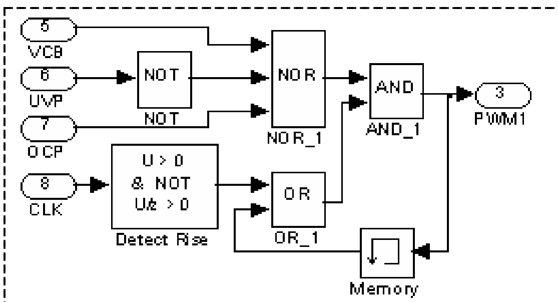

Fig.7 PWM state logical generator

The system state equation is constituted by all state equations of switching parts as follows.

$$\begin{cases} Q_1^{n+1} = f_1(Q_1{}^n, X_1) \\ Q_2^{n+1} = f_2(Q_2{}^n, X_2) \\ \ldots\ldots\ldots\ldots\ldots\ldots \\ Q_k^{n+1} = f_k(Q_k{}^n, X_k) \end{cases} \qquad (10)$$

where k is the total number of switching parts, Q_j^{n+1} (j=1,2,…,k) is the next step state of the *j-th* switching part, X_j the input variable vector of the *j-th* switching part, which is just used to decide the next step state.

The system driving equation is constituted by all driving equations of switching parts as follows.

$$\begin{cases} X_1(s) = H_{11}(s) * X(s) + H_{12}(s) * U(s) \\ X_2(s) = H_{21}(s) * X(s) + H_{22}(s) * U(s) \\ \ldots\ldots\ldots\ldots\ldots\ldots \\ X_k(s) = H_{k1}(s) * X(s) + H_{k2}(s) * U(s) \end{cases} \qquad (11)$$

where H_{j1} and H_{j2} are the current step transfer functions of the *j-th* switching part, *X(s)* the state variable vector of continuous system, and *U(s)* the input variable vector.

The system output equation is described by

$$y(t) = Cx(t) + Du(t) \ , \qquad (12)$$

where y(t) is the output variable vector of system, C and D the corresponding coefficient matrix.

Equations (11) and (12) institute the second level of system together. Based on (9)-(12), the model of complete hybrid system is built. It should be pointed out that under the impaction of switching parts, $H_{j1}(s)$ and $H_{j2}(s)$ in hybrid system may be variable.

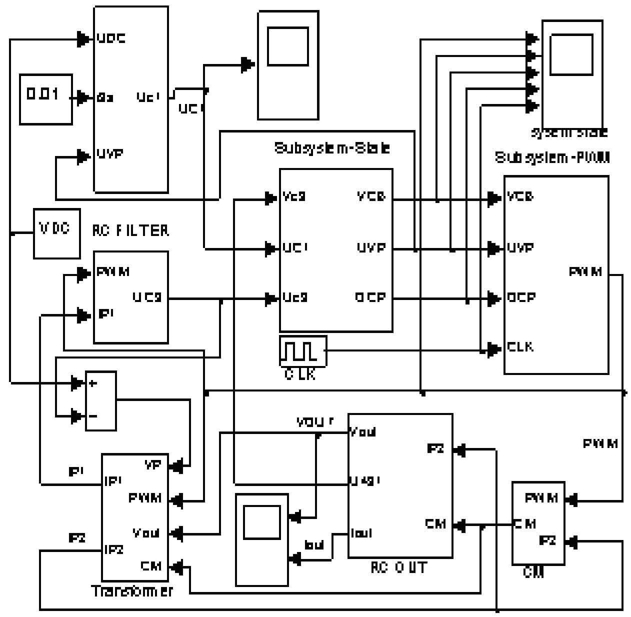

Fig.8: complete simulation model of flyback converter.

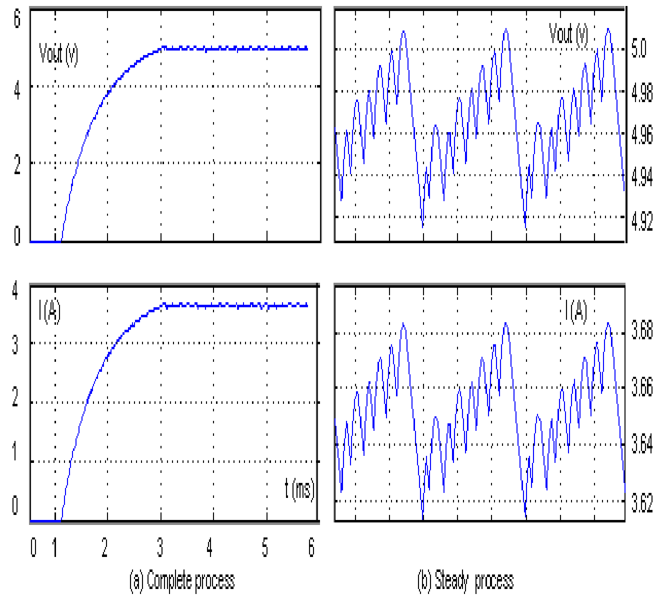

Fig.9: simulation results by using the modified transformer model at the rated load and VDC=102V.

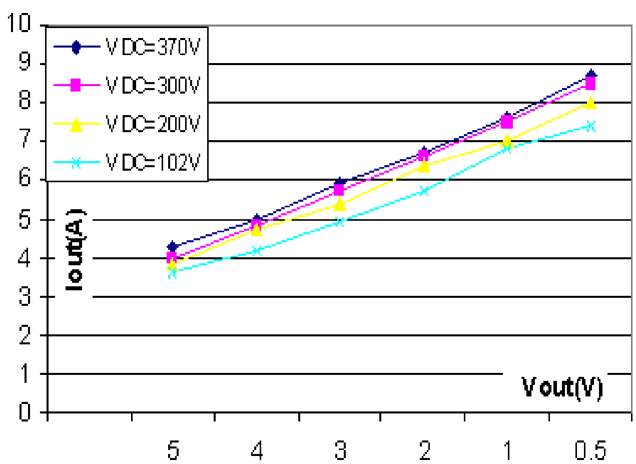

Fig.10: natural output curve of flyback converter at different input voltage.

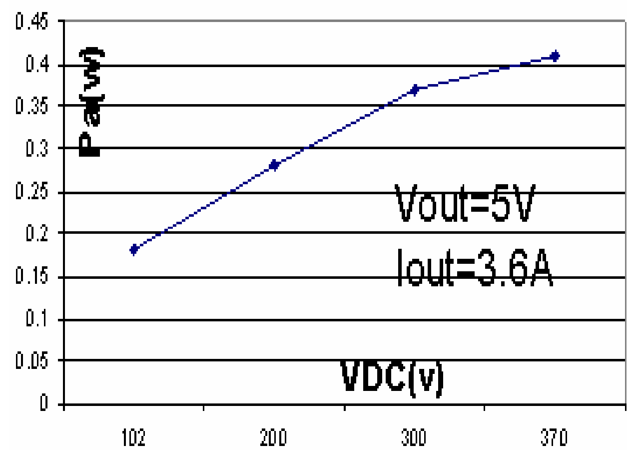

Fig.11: anomalous loss at different input voltage and rated load.

3.2 Dynamic simulation model

3.2.1 Simulation model of transformer

According to (2)-(5), the anomalous loss coefficient, C_a, and its equivalent resistance, R_a, can be obtained: C_a is a constant, 0.00005, but R_a will rely on the voltage across the inductance, L_m of transformer. Its corresponding simulation block is a MATLAB function of R_a. The differential inductance L_m can be obtained by the method of look-up table, in which the data of differential inductance vs current have been preset. Fig.6 shows the simulation model of transformer considering anomalous loss and differential inductance.

3.2.2 Pulse width modulation (PWM)

According to the principle of flyback switching converters, the PWM state is decided by follows equations

$$PWM^{n+1} = (CLK \uparrow + PWM^{n}) \,\&\, \overline{(VCB^{n} + \overline{UVP^{n}} + OCP^{n})} \quad (13)$$

where VCB is the logical state of output voltage, and it is true while the output voltage is larger than the rated value, or false otherwise; UVP is the logical state of UC3842, and it is true while the UC3842 works and can output PWM signal, or false otherwise; OCP is the logical state of over current protection, and it is true while the UC3842 is operating in the model of over current protection, or false otherwise; and *CLK*↑ means the rise of time clock. Corresponding to (13), the simulation model is shown in Fig.7.

3.2.3 Complete simulation model of flyback converter

Fig.8 shows the complete simulation model of flyback converter. Through this model, the performance of converters operating in different output loads and different input voltages can be obtained.

4 Simulation on an existing converter

The simulation model is applied to analyze an existing flyback AC-DC converter. The major data of the converter include: input voltage: 85-264 VAC (102-370 VDC); nominal output voltage: 5 VDC; rated output current: 3.6 A; and switching frequency: 60 kHz. The transformer-E25/FP40 has a primary winding inductance of 1.186 mH, and the numbers of turns of three windings are 96:8:17. Other parameters include: R1=160 KΩ/1W, C1=47 μF/35V, R_S=1.1 Ω, R3=100Ω, C3=470pF, MOSFET: SSS6N60A, R4=0 Ω, D3: MUR1620, D1: UF4006, D2: 1N4148, R2=100 KΩ/1W, C2=47 uF/400V, C4=3.3nF/1000V, Lav=3.6uH and C6=C7=470μF/25V. Through this simulation model, several performances of flyback converters can be obtained.

Fig. 9 (a) illustrates the simulated operation process of the converter with the rated load while V_{IN}=102 VDC. Fig.9 (b) shows the enlarged steady state. It can be seen that the result of simulation by using the modified transformer can satisfy the above nominal requirements of this existing converter. The natural output curve of flyback converter at different input voltage is shown in Fig.10. The anomalous loss at different input voltage and rated load is shown in Fig.11. From Fig.10 and Fig.11, it can be seen that the maximal output power will be increased while the input voltage increases, and anomalous loss will also be increased while the input voltage increases and the output is kept constant as the rated load.

5 Conclusion

This paper has presented a generalized dynamic model for flyback switching AC-DC converters based on nonlinear finite element analysis. Comparing with the models built in early literatures, in this model, a modified flyback transformer model and several important factors such as the differential inductance dependent on the winding current, the equivalent resistance dependent on the voltage across the differential inductance, and the saturation of magnetic cores, are taken into account. The systematic method to build the hybrid model, system switching state based on time sequence, is also introduced. A simulation model in MATLAB/Simulink is built and verified by executing this model on an existing converter. Several important performances are obtained automatically.

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