BOOST Inductor Optimizing Design Based on Finite Element Simulation

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Abstract—As the role of energy storage and filtering in DC/DC converter, the inductor is widely applied in switching power supply designs. BOOST inductor affects the input/output ripple voltage and current. Improper parameter design can cause inductor saturation easily, so the inductor design is the emphasis and difficulty in the Boost circuit design. In this paper, combining the traditional parameter calculation and finite element simulation, a design process of the BOOST inductor is given in detail, and the correctness of the design was validated by the experiments. It provides a more convenient and effective design approach of Boost inductor design.

Keywords- Inductor; Optimizing design; Finite element simulation; BOOST

I. INTRODUCTIONS

With the continuous development of power electronic technology, the switch power supply with miniaturization, lightweight and high reliability has become the research direction and trend at present. As an important part of switch power supply, magnetic components are not only the key determinants of switch power supply volume and weight, but also are the important reasons of affecting the reliability of switch power supply[1]. So how to design magnetic components with parameters meeting the performance requirements, small volume, light weight and low loss, has become the focus of research. Inductor, which plays the role of energy storage and filtering in DC/DC converter, is widely applied in switching power supply design[2]. The conventional design method has the disadvantages of long production cycle and it is also difficult to achieve the best effect[3]. Through an example of BOOST inductor design, this article gives the structure diagram of inductance model, then analyzes the distributions of the magnetic field, energy density and temperature field. In the way of combining the traditional parameter calculation and finite element simulation, the optimization design is carried out, and the correctness of the design is verified by experiments.

II. PARAMETER CALCULATION OF BOOST INDUCTOR

The BOOST converter circuit is shown in figure 1.

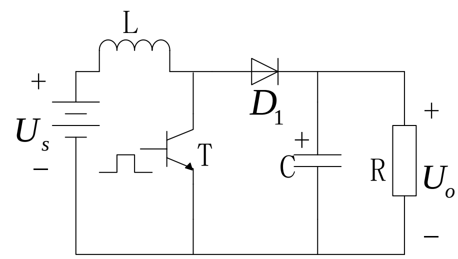

Figure 1. BOOST converter circuit

When the switch tube T is connected, the input voltage U_s is applied on the BOOST inductor L, so the inductance current i_L increases linearly and the electric energy is stored in the inductor coil L in the form of magnetic energy[4-6]. The increase of the inductor current i_L is expressed as,

$$\Delta i_{L+} = \frac{U_s}{L} t_{on} = \frac{U_s}{L} DT_s \tag{1}$$

When the switch tube T is disconnected, the magnetic field in the coil L will change the voltage polarity of the coil L, so as to keep the inductance current i_L unchanged. At this time, the voltage on the BOOST inductor L is ($U_s - U_0$)[7]. Because U_s is less than U_0, i_L will reduce linearly and the reduction is expressed as follows.

$$\Delta i_{L-} = \frac{U_0 - U_s}{L} t_{off} = \frac{U_0 - U_s}{L}(1-D)T_s \tag{2}$$

In the continuous mode, the input current i_L is not fluctuating, and the ripple current decreases with the increase of inductor L, while the input current i_L is fluctuating in discontinuous mode. But the current i_T of the switch tube is always fluctuating in the continuous or discontinuous mode, and the peak current is relatively large[8-9].

The technical indicators in this design are as follows. Input power: $P_{in} = 5.0KW$, switching frequency: f_s =65kHz, efficiency: $\eta \geq$ 90%, AC input voltage range: 220VAC±20%, power grid frequency: f =50Hz, output voltage: U_0 =380V, output power: $P_0 = 4.5KW$.

A. Calculation of ripple current and peak current

Because the maximum current is expressed as formula (3), the ripple current ΔI and the peak current I_{pk} can be calculated as formula (4),(5).

$$I_i = \frac{\sqrt{2}P_{in}}{U_{i\min}} = \frac{\sqrt{2}\times 5000}{176} \approx 40.17A \tag{3}$$

$$\Delta I = I_i \times 18\% = 40.17\times 0.18 \approx 7.23A \tag{4}$$

$$I_{pk} = I_i + \frac{1}{2}\Delta I = 40.17 + \frac{1}{2}\times 7.23 = 43.785A \tag{5}$$

B. Calculation of maximum duty cycle with minimum input voltage

$$D_{\max} = \frac{U_0 - U_{i\min(peak)}}{U_0} = \frac{380-249}{380} \approx 0.345 \tag{6}$$

In the formula, the output voltage of the Boost circuit is expressed in U_0 , and $U_{i\min(peak)}$ indicates the peak voltage after rectified with the minimum input voltage, where $U_{i\min(peak)}$ = 176×1.414=249V.

C. Calculation of critical inductance

$$L \geq \frac{U_{\text{in}}\times D_{\max}}{f_s \times \Delta I} = \frac{249\times 0.345}{65\times 10^3 \times 7.23} \approx 183\text{uH} \tag{7}$$

In the design, the inductance value of BOOST is 200 μH .

D. Selection of magnetic core specifications

Firstly, magnetic potential energy of magnetic core is calculated.

$$E = \frac{1}{2}LI_{\text{pk}}{}^2 = \frac{1}{2}\times 200\times 43.785^2 \approx 191712 \text{ Vus} \tag{8}$$

Then the design output capability of the magnetic core A_p is calculated.

$$A_p = \frac{2E\times 10^2}{K_m B_m J} = \frac{2\times 191712\times 10^2}{0.4\times 7000\times 500} \approx 27.39 \quad cm^4 \tag{9}$$

In the formula, B_m is the maximum working magnetic flux density, here taking B_m =0.7T; J is the current density, taking J =500; K_m is the core window of the fill factor, taking K_m =0.4.

After consulting the magnetic core table provided by the magnetic core manufacturer, the final choice which is close to the value of A_p above is the Fe-Si-Al core (CS777060) with three rings folded around. A single standard magnetic ring parameters are $\phi 77.8/\phi 49.2/12.7$ (outside diameter / inside diameter / height, unit: mm) and the permeability is 60. The basic parameters of magnetic core are as follows. A_ε =1.77 × 3=5.31 cm^2 , A_ω =17.99 cm^2 , l_ε =20 cm , A_p =95.53 cm^4 , $A_L = 204\text{nH}/N^2$, and the saturation magnetic flux density B_s =1.05T.

E. Calculation of winding turns

$$N = \sqrt{L/A_L} = \sqrt{200000/204} \approx 31.3 \tag{10}$$

Taking the winding turns into an integer, the value of this design is 32 turns.

F. Determination of winding wire diameter

Because the average current $I_{av} = \frac{P_{in}}{U_{i\min}} = 28.41A$, the current density J =500 A/cm^2 , the sectional area of the winding wire $S_1 = \frac{I_{av}}{J} = 5.682mm^2$. In order to keep a certain margin, the cross-sectional area of the wire is taken $S_1{}'$ =6 mm^2.

With the penetration depth of the switching frequency Δ =0.26 mm , according to the principle of the wire diameter selection ($\Phi \leq 2\Delta$), the paint package line of the bare wire diameter Φ =0.50 and cross-sectional area S=0.1963 is chosen. The maximum diameter of the wire Φ =0.56, so the number of parallel wire is:

$$n = S_1{}'/S = 6/0.1963 \approx 30.56 \tag{11}$$

Taking it into an integer, there are 31 enameled wires of Φ 0.56 paralleled winding.

III. OPTIMIZATION DESIGN AND SIMULATION OF INDUCTANCE

A. Optimization design and modeling of BOOST inductor

The BOOST inductor is designed by using PExprt design software of Ansoft company. Enter the technical parameters of the BOOST inductor[10], select the ring magnetic core of Magnetics, and finally come to the following design, as shown in table 1.

Considering from the temperature, power loss, cost and other aspects synthetically, the second options is chosen as an optimization scheme with the resulting optimal parameters as follows.

1) The magnetic core uses 55906A2 with size as Φ77.8/Φ49.2/15.(outside diameter ×inside diameter ×length, unit: mm), and the core material is Fe-Si-Al----Kool Mu(60μ);

2) The BOOST inductance is 205.99 uH and the winding turns is 49, winding with 2 strands round wires of AWG#10.

3) The maximum working magnetic flux density is 0.592T and the change of magnetic flux density is 0.132T.

4) The DC resistance of the winding coil is 8.432 mΩ and the DC loss is 6.841 W , while the AC resistance of the winding coil is 20.98 mΩ and the AC loss is 0.053 W .

5) The maximum temperature of the magnetic core is $67.72°C$ and the filling percentage of the winding window is 30.17%.

6) The core loss is 8.688 W , the winding loss is 6.894 W and the power consumption is 15.582 W .

TABLE I. BOOST INDUCTOR DESIGN SCHEME

Magnetic core model	Core material	Wire number	Wire strands	Volume (mm^3)	Turns	Temperature (℃)	Power consumption (W)
55906A2	High Flux(60μ)	AWG10	2	45286.5	49	62.62	13.7050
55906A2	Kool Mu(60μ)	AWG10	2	45286.5	49	67.72	15.5824
55866A2	High Flux(60μ)	AWG10	2	35400.0	56	65.03	14.9794
55866A2	Kool Mu(60μ)	AWG10	1	35400.0	53	69.71	20.2220
55906A2	Kool Mu(60μ)	AWG13	2	45286.5	49	76.96	17.2283
55866A2	Kool Mu(60μ)	AWG13	2	35400.0	53	78.49	16.4724
55906A2	Kool Mu(90μ)	AWG13	1	45286.5	35	77.14	15.7932
55866A2	Kool Mu(90μ)	AWG13	1	35400.0	35	80.47	16.3466
55906A2	Kool Mu(125μ)	AWG13	1	45286.5	25	82.53	15.6534
55866A2	Kool Mu(125μ)	AWG13	1	35400.0	25	98.88	18.2142

The schematic diagram of the BOOST inductor model is shown in Figure 2. It can be seen the winding process from the figure. First, 1 strands of AWG#10 are used to make 49 turns around the circle and the lead thread (or tail) is connected. Then 1 strands of AWG#10 are used to circle the 49 turns of the wire and the lead thread (or tail) is connected. Finally, the 2 strands of thread lead into a leading thread and the end of the line lead into a tail. The insulation layers are required between the winding and the winding and between the layer and the layer. The thickness of the former is 0.68mm, and the thickness of the latter is 0.683mm.

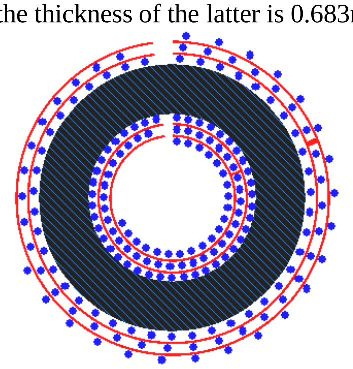

Figure 2. Schematic diagram of BOOST inductance model

B. Simulation analysis of BOOST inductor model

The transient magnetic field simulation results of BOOST inductor are as follows by the finite element analysis software Maxwell 2D.

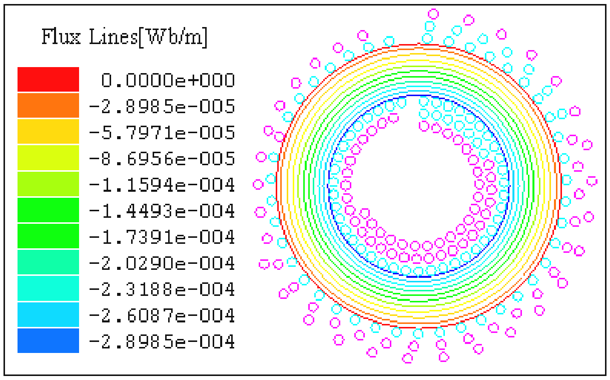

Figure 3. Magnetic field lines distribution

Figure 3 is the distribution of magnetic field lines. It can be seen that the magnetic field lines of the toroidal cores are closed lines and form concentric circles which are the pairwise disjoints. The magnetic field lines near the outer diameter of the toroidal core are relatively few so as that the magnetic field is weak. On the contrary, if the distance from the inner diameter is shorter, the distribution of the magnetic field lines is more intensive and the magnetic field is also increased. So the magnetic field near the inner diameter of the core is the strongest, and the magnetic induction intensity is maximal.

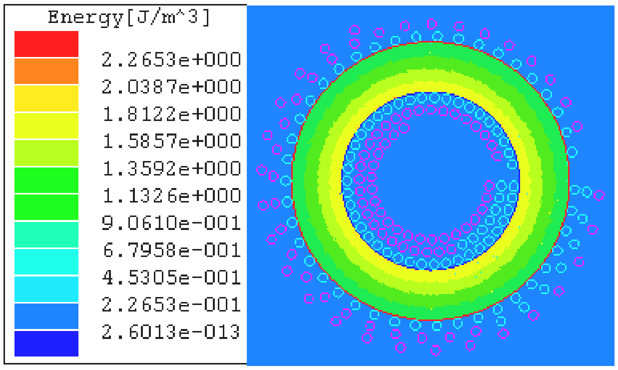

Figure 4. Energy density distribution

Figure 4 shows the distribution of the magnetic core energy density. The energy is mainly concentrated in the inner ring while a small number around the magnetic core. The maximum value of the energy density is located in the inner core of the magnetic core, and its value is about 2.04 J/m^3.

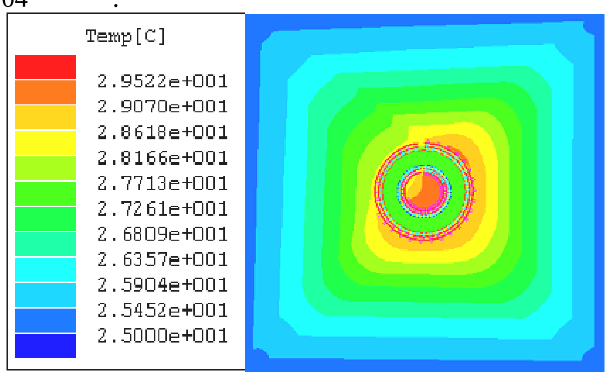

Figure 5. Temperature field distribution

Figure 5 is the temperature field distribution of magnetic core. In the figure, the ambient temperature is 25 $^{\circ}C$, and the maximum temperature of the inductance model is 29.522 $^{\circ}C$. Because the winding coil is easy to produce heat to cause the temperature increased sharply, the temperature is high in the place of many winding coils. So in the internal ring with the highest temperature, the winding coil is too concentrated that the heat can not spread out. On the contrary, in the external ring, the temperature around the coil is high enough to make the heat radiating outwards and reducing the temperature. As a result, in the process of winding, should be selected as far as possible. The winding loss can be reduced because the larger diameter wires heat difficultly can carry a large current to make the temperature rise smaller. Besides, when the component is arranged, the wires should be far away from the components which are liable to cause heat.

IV. Experimental Results Analysis

In accordance with the above data, a BOOST inductor has been made, which can form a BOOST control circuit with a dedicated power factor correction chip. The rationality of this BOOST inductor design can be verified by the experiments on this BOOST control circuit.

Figure 6, Figure 7 and Figure 8 are the driving signals and the inductor current waveforms under different powers. The channel 1 indicates the drive signal waveform of the MOSFET tube, and the channel 2 indicates the inductor current waveform.

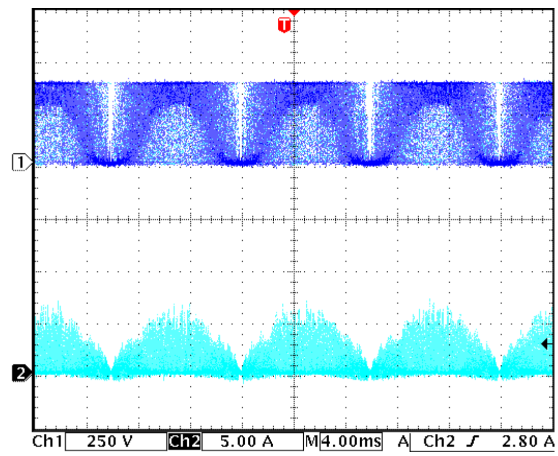

Figure 6. Waveform when the output current is 0.5A

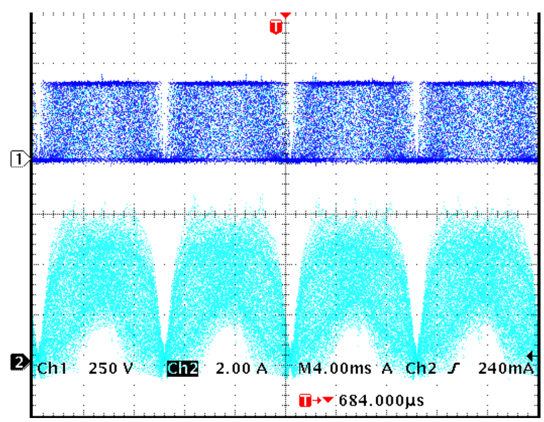

Figure 7. Waveform when the out put current is 2A

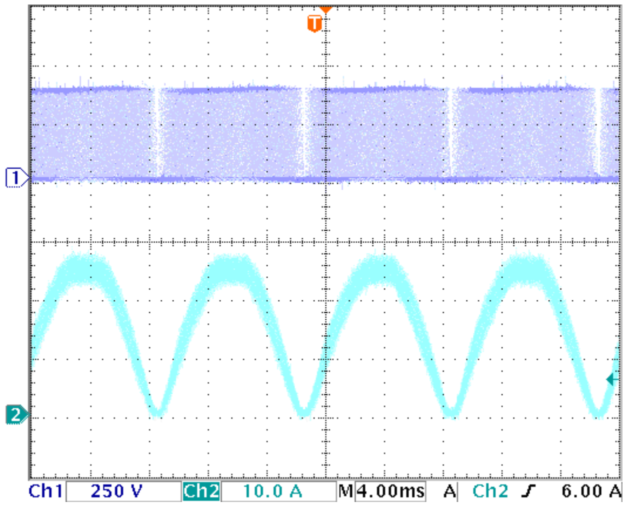

Figure 8. Waveform when the output current is 13A

From the figures, it can be seen that the inductor current is working in the discontinuous mode when the power is small, and with the increase of the power, the inductor current is in the continuous mode. When the input power reaches 5kW, the output current is 13A, the power factor is as high as 0.96, and the work efficiency is as high as 92.1%.

V. CONCLUSION

In engineering practices, the design of conventional parameters is more complicated, and the results may not be the best. By using the combination of traditional parameter calculation and finite element simulation, the paper gives the detailed design steps of the BOOST inductance, establishes the inductance model, and carries on the related electromagnetic simulation analysis to the model. Finally, through the prototype test, the results show that the BOOST inductor design is reasonable and feasible.

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REFERENCES

[1] [1] Hu Yanshen, Xie Yunxiang, "Engineering Design of Boost Inductance with Sendust Core", Electrotechnical Application, vol.25, no. 7, (2006), pp.83-86.

[2] [2] Liffran, Florent, "A Procedure to Optimize the Inductor Design in Boost PFC Applications", 13th International Power Electronics and Motion Control Conference, Poznan, POLAND(2008), September 01-03.

[3] [3] Sartori, Hamiltom Confortin; Hey, Helio Leaes; Pinheiro, Jose Renes, "An Optimum Design of PFC Boost Converters", 13th European Conference on Power Electronics and Applications, Barcelona, SPAIN (2009), September 08-10.

[4] [4] Ye, Yuanmao; Cheng, Ka Wai Eric, "Single-switch Single-inductor Multi-output Pulse Width Modulation Converters Based on Optimised Switched-capacitor", IET Power Electronics. vol.8, no.11, (2015), pp.2168-2175.

[5] [5] Kim, Dong-Hee; Choe, Gyu-Yeong; Lee, Byoung-Kuk, "DCM Analysis and Inductance Design Method of Interleaved Boost Converters", IEEE Transactions on Power Electronics, vol.28, no.10, (2013), pp.4700-4711.

[6] [6] Nussbaumer, Thomas; Raggl, Klaus; Kolar, Johann W, "Design Guidelines for Interleaved Single-Phase Boost PFC Circuits", IEEE Transactions on Industrial Electronics, vol.56, no.7, (2009), pp.2559-2573.

[7] [7] Feng, Gaohui; Yuan, Liqiang; Zhao, Zhengming, "Transient Performance Improvement in the Boundary Control of Boost Converters Using Synthetic Optimized Trajectory", Journal of Power Electronics, vol.16, no.2, (2016), pp.584-597.

[8] [8] Kim, Jung-Won; Yi, Je-Hyun; Cho, Bo-Hyung, "Enhanced Variable On-time Control of Critical Conduction Mode Boost Power Factor Correction Converters", Journal of Power Electronics, vol.14, no.5, (2014), pp.890-898.

[9] [9] Cao, Guoen; Kim, Hee-Jun, "Improved Bridgeless Interleaved Boost PFC Rectifier with Optimized Magnetic Utilization and Reduced Sensing Noise", Journal of Power Electronics, vol.14, no.5, (2014), pp.815-826.

[10] [10] Thirumurugan, V.; Manoharana, S, "Optimized interleaved boost converter with high step up voltage gain for photovoltaic applications", Optoelectronics and Advanced Materials-rapid Communications, vol.9, no.5-6, (2015), pp.613-618.