Research on Efficiency Improvement of High Frequency Transformer in UPS based on Maxwell

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Abstract. On-line UPS occupies a large proportion in today's standby power market due to its rapid dynamic response and clean power output. The bi-directional DC-DC converter can replace the directional DC-DC in both commercial mode and battery mode of UPS, and realize the sharing of power transformer, inductor and power switch components in two DC-DC circuits, so as to achieve the goal of large charging current, high power density and low cost. In UPS, the loss of magnetic components is the main factor affecting the efficiency of bi-directional converter. In order to improve the efficiency of bidirectional DC-DC, a high frequency transformer is designed. Maxwell software is used in this paper to simulate the transformer losses in different winding arrangements, so as to select the optimal winding arrangements, reducing the transformer winding losses and improving the converter efficiency. Finally, the prototype is made and debugged to verify the feasibility of the design.

1. Parameter design and simulation analysis of high frequency transformer
DC-DC circuits are required in both charging and discharging process of UPS [1][2]. In order to achieve the goal of large charging current, transformer, inductor, capacitor and other power components with larger power capacity need to be selected, which leads to the increase of system volume, reduction of power density and increase of cost [3][4]. Bi-directional DC-DC converter can realize bi-directional energy transfer between two DC sources [5]. In this paper, a high-frequency transformer isolation type push-pull bi-directional current full bridge topology is designed, the battery is located in the side of push-pull, bus bar is located in the bridge side, S1, S2, Q3 and Q4, Q5, Q6 for switch tube, D1, D2, D3, D4, D5, D6 for the corresponding switch tube body diode, capacitor C3 to battery side, C1 and C2 is busbar capacitance, inductance L for booster and filtering.

Figure 1. Current type push-pull full bridge topology
The high frequency transformer can greatly booster, buck voltage, with electrical isolation protection. Current mode topology with inductance, the characteristics of the current ripple is small. The push-pull topology is suitable for low voltage, high power occasions, full bridge topology is suitable for high voltage, high power occasions, so the current type push-pull topology of the whole bridge is applicable for bi-directional DC - DC converter of UPS. In order to improve the efficiency of the converter, this paper will study the design of high-frequency transformers, design the parameters of high-frequency transformers, using Maxwell to conduct loss simulation under different winding arrangements to select transformers with relatively small loss.

1.1. Magnetic core selection
According to the transformer power capacity formula:

\[ A_p = A_e \times K_c \times K_u = \frac{(1-D) \times T \times P_i}{\Delta B \times \eta \times K_c \times K_u \times j} = 1.185 \text{cm}^2 \]  

\( K_c \): core filling coefficient; \( K_u \): Copper filling coefficient; \( \Delta B \): change in magnetic induction intensity; \( \eta \): efficiency of DC-DC converter.

After comprehensive consideration, ETD34 magnetic core made of manganese-zinc ferrite is selected. The relevant parameters are as follow: \( A_e=98 \text{mm}^2; A_w=179.1 \text{mm}^2; A_p=1.755 \text{cm}^2; l_e=79.4 \text{mm} \).

1.2. Calculate the number of turns on the primary side
According to the principle of full bridge pipe duty ratio less than 50%, the variable ratio can be obtained

\[ n = \frac{N_1 + N_4}{N_1} = 15 \]  

According to the formula (2) and (3) and considering the actual winding situation of transformer, the two windings on the push-pull side are selected for 6 turns each, and the winding on the whole bridge side is for 90 turns. Then, the maximum duty ratio of the push-pull switch tube is 0.657.

\[ N_1 \frac{\Delta \Phi}{\Delta t} = V_{in} = \frac{V_1}{n} \]  

\( V_{1} \): Primary side winding voltage of transformer.

1.3. Selection of wire diameter
At high frequency, it is necessary to consider the skin effect of the winding that causes the loss increase. Generally, the wire diameter less than 2 times the skin depth is selected when winding the transformer. According to the skin depth calculation formula, the selected transformer wire diameter should be less than 0.591mm.

\[ \Delta = \frac{2}{\sqrt{2\pi f \mu \gamma}} = 0.2955 \text{mm} \]  

Input mean current

\[ I_1 = \frac{P_i}{\eta V_1} = 27.778 \text{A} \]
The current waveform of the transformer winding is shown in Figure 2, which is the push-pull side current and the full-bridge side current from top to bottom. The DC average value of the push-pull side winding current is calculated by piecewise linearization

\[ I_{dc} = D I_p - \frac{\Delta I}{4} = \frac{I}{2} = 14A \]  

(6)

\[ I_1 = \sqrt{\frac{1}{T} \left[ \int_0^{(1-D)T} (I_p - \frac{\Delta I}{(1-D)T})^2 dt + \int_{(1-D)T}^{T/2} (I_p - \frac{\Delta I}{4})^2 dt \right]} = \sqrt{I_p^2 D - \frac{I_p^2 + \Delta I_1^2}{2} + \Delta I_1^2 \frac{13}{48} - \frac{5D}{24}} \]  

(7)

Figure 2. Transformer winding current

\[ D=0.63, \Delta I_1=3A, \text{so we can calculate that } I_p=23.4A. \]

The effective current value of one winding on the primary side of the transformer is calculated \( I_1=18A. \)

Take the current density of copper wire \( j=7A/mm^2, \) calculate the cross section area of copper wire on primary side of transformer \( S_{cu1}=I_1/j=2.57mm^2. \) Due to the large overcurrent of the primary side coil, copper foil is used for winding. Considering the margin, copper foil is selected as \( d_c=0.16mm, w_s=18mm. \) In the same way, 4 wires with the diameter of the secondary side winding 0.25mm are selected and wound.

1.4. Correction window utilization factor

\[ k_w = \frac{S_{cu1}(N_1 + N_2) + S_{cu2}(N_3 + N_4)}{A_y} = 0.2917 < 0.3 \]  

(8)

According to the design experience, the window coefficient meets the requirement.

1.5. Check the saturation of transformer core

\[ B_m = \frac{V_{in}(1-D_{max})T}{2N_yA_y} = 252mT \]  

(9)

It is known that the saturation magnetic induction intensity of the magnetic core material DMR44 is 510mT at 25°C and 400mT at 100°C, so the saturation phenomenon of the magnetic core will not occur.

1.6. Transformer loss simulation based on Maxwell

Transformer losses mainly include coil losses and core losses, which is one of the main sources of transformer losses. Therefore, reducing transformer losses has important guiding significance for improving converter efficiency.
The improvement design of transformer is a complicated process, and there are many factors affecting the loss, such as core material, shape, size, winding wire diameter, winding mode, working frequency and temperature, etc. All factors should be considered comprehensively in the design, and the traditional theoretical calculation method is often difficult to get a satisfactory scheme. Compared with the traditional theoretical calculation methods, the finite element method software simulation has its unique advantages. Maxwell is a powerful finite element analysis software, which includes modules of electrostatic field, eddy current field, transient field, temperature field, etc. By using this software, the influence of various factors in magnetic element design can be comprehensively considered, so as to obtain a more reasonable design scheme for guiding practice.

The steps for transformer loss simulation using Maxwell software include (1) creating an engineering project; (2) Specify the type of solver; (3) Create the geometric model and specify the properties of the material; (4) Set boundary conditions and add excitation sources; (5) Add solving parameters and options; (6) solving method; (7) Obtain simulation waveform and data through post-processing.

According to the above steps and transformer design parameters, the 2Dxy model is established, and then the transient magnetic field solver is used for simulation. The transformer 2Dxy model, winding excitation waveform and transformer loss simulation waveform are shown in Figure 3.

Figure 3. Associated waveforms in Maxwell simulation
According to the above loss curve, the model with a length of 1 m in the Z direction has a magnetic core loss of 1.3884 kW and a winding loss of 1.1595 kW.

In practice, the ETD34 magnetic core is selected, and the length in Z direction is 10.8 mm, so the core loss in this winding arrangement is $1.3884 \times 10.8 = 14.9947 \text{W}$, the winding loss is $1.1595 \times 10.8 = 12.5226 \text{W}$, and the total transformer loss is 27.5173 W.

According to the experiment, the total transformer loss is about 30 W, and the Maxwell simulation error is approximately 8.276%, which is not far from the actual result. Therefore, Maxwell simulation method is feasible for improving the design of high-frequency transformers.

2. Improvement design and test verification of transformer winding based on Maxwell

2.1. Improvement design of transformer winding based on Maxwell

Among the two sources of transformer losses, core losses are mainly affected by the characteristics of material losses, which is relatively stable. Winding loss is mainly related to working frequency, wire diameter, winding mode, temperature and other factors. With the increase of working frequency, high frequency effects such as skin effect and proximity effect are obvious, which increases the loss of winding. Under the condition of certain frequency and wire diameter, the loss of winding is mainly related to winding mode. Under different winding modes, the high frequency transformer shows different leakage inductance and high frequency effect, which affects the winding loss to different degrees. Therefore, this paper mainly from the winding arrangement aspects of transformer improvement design.

Considering the shape and characteristics of each transformer core, application and cost, ETD core is selected for the experiment. However, due to the limited window width of ETD core, multi-layer winding is inevitable when the winding number of high frequency transformer is large. The winding methods of transformer include ordinary sequential winding, "sandwich" winding, segmenting staggered winding and so on. When the former vice edge transformer staggered winding, on the edge of the structure to improve the former deputy coupling degree, reduce the winding up and down on the surface of the magnetic field intensity, reduce the leakage inductance of the magnetic field energy and energy in the magnetic core window, make the flows through the coil winding current distribution more uniform, and reduce the effects of high frequency proximity effect and the leakage inductance of the winding, so as to reduce the winding loss. Figure 4 shows the magnetic field distribution of the core window under several winding arrangements with two-winding transformer as an example, where P represents the primary winding and S represents the secondary winding.

In the sequential winding method in Figure 4 a), as the primary ampere-turns number increases, the magnetic field intensity gradually increases, reaches the maximum value at the junction between the primary and secondary, and then gradually decreases, and decreases to 0 at the end of the secondary. In comparison, under the winding mode of Figure b), c) and d), the maximum magnetic field strength of the core window decreases, resulting in smaller high-frequency effect and leakage sensation.

In addition, to further segment the winding, the maximum magnetic field strength of the core window can be further reduced, but it is not the more segments the better. As the number of winding segments increases, the winding difficulty increases and the insulation requirement increases, the capacitance effect between different layers of windings increases and the loss of winding does not necessarily continue to decrease.
According to the above analysis, Maxwell software is used to simulate the loss of transformer under different winding arrangements. Among them, ETD fierce zinc ferrite (DMR40) magnetic core with reasonable price, good shielding performance, easy winding and small volume under the same transmission power is selected. The simulation results of transformer losses are shown in Table 1. It can be seen from the table that under the condition of the same shape and material of the magnetic core, among the four winding arrangements, the last winding under staggered winding has the minimum loss. The winding loss of "sandwich" winding method is obviously reduced compared with ordinary sequential winding method. Staggered winding is also conducive to the reduction of winding loss, but it does not mean that the more segments, the less winding loss, which is consistent with the above theoretical analysis.

| Winding arrangement                                      | Core loss(W) | Winding loss(W) | total loss(W) |
|----------------------------------------------------------|--------------|-----------------|---------------|
| i. Vice→primary                                          | 14.954       | 18.590          | 33.544        |
| ii. 1/2 Vice→1/2 primary→1/2 Vice→1/2 primary            | 14.757       | 16.511          | 31.268        |
| iii. "Sandwich"                                          | 14.882       | 12.579          | 27.461        |
| iv. 1/3 Vice→1/2 primary→1/3 Vice→1/3 primary            | 14.920       | 11.708          | 26.628        |

Taking the difference between transformer performance and manufacturing process complexity under different winding arrangements into consideration, the transformer with "sandwich" winding method (vice side-primary side-vice side) is selected for proofing. The efficiency table of DC-DC converter under booster mode obtained by experimental test is shown as Table 2, and the curve is shown as Figure 5.

| P_{in}(W) | U_{i}(V) | I_{i}(A) | P_{o}(W) | η |
|-----------|---------|---------|---------|---|
| 25%R=225W | 37.3    | 6.7     | 249.90  | 90.03% |
| 50%R=450W | 36.3    | 13.4    | 486.42  | 92.51% |
| 75%R=675W | 35.7    | 20.7    | 738.99  | 91.34% |
| 100%R=900W| 35.2    | 28.5    | 1003.20 | 89.71% |
The simulation results show that the loss of the sandwich winding is significantly reduced compared with that of the ordinary sequential winding, and staggered winding is also beneficial to reduce the loss of the winding and improve the efficiency of the converter.

2.2. Experimental results

A 1kVA on-line UPS hardware circuit is shown in Figure 6. Temperature rise test is the main way to verify converter loss and efficiency. There are strict standards for the temperature rise of switching devices, inductors, transformer coils and iron cores, which should not be exceeded in the experiment, otherwise it is easy to cause device damage and system abnormality. The system temperature rise experimental waveform Figure 7 shows that after a period of time, the temperature of each power device can reach a stable state, the temperature rise line remains flat, and the power device is within the required range. Therefore, the selection of bidirectional DC-DC devices meets the design requirements.
3. Conclusion
This paper mainly studies the push-pull full-bridge bi-directional DC converter based on UPS, analyzing the efficiency improvement of the converter. To solve the problem of reducing the loss of high-frequency transformer, Maxwell software is used to simulate the loss of transformer under different winding arrangement. The results show that sandwich winding is more efficient than ordinary sequential winding, and staggered winding is also beneficial to the reduction of winding loss, but it does not mean that the more segments, the smaller the winding losses. The results show that the design improvement can reach the expected goal.

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