LOSS ANALYSIS OF INSULATED CORE TRANSFORMER HIGH VOLTAGE POWER SUPPLY*

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Abstract

Insulated core transformer (ICT) electron accelerator is an ideal prototype in low energy radiation processing industry, and ICT high voltage power supply is the essential apparatus. Conventional ICT high voltage power supply uses laminated silicon steel sheets as magnetic cores and works at 50 Hz. In a novel design of the ICT high voltage power supply, the magnetic cores made of ferrite material are adopted to increase the frequency and improve the performance. Focusing on the new scheme, the loss calculation of the high voltage power supply was carried out. The loss of ferrite magnetic cores and the windings was analysed and simulated.

INTORDUCTION

Insulated core transformers (ICT) are widely used in electron accelerators in irradiation processing industry [1]. Conventional ICT high voltage power supply uses laminated silicon steel sheets as magnetic cores and works at 50Hz. At present, the rapid developments of the fields of power electronics, electrical materials and high voltage technology make it possible to adopt new technologies and designs in ICT high voltage power supply, and a novel design of high frequency ICT high voltage power supply was proposed (see Fig. 1): ferrite magnetic cores, 4-phase structure and 5 kHz square wave as the excitation source are adopted [2]. As the frequency of the ICT is raised, the volume and the weight of the ICT high voltage power supply will be improved, and the output voltage will be more stable.

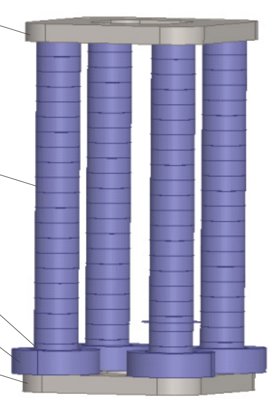

Figure 1: The 3D model of the 4 phase high frequency ICT.

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The high frequency ICT consists of 4 phases and each phase has a primary core and 20 secondary cores. There are insulated sheets to isolate the potential of the magnetic cores. Each secondary core has a rectifier circuit, and all rectifier circuits are connected in series to get the high DC voltage. With the existence of the insulated sheets, the leakage magnetic flux cannot be ignored. The induced voltage will be lower in the coils, which are further from the primary coil. The total number of the cores is 84 and there are also two yokes. The loss of magnetic cores cannot be neglected. The eddy current loss of the coils should also be considered with the high frequency of the excitation source and the leakage magnetic flux acts on the coils. These two kinds of loss need to be calculated when analyzing high frequency ICT efficiency.

FERRITE MAGNETIC COER LOSS

The magnetic core loss includes eddy current loss, hysteresis loss and excess loss. The rapidly changing magnetic flux density dB/dt will cause the induced voltage $E(r, t)$, where r is the radius of the magnetic core. Because of the resistance of the ferrite core, the eddy current exists, which causes the eddy current loss per unit volume:

$$P_e = \frac{1}{V}\cdot\frac{1}{T}\int_0^T\int_0^{r_0} dP_e drdt \quad (1)$$

Where V is the volume of the ferrite core, T is the time period, r_0 is the radius of the ferrite core, and dP_e is the instantaneous power which given by

$$dP_e = \frac{E(r,t)^2}{R} \quad (2)$$

R is the equivalent resistance of the instantaneous induced current.

Using (1) and (2), we can obtain:

$$P_e = \frac{1}{2\rho r_0 T}\int_0^T\int_0^{r_0} r^3\cdot\left(\frac{dB}{dt}\right)drdt \quad (3)$$

Transform the formula (3), the eddy current loss per unit volume is obtained finally by:

$$P_e = \frac{U_1^{\,2}}{8\pi\rho N^2 A} \quad (4)$$

Where U_1 is the input excitation voltage, ρ is the resistivity of the ferrite core, A is the area of the cross section of the magnetic core, N is the number of turns. For the high frequency ICT, the waveform of the input excitation voltage is square, so the eddy current loss can be presented by [3]:

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$$P_{\mathrm{E}} = \frac{2A}{\pi\rho} \cdot B_m{}^2 f^2 \cdot V \tag{5}$$

B_m is the peak value of the magnetic flux density, and f is the frequency of the excitation voltage.

Hysteresis loss is also caused by the rapidly changing of the magnetic flux in the magnetic core. There is no accurate numerical computation suit for different kinds of materials to obtain the hysteresis loss. Therefore, the experimental method is adopted to obtain the hysteresis loop of the ferrite material which used in the high frequency ICT, then the hysteresis loss can be calculated from the hysteresis loop by [3]

$$P_{\mathrm{H}} = V \cdot f \cdot \oint HdB \tag{6}$$

V is the volume of the ferrite core. According to the experimental method, the hysteresis loop is shown in Fig. 2. The value of the maximum working flux is 0.08 T, so the hysteresis loss can be calculated precisely.

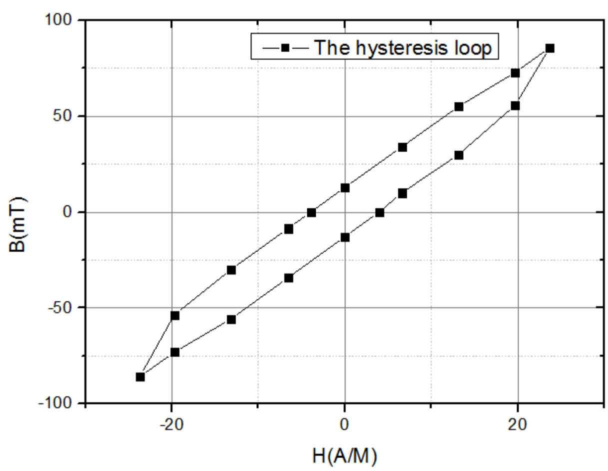

Figure 2: The hysteresis loop of the ferrite core working at 0.08 T.

The computation of the excess loss uses the formula in [4]:

$$P_{\mathrm{EX}} = 8\sqrt{\frac{A\alpha n_0}{\rho}}\left(B_m f\right)^{3/2} \cdot V \tag{7}$$

Finally the magnetic core loss is obtained by adding the three kinds of magnetic core loss:

$$P_{core} = P_E + P_H + P_{\mathrm{EX}} \tag{8}$$

WINDING LOSS

The winding loss mainly includes exciting current loss and eddy current loss. In the high frequency ICT, the eddy current loss caused by exciting current and leakage flux due to air gap between upper core and lower core. For the secondary winding, the induced current is so small that the loss of the winding is negligible, so the primary winding loss is the main loss. Before computing the winding loss, the right size of the wire of the primary winding should be selected. First, the skin depth of the wire at the frequency of 5 kHz is calculated by

$$\Delta = \sqrt{\frac{\rho}{\pi\mu_0\mu_r f}} \tag{9}$$

Where ρ is the resistivity of the copper wire, μ_r is the relative permeability of the copper wire, and f is the frequency of the exciting current. The skin depth of the copper wire at 5 kHz is 0.935 mm. In order to reduce the eddy current loss caused by skin effect, the diameter of the wire must less than 1.87 mm. The wire size should be analysed by taking the leakage magnetic flux into account, as shown in Fig.3 there are large leakage flux getting through the primary winding, which will cause the eddy current loss in the primary winding [5].

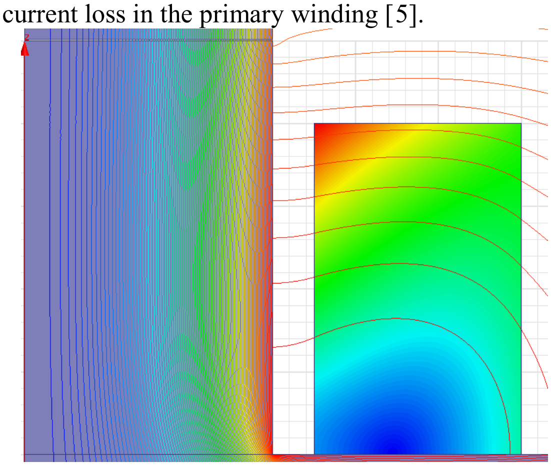

Figure 3: The magnetic flux density distribution nearby the primary winding.

To reduce the eddy current of the primary winding, the stranded wire is adopted under the circumstance of the same cross-section of the winding. In this case, different number of the parallel wires corresponds to certain size of the wires. Fig.4 shows the eddy current loss of the windings when working without a load, the diameter and paralleled number of which is 1 mm and 9 respectively.

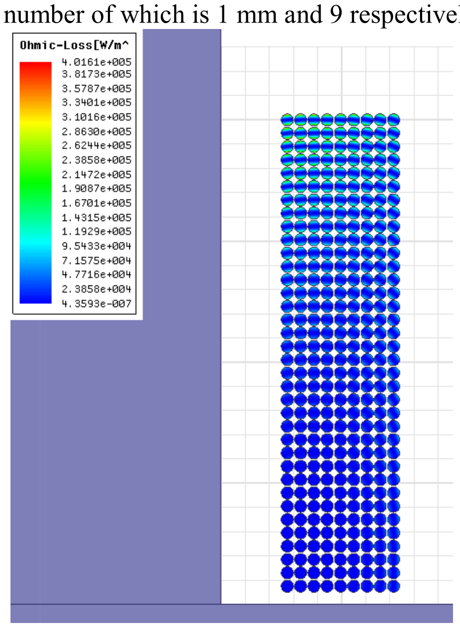

Figure 4: The distribution of eddy current loss in primary winding at the size of 1 mm.

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The exciting current of the primary winding is triangular wave as the exciting voltage is square waveform, so the magnetic flux density in the magnetic core is also triangular waveform, the eddy current loss can be computed when the exciting current changes to 0, at which time the current in the primary winding is produced by the changing leakage flux, so the eddy current loss is obtained individually which is shown in Fig.4.

To verify the correctness of the FEM result in calculating the eddy current loss, the numerical method [6] is adopted, which can be calculated by

$$P_e = \frac{(4fBd)^2}{12\rho}V \tag{10}$$

Where f is the frequency, B is the peak value of the leakage magnetic flux density, d is the diameter of the wire, and V is the volume of the winding. The results of the eddy current loss calculated by FEM and numerical method are shown in Fig.5, which shows that there is little difference between the two methods. Fig.6 shows the computation results of the eddy current loss in different size of the wire by finite element method (FEM).

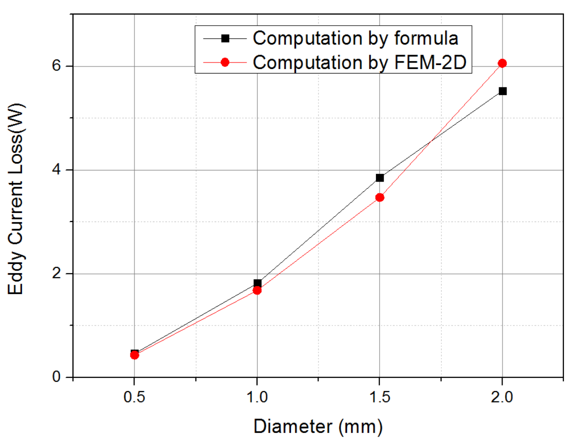

Figure 5: The eddy current loss in different size of the wire by two different method.

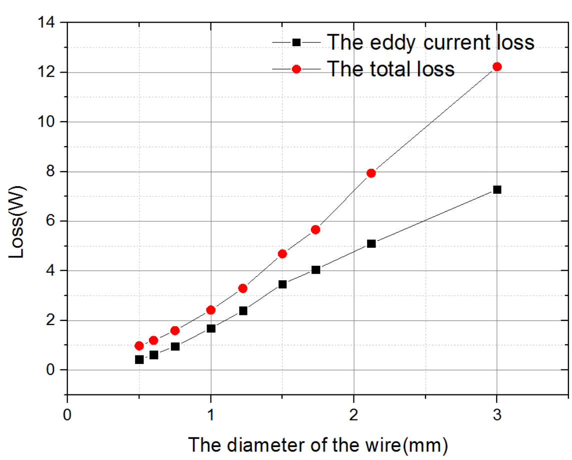

Figure 6: The eddy current loss in different size of the wire.

As shown in Fig.6 the eddy current loss decreases as the diameter of the wire raises, and the decreasing speed of the eddy current loss and the total loss become slow as the size of the wires less than 1 mm, in this case the eddy current loss and the total loss are both rather small. Moreover, as the size of the wire decreases, the cost and the difficulty of production will increase, but there is less contribution to reducing the loss. Above all, 1 mm is selected as the size of wire for the primary winding.

CONCLUSION

High frequency ICT has better performance than conventional ICT, but the leakage flux cannot be neglected as well. Furthermore, with the increasing of the frequency and the current, the eddy current in primary winding should be paid more attention. The magnetic core loss was calculated by numerical method, then the primary winding loss was analysed by FEM. According to the computation result, the design of the primary coil was optimised. This paper analysis the two kinds of loss in high frequency ICT, a loss calculation method for the high frequency ICT is completed. The total core loss of the high frequency ICT is less than 60 W, and the total primary winding loss of the high frequency ICT is less than 10 W when working without a load, which meet the design requirement and it is practicable in engineering.

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