STUDY ON EDDY CURRENT POWER LOSSES IN INSULATED CORE TRANSFORMER PRIMARY COIL*

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Abstract

Insulated core transformer (ICT) high-voltage DC power supply is widely used in electron beam accelerator. With air gaps in ICT, the reluctance of magnetic circuit is larger than other transformers, and the transverse magnetic flux leakage around the primary coil is more serious. Because the magnetic flux on the radial direction of coil cannot be ignored, the eddy current loss on the wire should be discussed. In this paper, simulation and analysis of the eddy current loss is presented. The relationship between the sizes of the coil wire and eddy current power loss is also discussed. An optimal design of the primary coil is shown.

INTRODUCTION

An ICT is consisted of two yokes (up and down) and the cores which are insulated from each other. The voltage between the upper and the lower adjacent cores usually is dozens kilo volts. One high dielectric strength insulating disc is between the upper and the lower cores. The thickness of the disc is about 1mm to 3mm. This insulated core structure solves the problem of insulation between the core which is at ground potential and the secondary coils which are at high voltage potential. The insulation between the core and the secondary coils is instead of the insulation between the cores. So the distance between the core and the secondary coils is smaller. The secondary coils can couple with the primary coils more efficient. On the other hand, because the cores are divided into several sections, there will be several gaps in the magnetic circuit. So the resistance of the magnetic circuit increases. The flux leakage of the ICT is much more than an ordinary transformer. The flux leakage which distribute across the area of the primary coils can stimulate eddy current in the wire of the primary coils, and the eddy current power loss cannot be ignored.

CALCULATION OF THE MAGNETIC FIELD DISTRIBUTION

The ICT is the most important part of the high-voltage DC power supply, and it is a three-phase transformer. The main parameter of the DC power supply is 400kV/60mA. There are 6 layers in the power supply, and every layer can produce a DC voltage of 66kV. 7 gaps are in the magnetic circuit. A double voltage rectifier circuit is connected to every second coil, and one second coil can produce a voltage of 11kV (p-p) in average. The turns of a primary coil are 92, and the turns of a secondary coil are 3000 in average. The exciting current in the primary coil is 54.5A (peak value). The Figure 1 shows the magnetic distribution of the ICT when the exciting current of one phase is peak value. It is calculated by the TOSCA [1].

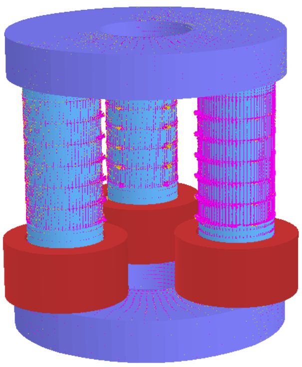

Figure 1: The magnetic distribution of the ICT when the exciting current of one phase is peak value.

The Figure 2 shows the magnetic distribution on the centre axis of the column in which phase the exciting current is at peak value. The maximum magnetic field is about 0.75T at the place which is around the core of the primary coil. The magnetic field decrease rapidly along the centre axis and it is only about 0.4T at the place where the core connects with the up-yoke. Especially, the magnetic field reduces very rapidly around the primary coil. Up to the first insulation gap, magnetic field drops to 0.55T. It illustrates that there is a lot of leakage flux near the primary coil.

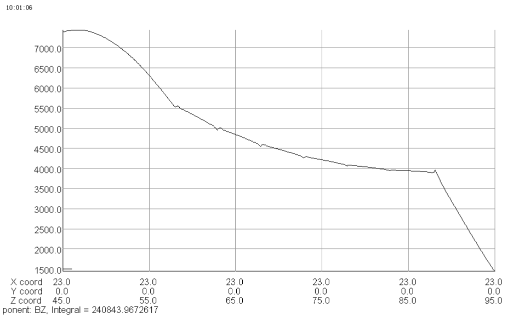

Figure 2: Magnetic distribution on the center axis.

Figure 3 shows the magnetic distribution nearby the primary coil, and the line in the picture is the magnetic induction line. It can be seen that a large flux get through the primary coil area indeed. The magnetic induction strength in the area of primary coil is about 5% of the

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magnetic in the core. This part of flux will produce the eddy current loss in the primary coil.

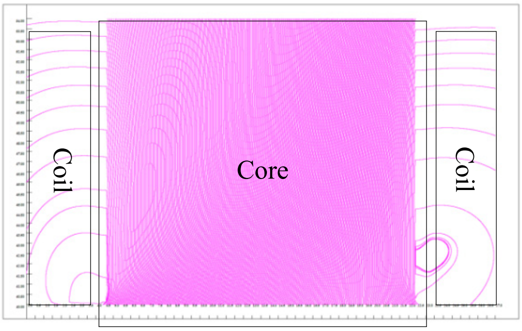

Figure 3: Magnetic distribution nearby the primary coil.

ANALYSIS OF THE VORTEX LOSS IN THE PRIMARY COILS

If the input voltage of the transformer is set as U, the active input current has the same phase as the input voltage, and it can be set as I_1.

The U can be expressed as Eq.1.

$$U = U_m e^{j\omega t} \tag{1}$$

The active input current density can be expressed as Eq. 2. S is the total sectional area of the primary coil wire.

$$J_1 = \frac{I_1}{S} = J_{1m} e^{j\omega t} \quad , \quad J_{1m} = \frac{I_{1m}}{S} \tag{2}$$

The exciting current density can be expressed as Eq. 3. Z_L is the exciting impedance of the transformer.

$$J_0 = \frac{U}{Z_L}\frac{1}{S} = -jJ_{0m} e^{j\omega t} \quad , \quad J_{0m} = \frac{U_m}{\omega LS} \tag{3}$$

The leakage flux has the same phase with the exciting current, so it can be expressed as Eq. 4.

$$B_L\left(\vec{r}, t\right) = -jB_{L0}\left(\vec{r}\right) e^{j\omega t} \tag{4}$$

According to the low of electromagnetic induction, the vortex electric-field strength can be expressed as Eq. 5.

$$E\left(\vec{r}, t\right) = E_m\left(\vec{r}\right) e^{j\omega t} \tag{5}$$

The vortex electric-field has the same phase as the input voltage. The eddy current has the same phase as vortex electric-field, so the eddy current can be expressed as Eq. 6.

$$J^v\left(\vec{r}\right) = J^v{}_0\left(\vec{r}\right) e^{j\omega t} \quad , \quad J^v{}_0\left(\vec{r}\right) = \sigma E_m\left(\vec{r}\right) \tag{6}$$

σ is the conductivity of the wire.

When the transformer has no-load, the Joule heat power in one primary coil can be calculated by Eq. 7. It equals to the eddy-current power plus Joule power of the exciting current.

$$\begin{aligned} P &= \frac{1}{T}\int_V \int_0^T \left(J^v + J_0\right)^2 \rho\, dt\, dV \\ &= P_v + P_0 \end{aligned} \tag{7}$$

P_v is the vortex power loss, and P_0 is the heat power produced by the exciting current. The Eq. 7 shows that the phase difference between the eddy current and exciting current is 90 degree, so the vortex power loss and exciting Joule power loss can be calculated independently.

When the transformer has a load, the Joule heat power in one primary coil can be calculated by Eq. 8.

$$\begin{aligned} P &= \frac{1}{T}\int_V \int_0^T \left(J^v + J_0 + J_1\right)^2 \rho\, dt\, dV \\ &= P_v + P_0 + P_1 + P_{1v} \end{aligned} \tag{8}$$

$$P_{1v} = \frac{1}{T}\int_V \int_0^T 2J^v{}_0\left(\vec{r}\right) J_{1m} e^{2j\omega t} \rho\, dt\, dV$$

P_1 is the heat power in one primary coil produced by the active input current; P_{1v} is the crossover power produced by the active input current and the eddy current. The eddy current has the same phase as the active input current, so there is crossover power in the coils. Below is the computational process of eddy current power loss in the primary coil by numerical method.

CALCULATION OF THE EDDY CURRENT POWER LOSS

The eddy current power loss can be calculated by the formula 9 [2]. It is used to calculate the eddy current power loss in a long conductor. As the value of the magnetic field is different at different places, the formula 9 can't be used directly. If the primary coil is divided into many little elements, the formula 10 can be used to calculate the vortex power loss. In every element, the formula 10 is used to calculate the power loss. The total power loss is the sum of all the elements.

$$P_v = \frac{1}{12\rho}\omega^2 b^2 B^2 V \tag{9}$$

$$\begin{aligned} P_{eri} &= \frac{1}{12\rho}\omega^2 b^2 B_{ri}{}^2 V_i \\ P_{ehi} &= \frac{1}{12\rho}\omega^2 h^2 B_{hi}{}^2 V_i \end{aligned} \tag{10}$$

The magnetic field in the area of primary coil is mainly at the radial direction (see Fig. 3). In order to decrease the vortex power loss, the axial size of wire should be reduced. At the same time, it is difficult to wind the coil when the radial size of the wire is larger than the axial size. In considering these two factors, a square wire is a compromise.

The section area of the all parallel wires is $36mm^2$. The inside radius of the primary coil is 98mm, and the height of it is 120mm. The number of parallel wires can be from 1 to a large number. If the power loss don't reduce obvious or the power is small enough, the number can no longer increase.

The magnetic induction strength of every element can be obtained from the FEM software. Then, the vortex power loss of every element can be calculated according to formula 10. Finally, the total vortex power loss of one primary coil can be gotten by summing up all elements.

Table 1: Vortex Power Loss in Each Case

Number of wire	1	2	3	4
Size of wire/mm	6	4.25	3.45	3
Vortex power loss/W	47.0	23.2	15.4	10.8

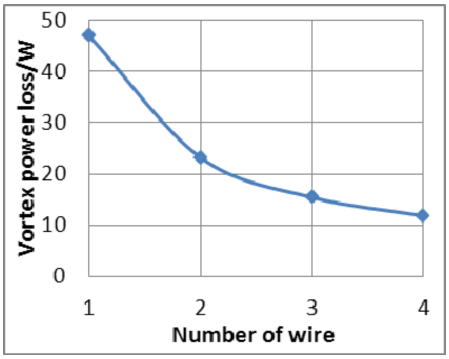

Figure 4: Relationship of vortex power loss and number of parallel wire.

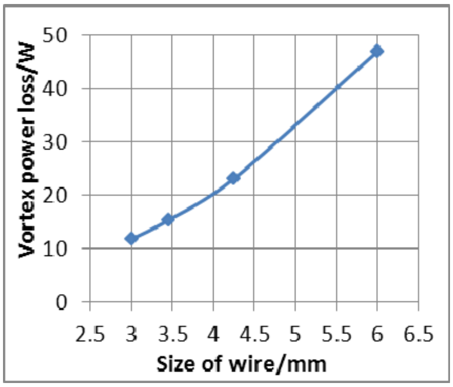

Figure 5: Relationship of vortex power loss and size of wire.

RESULT ANALYSIS

It can be summarized from Figure 4 that the vortex power loss doesn't reduce rapidly when the number of the parallel wire is more than 3. This calculation doesn't consider the load, and the actual loss must more than this calculation result. When the transformer has a load, the direction of the flux produced by the secondary coil is opposite to the primary coil. So the leakage flux nearby the primary coil will increase, and the vortex power loss in the primary coil will increase as well. In addition, according to Eq. 8, the active current and vortex current have superposition power (P_{1v}), and the superposition power will reduce when the size of wire decreases (see Fig. 5). In considering these two factors, 4 parallel wires is an optimal choice.

Figure 3 shows that the direction of most of the leakage flux in the primary coil area is radial. To simplify the calculation model, we can assume that the magnetic field is a uniform field. The strength of the field is the root-mean-square of the actual field. According to the FEM result, the root-mean-square value is about 0.026T. At the same time, the volume of the coil can pass for a fixed value which has no relationship with the size of wire. Then, the formula (10) can be used to calculate the vortex power loss in different wire size. Figure 6 shows the result in the simplified model. Although there is an error in the simplified model, it also can be used to estimate the power loss in different wire size. So it is helpful to select the size of the wire.

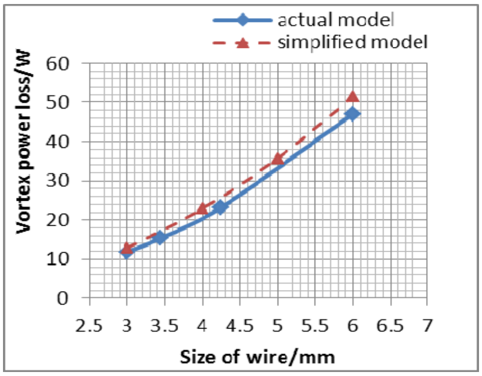

Figure 6: Results calculated in the simplified model and actual model.

SUMMARY

There are several gaps in the ICT magnetic circuit. So the magnetic resistance is bigger than the ordinary transformer, and there is a lot of magnetic flux leakage. Especially, it is more serious in the area of primary coil. At the same time, the cross section of the primary coil wire is relative large because of the high current. The magnetic flux leakage which is in the area of the primary coil will excite eddy current in the wire, and the power loss will be generated. The magnetic field distribution is calculated by the FEM software TOSCA, and the vortex power loss in one primary coil is calculated in numerical method. Finally, 4 parallel wires which cross section size is 3mm × 3mm is selected to make the primary coils. According to the numerical calculation, every coil will produce 11.8W vortex power loss when the transformer hasn't a load. This coil design will meet our requirement and it is feasible in the engineering.

REFERENCES

[1] TOSCA/OPERA-2D/3D user guide, Vector Fields Limited.

[2] Cheng Zhiguang et al., *Electromagnetic and Thermal Field Modelling and Application in Electrical Engineering*, (Beijing: Science Press, 2009), 373.