A NOVEL DESIGN OF INSULATED CORE TRANSFORMER HIGH VOLTAGE POWER SUPPLY*

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Abstract

Insulated core transformer (ICT) high voltage power supply is an ideal model for industrial radiation accelerator at energy below 1MeV. Compared to the traditional scheme, a novel ICT high voltage power supply was put forward. Conventional silicon steel sheets were replaced with manganese zinc ferrites, raising working frequency from 50Hz to thousand hertz. Magnetic structure was changed from three-phase structure to four-phase structure. Accordingly, excitation voltage was changed from three-phase sinusoidal wave to square wave. Polyimide was chosen as insulation material instead of teflon or mica. A prototype of 400kV/50mA was designed, simulated and verified with the aid of finite element analysis software. To optimize the voltage distribution, corresponding flux compensation methods were raised to solve the problem of flux leakages.

INTRODUCTION

ICT high voltage power supply has been widely used in electron accelerator [1][2]. ICT is the kernel component of the accelerator, and its conventional magnetic core structure is shown in Fig.1. There are three groups of cores between the top yoke and the bottom yoke. Each group consists of a primary core and a plurality of segmented secondary cores. Each primary core is wound with primary coil. Each secondary core is wound with secondary coil and then connected to corresponding voltage doubler rectifier circuit, which converts AC voltage to DC voltage. Finally, all rectified voltages are connected in series to obtain the desired high voltage. Between all neighbouring cores are gaps filled with insulation materials of high dielectric strength. For the purpose of clarity, coils and circuits are not shown in Fig.1.

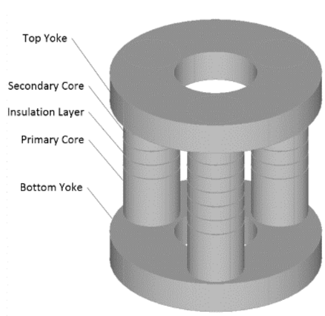

Figure 1: Structure of conventional ICT.

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The conventional design is as follows [3][4]: silicon steel sheets are selected as magnetic materials; three-phase sinusoidal wave with the working frequency of 50Hz is selected as excitation voltage; teflon or mica sheets with a thickness of several millimeters are selected as insulation material. When in operation, three-phase AC voltage (380V) is connected to delta-connected primary coils through a three-phase column type variable transformer, which controls the output voltage.

With the rapid development of power electronics, magnetic materials and insulation materials, new materials and technology can be introduced to improve the performance of ICT high voltage power supply, and the new design was proposed. Compared to the traditional scheme, it can effectively improve the efficiency of energy transfer, and reduce the volume of power supply and the requirement of rectified capacitance. It can finally achieve fast and precise control of the high-voltage output, and it's also stable and easy to maintain.

GENERAL DESIGN

Magnetic Material

Raising working frequency is an effective method to reduce the volume of ICT. As frequency increases, however, eddy-current loss of the silicon-steel sheet increases sharply, resulting in severe Joule heat and low efficiency. To solve this problem, manganese zinc ferrite is introduced. Compared to silicon steel, although the relative permeability and saturation magnetic flux density of manganese zinc ferrite fall, its electrical resistivity increases greatly, which effectively restrain the eddy-current loss and enable it to function well at high frequency.

Magnetic Structure

The magnetic structure of designed ICT is shown in Fig.2. To increase the breakdown voltage, the whole power supply is enclosed in an airtight steel barrel, fulfilled with sulfur hexafluoride at certain pressure. The working frequency can reach thousand hertz as manganese zinc ferrite is introduced. Consequently, the size of magnetic cores and the capacity of the rectifier capacitors decrease greatly. As magnetic structure is changed from three-phase structure to four-phase structure, excitation voltage is changed from three-phase sinusoidal wave to square wave consequently. This kind of structure improves the utilization of space and further reduces the volume of ICT.

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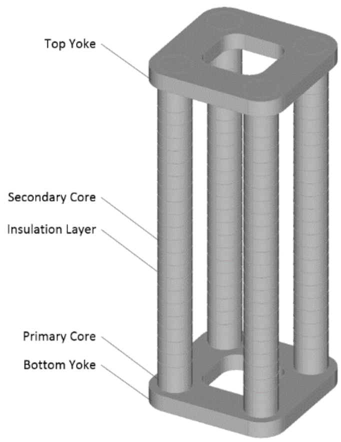

Figure 2: Structure of new ICT.

Insulation Material

Insulation layer between segmented secondary cores greatly reduces the difficulty of insulation, which effectively improves the level of output voltage. However, the reluctance increases a lot, since the permeability of insulation material is nearly the same as that of air. As a result, flux leakage is not negligible. Consequently, the induced output voltages of secondary coils taper off as the stage increases. Conventionally, teflon or mica sheet is selected as insulation material with a thickness of several millimeters. Decreasing the thickness of the insulation layer will effectively reduce the reluctance, and the flux leakage will reduce as well. However, high voltage of each stage and dielectric strength of the insulation material restrict the thickness from decreasing. As insulation technology develops, new materials can be introduced. A kind of polyimide film, the dielectric strength of which is as high as 3MV/cm [5], is a good choice. Considering that thicker film results in lower dielectric strength, the thickness of polyimide film is usually set to less than one millimeter. Although the number of stages increases, the total thickness decreases a lot, resulting in less flux leakage.

Output Voltage Control

As mentioned before, the output voltage in conventional ICT is controlled through a three-phase column type variable transformer. The transformer is bulky and the control accuracy is not continuous since the number of turns of the coil is limited. In the designed ICT high voltage power supply, a programmable DC power supply and a square wave inverter is used to obtain the square wave excitation voltage. Then the output voltage can be controlled through the programmable DC power supply, which is faster, more accurate and more continuous.

DESIGN CASE

Dimension Parameters

The general design scheme of ICT (400kV/50mA) is presented. The output voltage in each stage is set to 20kV, and then the number of stages is 20. Considering that the dielectric strength of polyimide film is about 3MV/cm, the thickness of polyimide film should be at least 0.067mm. To ensure safety, the thickness of polyimide film is set to 0.125mm. The diameter of primary core and secondary core is 60mm. The height of primary core and secondary core is 50mm and 25mm respectively. The whole power supply is enclosed in a grounded airtight steel barrel, fulfilled with sulfur hexafluoride of about 0.5-0.6MPa. The diameter and height of steel barrel is about 700mm and 1100mm respectively.

Electrical Parameters

The constructed magnetic circuit model is shown in Fig.3. Here, F is the magnetomotive force provided by corresponding primary coil. R_1 is the total reluctance of each group of cores, including primary cores, secondary cores and gaps between neighbouring cores. Each yoke is divided into four parts by magnetic cores, and R_2 is the reluctance of each part. Considering that the thickness of the insulation is much smaller than that of the cores, it is acceptable to ignore leakage reluctance. The working frequency is f. The magnetic flux density in magnetic core is B. The sectional area of magnetic core is S. The following formula can be concluded from Fig.3:

$$F = (R_1 + 0.5R_2)BS \qquad (1)$$

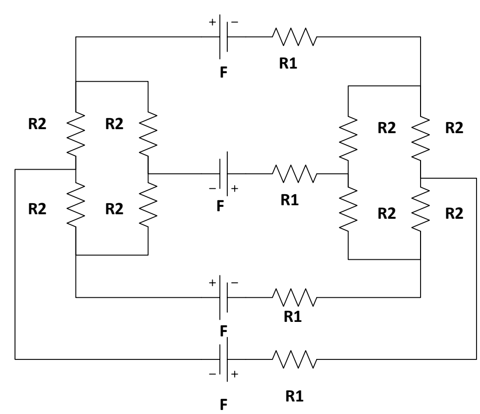

Figure 3: Magnetic circuit model.

The selected manganese zinc ferrite is PC44 (relative permeability 2400, saturation magnetic flux density 0.51T at 25℃,1194A/m). B is set to 0.08T, f is set to 5kHz. It can be concluded from formula (1) that F equals to187A.

RESULT AND DISCUSSION

The three-dimensional model of ICT is built (Fig.2). The induced voltage in each secondary core mainly depends on the magnetic flux density in corresponding core. Fig.4 shows magnetic flux density distribution of the power supply. Considering its symmetry, only one group of cores need to be studied. Choose one group of cores, and choose the axis of the cores as a path. Fig.5 shows the magnetic flux density mapped to the axis from

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bottom yoke to top yoke. The average value of magnetic flux density is approximate to the designed value 0.08T. However, magnetic flux density decreases as the secondary cores goes far away from the primary core. On the top secondary cores, it falls to about 0.06T. The flux leakage will lead to the inhomogeneity of the induced voltage and a decrease of output voltage. Compensation methods should be taken to improve the voltage uniformity of each layer.

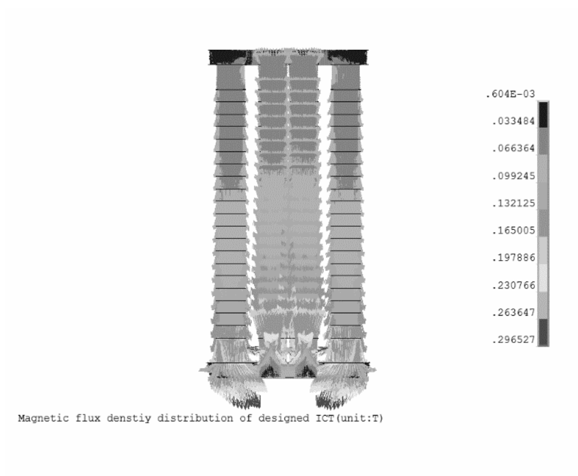

Figure 4: Magnetic flux density distribution.

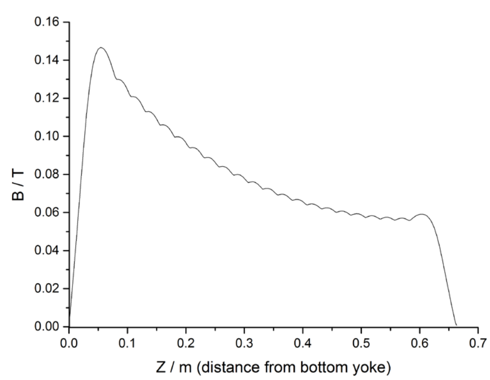

Figure 5: Magnetic flux density distribution on the chosen path.

There are different kinds of methods to compensate the magnetic flux leakage. One method is to increase the turns of the secondary coils to keep each coil at the same induced voltage. Another method is to use capacitors. Compensation capacitors are connected to primary coils or secondary coils in parallel. Capacitive current flows through the corresponding coils and the induced magnetic flux density has the same direction as the main flux, thus compensating the flux leakage.

In this design, an additional layer of cores together with specific turns of coils and paralleled capacitors are introduced on the top secondary cores. The additional coils can serve as a new excitation coil, the capacitive current of which will compensate the flux leakage. Choose proper capacitor and proper number of turns, the introduced excitation coils will provide the same magnetomotive force as the primary coils. With two excitation coils up and down, the excitation current needed will halve in an ideal case. Fig.6 shows the magnetic flux density (after compensation) on the same path as that of Fig.5. It can be seen that the flux leakage decreases a lot after compensation. To keep the induced voltage in each stage the same, the number of turns of secondary coils in the middle should be a little more than that of the two sides.

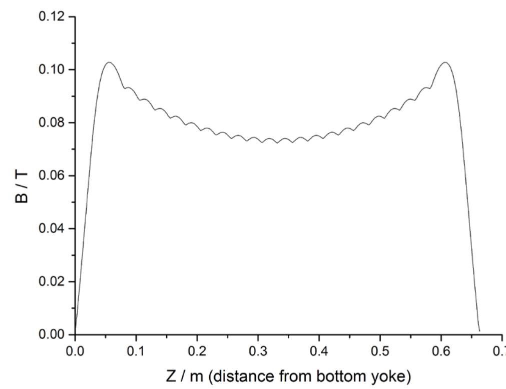

Figure 6: Magnetic flux density distribution on chosen path (after compensation).

CONCLUSION

A novel ICT type high voltage power supply was put forward to overcome the disadvantages of conventional one. And specific design process was given. By finite element simulation software, the rationality of the scheme was verified and the methods of flux leakage compensation were given.

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