Abstract—Multi-channel high-power electrical prospecting instrument (MTEM) transmitter is developed on the basis of the bipolar switching power’s principle. The design of the transformer’s main components is critical to the performance of MTEM transmitter system. The dual-input dual-output 60KW of power transformers was designed after analyzing the working principle of bipolar full-bridge power transformer. The Finite Element Analysis software Maxwell built a 3D model of the transformer and analyzed its internal distribution of the electromagnetic field. While the transformer has been designed out to put into use in the MTEM transmitter system, and applied in the relevant field experiment. The simulation and experiment indicated that this transformer is designed reasonably with small ripple, low loss, low temperature, high efficiency, stability and reliability.

Keywords: electrical prospecting; Maxwell; Power transformer; Finite Element Analysis.

I. INTRODUCTION

With the exploitation and utilization of energy, the performance of multi-channel high-power electrical prospecting instrument (MTEM transmitter) has become a key factor for the depth of restricting metal mineral resources. As the key component of MTEM transmitter, transformer design is related to the accuracy and performance of the entire transmitter. Taking into account the limitations of rectifiers’ overvoltage and overcurrent and the whole transmitter’s volume and weight, designing a reasonable transformer scheme is crucial to the development of the entire transmittersystem.

Firstly, this paper analyzes the basic principles of the transmitter, using the AP method for transformer’s selection and parameter calculation. Then the software of Maxwell build the 3D model of transformer. Simulation results indicate that when working on normal, transformer has not reached saturation, So it verified the reasonableness of transformer’s design scheme. Besides dual-input dual-output design of transformer makes the system decreasesemiconductor’s requirements for overvoltage and overcurrent and the whole transmitter’s volume and weight, designing a reasonable transformer scheme is crucial to the development of the entire transmitter system.

II. MTEM TRANSMITTER’S STRUCTURE AND WORKING PRINCIPLE

Figure 1 shows the main topology Schematics of MTEM transmitter. The core structure is phase-shifted full-bridge bipolar converter. The system is powered by a generator, then connected to a non-controlled rectifier Bridge Converter. The high-frequency converter controls the opening of the IGBT turn-off to achieve power transmission of transformer. Then it is rectified and filtered so that obtaining a large voltage of 1000V. Finally, the system transmits voltage that is ranging from 100V to 1000V to the earth continually by adjusting the duty cycle of the launching bridge, which is equivalent to transmit different high frequencies current to the earth, then gets feedback data to analyze geological structure of formation. The system uses a dual-input dual-output transformer model and makes primary windings in parallel, the secondary windings make in parallel output after rectified when it is working at high voltage and low current, or making it in series output when it is working at high voltage and high current. Figure 1 shows the mode of series. So the system requirements for voltage and current values of rectifier halve than before that greatly reduces transmitter’s cost and size, which ensures the system operates stably and efficiently.

III. PARAMETERS’ DESIGNATION OF BIPOLAR SWITCHING POWER TRANSFORMER [3]

A. Selection of transformer’s core material

The transformer core must have a high Curie temperature and saturation flux, low core loss and residual flux because of the bipolar full-bridge switching power transformers’ characteristics that are high-frequency and high-power. There are many transformer core material types, such as permalloy, soft magnetic ferrite, amorphous, nanocrystal, etc. At last the system chooses EE-type Manganese-zinc soft magnetic ferrite core which has low loss magnetic, excellent heat dispersing and low eddy current losses. Now Ferrite core technology is already quite mature in China. It has not only a cost-effective, but also a stable winding process and stable...
operating performance \[^1\] [^4]. The parameters are shown in Table 1:

| Material | B  | Pte | Curie temperature | Permeability | Remanence |
|----------|----|-----|-------------------|--------------|-----------|
| Mn-ZnFerrite | 0.5 | 9W/kg | 215°C | 2500 | 0.09T |

B. Parameters calculation step of dual-input dual-output transformer.

In transmitter, the parameters of transformer are designed as follows: Input voltage is 540V ± 10% (dual input); output voltage is 729V (dual output); Output Current is 50A; ratio is 1: 1.35; maximum duty cycle is 0.8.

The transformer’s computation use \( A_p \) method[^3]:

\[
A_p = A_e \cdot A_Q = \frac{P_t \times 10^2}{4K_m f_{m.t}} = 518.4 \text{ cm}^4
\]

Where \( A_p \) is effective cross-sectional area of the core (cm\(^2\)); \( A_Q \) is effective window area of core (cm\(^2\)); \( P_t = 116.64 \times 10^4 \text{W} \) (transformer apparent power); \( K_m \) takes 0.25 (the copper space factor in the core window); \( f = 20 \text{ KHZ} \) (switching frequency); \( B_m \) take 250mT (operating flux density); \( j \) take 4.5A/mm\(^2\) (current density).

Considering the influence of various factors such as switching devices’ transient voltage spikes between turn and off in the full-bridge switching power, practical temperature application and others, the value of \( A_p \) must stay out a certain safety margin when choosing the core. Therefore the selected value of \( A_p \) is from 1.5 to 3 times larger than the calculated value in general[^3]. The bigger the value of \( A_p \) is made, the greater the volume and quality of the core is, which will affect the volume and quality of the entire transmitter. While if \( A_p \) makes a small value that may result transmitters work saturated easily. It will affect the performance of the whole transmitter. At last the system selected the core of EE195 after simulating again and again with software of Maxwell. Where \( A_p \) is 1212.12 cm\(^2\), \( A_e \) is 16.8 cm\(^2\), \( A_Q \) is 72.15 cm\(^2\).

Primary and secondary winding turns are calculated as follows:

Primary winding turns \( N_{p1} \):

\[
N_{p1} = \frac{u_{p1} \times T_{on}}{2B_m A_e} = 25.7 \approx 26
\]

Secondary winding turns \( N_{s1} \):

\[
N_{s1} = \frac{u_{p2}}{u_{p1}} N_{s1} = 35.1 \approx 35
\]

Where \( u_{p1} = 540 \text{V} \) (primary winding voltage); \( u_{p2} = 729 \text{V} \) (secondary winding voltage); \( T_{on} = 20 \mu \text{s} \) (switch conduction time). Taking into account the special situations that transformer’s secondary winding requires series when in the high-voltage and parallel when in the high-current, so that \( N_{p1} = N_{p2}, N_{s1} = N_{s2} \).

Primary and secondary coils’ diameter:

Primary coils’ diameter, \( d_1 \):

\[
d_1 = 1.13 \sqrt{\frac{f_1}{f}} = 4.139 \text{mm}
\]

Secondary coils’ diameter, \( d_2 \):

\[
d_2 = 1.13 \sqrt{\frac{f_2}{f}} = 3.562 \text{mm}
\]

Where \( f_1 = 60.37 \text{A} \) (primary valid current); \( f_2 = 44.72 \text{A} \) (secondary valid current); As we all know, currents skin effect will increase the effective resistance values of the conductor in the high-frequency and increase system losses. Which will cause transformer heat seriously. The higher the frequency is, the more significant the skin effect is. While it can be decreased by reducing the diameter winding. For example, it can be winding parallel with multi-strand wires or litz wires. The smaller the diameter is, the smaller the skin effect is[^5]. At last insulated litz wire is the better choice.

Skin depth:

\[
\Delta = \sqrt{\frac{2}{\mu \sigma}} \times 10^{-3} = 0.467 \text{mm}
\]

Where the angular frequency \( w = 2\pi \); copper wire permeability \( \mu = 4\pi \times 10^{-7} \text{H/m} \); copper wire conductivity \( \sigma = 58 \times 10^{-6} \text{S/m} \). In the designing of switching power, the choice of diameter can’t greater than \( 2\Delta = 0.9346 \text{mm} \) account to the skin effect. Here it chooses 7500.127 (mm) double-insulated litz wire that is suitable the current of 20kHz ~ 50kHz. The primary coil use 6 shares routing in parallel, the secondary coil use 4 shares routing in parallel[^6].

The producing of transformer’s leakage inductance is due to the flux that not only between primary and secondary winding but also between turns and turns isn’t coupling completely[^6]. Usually in order to reduce the leakage inductance of the transformer, it takes primary and secondary winding wound with layered alternately. But to avoid increasing the distributed capacitance[^3], the layers can’t be too many. The winding’s winding manner is shown in figure 3. In addition, as the primary and secondary voltage of transformer are so large that transformer increased three to four insulating paper between each plus to ensure system’s safety.
IV. THE 3D SIMULATION OF MAXWELL WITH FINITE ELEMENT ANALYSIS

In this paper, the finite element analysis software Maxwell build a 3D model of the transformer. The electromagnetic field analysis software of Maxwell has been widely used in electrical engineering, especially for electromagnetic motor and transformer simulation [3]. The software could analyze transformer’s change of the internal magnetic field, electric field and magnetic flux density at any time. When adding an external excitation that is 20KHz superimposed wave to the designed transformer to analog transmitters’ working condition which maximum duty cycle is 0.8, the simulation results are shown in Figure 4-6.

The simulation results in Figure 4-6 indicate that transformer’s input and output voltage, current and flux linkage are stable relatively. Figure 7 shows the distribution of transformer’s magnetic flux density and vector, in which magnitude and direction of the flux density can be seen at every point. When the transformer working at full load, most of the magnetic flux between the 0.1T-0.25T, only partial point reaches 0.3T. All of these simulation results show that transformer have a stable output, reached pre-test indicators. And it has not yet reached saturation at full load which verified the rationality of the designing.

V. PRODUCT AND FIELD EXPERIMENTS

The designed transformer has been put into the transmitter system use, as shown in Figure 8, and it have achieved good results in field experiments. The waveforms of output voltage and current are shown in Figure 9 and the voltage ripple of output is shown in Figure 10.
Fig. 9 shows that transformer maintains good output characteristic when the duty cycle is in maximum. What’s more, the transformer has not reached saturation and the output doesn’t produce a big shock and shake. In addition, transformer’s temperature is maintained at about 60 °C which is measured by infrared thermometer. Figure 10 shows the ripple peak is 0.9V (0.12%). Experiments fully explain that transformer has a small ripple, a small temperature rise and a high efficiency, the design is reasonable which fully meets the requirements of MTEM transmitter’s system. In addition, transformer adopts dual input and dual output structure successfully, which not only greatly reduce the difficulty and cost of system’s designing, but also reduce the weight and volume of the entire transmitter. All of this laid an important foundation for the mass production of transmitters in future.

VI. CONCLUSIONS

Maxwell simulation and field experiments verify the rationality of the design method. Dual input and dual output transformer’s characteristics are that leakage inductance small, output stability and temperature rise low, which solved the problem that the excessive demands of entire transmitter system to rectifier pieces. It also reduces the size and weight of the entire transmitter system, enhancing the overall performance of the transmitter. All of this laid a solid foundation for the applying of transmitters in exploration industry in future.

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