Design and Analysis of PCB Transformer in Direct Current Distribution Network

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Abstract. In order to accurately calculate the leakage inductance of the PCB transformer and improve the reliability of the PCB transformer, a PCB transformer is designed and analyzed in this article. Firstly, the magnetic core and winding design of the PCB transformer are studied in this paper, and the leakage magnetic field and temperature field of the PCB transformer are calculated by using the finite element software. Finally, experiments were performed on the leakage magnetic field and temperature of the PCB transformer to verify the correctness of the proposed scheme.

1. Introduction

In recent years, with the rapid development of power electronic converter technology and control technology, smart grid has been applied and promoted all over the world, especially after the change of energy supply and demand mode, industry, agriculture and life have put forward higher requirements on electricity demand, power quality and power supply reliability. Therefore, the alternating current distribution grid is facing the challenges of distributed new energy access, diversification of user-side demand, power supply quality and high efficiency and reliability [1]-[2].

One type of distribution network – direct current distribution network - eliminates the AC-DC conversion link, which makes it easier to access distributed power generation, energy storage, and variable speed control devices, and will be more efficient compared to traditional alternating current networks. As one of the main links of direct current distribution network, the double active bridge converter, also known as power electronic transformer, provides real-time digital control of the amplitude and phase of the primary and secondary voltages by introducing power electronic converters on the primary and secondary sides, which enables more accurate, flexible, stable and reliable regulation of the output side compared to the traditional power transformer. The advantages and features of power electronic transformers can be very promising for many difficult problems in many environments. Figure 1 shows a typical low and medium voltage distribution network topology.
As can be seen from Fig 1, it mainly includes 10kV distribution network, AD/DC converter, DC/AC converter, DC bus, DC/DC converter, various types of loads, etc. Among them, the AD/DC converter and DC/AC converter use the MMC (Modular Multilevel Converter, MMC) converter [3].

Figure 2 shows the topology of the intermediate level bidirectional active DC/DC converter in Figure 1. As shown in Figure 2, the DC/DC converter mainly includes: H-bridge converter, high-frequency transformer, detection and control system, etc.

As an important part of DC/DC converter, high-frequency transformer has an important impact on the size, weight, loss, and price of DC/DC converter [4]. The traditional high-frequency transformers have large leakage inductance, large size, and large parasitic parameters, which restrict the development and application of DC/DC converters. Compared with traditional high-frequency transformers, PCB transformers reduce high-frequency parasitic parameters and substantially improve the performance of switching power supplies due to their special planar structure and close coupling of windings. PCB transformers have the characteristics of small winding resistance, leakage inductance, distributed capacitance, and eddy current loss, which reduce high-frequency and RF interference and can effectively solve the contradiction between performance and volume and quality [5].

However, as the power density of PCB transformers increases and the assembly space is further reduced, transformer overheating caused by flux leakage and eddy current losses in PCB transformers affects the further widespread use of PCB transformers [6-8].

Based on this, the design and analysis of the high-frequency transformer for DC/DC converter for DC distribution network is carried out in this paper. The detailed design process of the PCB transformer is
given, the leakage inductance and temperature field of the PCB transformer are calculated by finite element software, and finally the leakage field and temperature field of the PCB transformer are experimented under rated load to verify the correctness of the proposed scheme.

2. PCB transformer electromagnetic design
PCB transformer and conventional high-frequency transformer core is basically the same, there are differences in the winding, conventional high-frequency transformer winding is mainly enameled wire or insulated wire, PCB transformer winding for the printed circuit board, the following PCB transformer core, winding, etc. to develop the design. Table 1 shows the PCB transformer design indicators.

Table 1. PCB transformer design specifications

| Items           | Parameter Values |
|-----------------|------------------|
| Input Voltage   | 480V             |
| Input Current   | 2A               |
| Output Voltage  | 48V              |
| Output Current  | 20A              |
| Operating Frequency | 100kHz         |

- PCB Transformer Core Design
According to the design index of PCB transformer shown in Table 1, the AP method is used to develop the design of PCB transformer, and the equation (1) is the relationship between the effective area of core and power.

\[ A_p = A_e \times A_w = \frac{P_t \times 10^4}{K_w B f J} \]  

where, \( A_p \) is the product of the effective core area \( A_e \) and core window area \( A_w \), \( f_s \) is the operating frequency of the PCB transformer, \( J \) is the current density, \( B \) is the core working flux density, \( P_t \) is the rated power of the PCB transformer, and \( K_w \) is the core utilization rate.

- PCB Transformer Winding Turns Design
The number of turns of PCB transformer windings can be calculated from the working flux density of the core, the working frequency and the effective cross-sectional area of the core, as shown in equation (2).

\[ N = \frac{V}{K_f f A_e B} \]  

where, \( K_f \) is the winding factor.

- PCB Transformer Winding Width Design
Once the PCB transformer winding is manufactured, its winding parameters and parasitic parameters are determined, it is not easy to change, shown in equation (3) for the PCB transformer winding width expression.

\[ W = \frac{I}{J H} \]  

where, \( W \) is the winding width, \( H \) is the winding thickness, and \( I \) is the current flowing through the winding.

Further analysis, the insulation between the windings of the PCB transformer, can be determined by the formula (4).

\[ \log_{10}s = 0.78 \times \log_{10}(U/300) \]  

where, \( S \) is the distance between adjacent layers of the PCB board and \( U \) is the input voltage of the winding.
Finally, the formula of PCB transformer winding width is obtained as shown in equation (5).

\[ W = \frac{a - 2g - (N_p - 1)s}{N_p} \]  

(5)

where \( a \) is the PCB board width, \( g \) is the minimum distance from the PCB board to the core, and \( N_p \) is the maximum number of turns of the transformer on each PCB board layer.

The number of PCB board layers of the PCB transformer is determined by the core height and width, and the thickness and width of the winding is determined by the rated current. Table 2 shows the PCB transformer winding design parameters. The three-dimensional structure of the PCB transformer is shown in Figure 3.

| Items                        | Parameter Values |
|------------------------------|------------------|
| Number of primary side PCB layers | 2                |
| Number of primary side PCBs   | 5                |
| Number of turns on primary side | 40               |
| Number of secondary side PCB layers | 2                |
| Number of secondary side PCBs   | 1                |
| Number of turns on the secondary side | 2                |
| Core type                     | EE50             |

**Table 2. PCB transformer winding parameters**

3. PCB transformer three-dimensional magnetic and temperature field analysis

In order to verify the correctness of the designed PCB transformer, the magnetic and temperature fields of the transformer were subjected to finite element analysis [9]. The magnetic flux density distribution of the PCB transformer is shown in Figure 4.
As can be seen in Figure 4, the maximum value of PCB transformer core magnetic density is 0.6T, the average value is 0.52T, and the design value is 0.5T, which initially verifies the correctness of the proposed scheme. Figure 5 shows the PCB transformer leakage field distribution.

From Figure 5, it can be seen that the maximum flux density of the PCB transformer leakage field is 0.179 T. This value can be used in the subsequent DC/DC converter control algorithm for DC distribution networks. The temperature field distribution of the PCB transformer is shown in Figure 6.
As can be seen in Figure 6, the maximum temperature of the PCB transformer core is 63°C and the maximum temperature of the windings is 64°C at rated load, which meets the system requirements.

4. PCB transformer three-dimensional magnetic and temperature field analysis

The prototype PCB transformer is shown in Figure 7. The PCB transformer test platform is built, and the PCB transformer is tested under rated load using a three-dimensional dynamic magnetic measurement device and temperature sensor. The PCB transformer core flux density, leakage flux density, and temperature test data are shown in Table 3.

| Items                                    | Finite Element | Experiment | Error  |
|------------------------------------------|----------------|------------|--------|
| Bypass column magnetic flux density      | 0.412T         | 0.46T      | 10.4%  |
| Side column leakage flux density (measurement point 1) | 0.144T       | 0.17T      | 15.3%  |
| Side column leakage flux density (measurement point 2) | 0.31T         | 0.29T      | 6.9%   |
| Side column leakage flux density (measurement point 3) | 0.13T         | 0.16T      | 18.8%  |
| Core temperature                         | 60°C           | 65°C       | 7.7%   |
| Winding temperature                      | 60°C           | 64°C       | 6.3%   |

From Table 3, it can be seen that the finite element method is close to the test value, and the error is analyzed. For the measurement of leakage magnetic field and temperature, on the one hand, there are errors in the instrument itself; on the other hand, the results obtained from the finite element simulation...
are the calculated values for the ideal situation, and in fact, when the three-axis dynamic magnetic measurement sensor is applied to test the leakage magnetic field and the temperature sensor is applied to measure the temperature, there is a certain amount of magnetic field in the environment, and the ambient temperature and there are also differences in the actual boundary conditions set. From the calculated values of errors in Table 3, it can be seen that the errors are within 20%. It meets the engineering requirements. The correctness of the proposed scheme is verified.

5. Conclusion
In this paper, we firstly discuss the composition of low and medium voltage distribution network and domestic and international research developments; secondly, we study the PCB transformer for low voltage distribution network and give the design process of core and PCB winding; secondly, we establish the 3D finite element model of PCB transformer and simulate its main magnetic field, leakage field and temperature field; finally, we build a prototype and test its main and leakage flux density and temperature. The simulations were compared with the experiments, and the errors were within 20%, which verified the correctness of the proposed scheme.

6. References
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