Based on Optimized Mag-thermal Coupling Method
Simulation Research on Temperature Rise of Switching Power Transformer

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Abstract. In this study, a bidirectional mag-thermal coupling method is used to simulate the temperature rise of the switching power supply transformer. According to the loss and temperature rise characteristics of the transformer, theoretical analysis and simulation are carried out. A set of optimized windings and design methods based on the upper limit of temperature rise are proposed. The simulation results show that the optimized windings reduce the winding loss, and improve the efficiency of the transformer by 5%, and reduce the temperature rise by 10%. The average temperature rise curve is consistent with the experimental ones of the transformer. Compared with unidirectional coupling, the method greatly improves the simulation accuracy by 4%. This research has certain guiding significance for the thermal design of switching power transformer.

1. Introduction

The switching power transformer is the core component and one of the important heating sources of the switching power supply. Its quality and volume are relatively large. The coil and core losses determine the energy loss of the transformer. The heat dissipation characteristics of the transformer at a given loss determine the temperature rise. The insulation level determines the maximum allowable temperature rise. If the temperature rise limit is exceeded, it will cause insulation aging and reduce the reliability and life of the transformer. Therefore, the thermal design of the switching power transformer must be carried out. By optimizing the core and windings, and the heat dissipation characteristics of the transformer, the temperature rise is controlled at a reasonable level.

In recent years, switching power transformer is developing towards miniaturization and high power density. H.W Zhang and H.N Ji studied the design of switching power transformer and the analysis of loss and temperature field [1-2]. N.N Wang et al. investigated the theoretical model and optimal design of power magnetic devices, and made a breakthrough in the field of integrated magnetic devices on silicon substrate [3-4]. Xu Yang et al. studied the switching power supply technology, and the circuit characteristics laid the foundation for the design of the switching power transformer [5-7]. In addition, the optimization of loss and the analysis of temperature rise for switch power transformer are also important.

In this paper, a 60 kHz, 22.5W switching power transformer is designed. The optimal designs of winding size and distribution reduce winding loss and temperature rise. The accuracy of simulation is greatly improved by using the bidirectional mag-thermal coupling algorithm.
2. loss analysis of transformer

2.1. Core loss and winding loss
The loss of transformer mainly includes core loss, winding loss and stray loss. The core loss consists of hysteresis, eddy current and residual loss. The winding loss includes DC loss and AC loss. The stray loss is relatively small and can be ignored. The core loss is defined as follows [8]:

\[
P_{\text{core}} = k_h f B_m^\alpha + b B_m^2 f^2 + c B_m^{1.5} B_m V
\]

\( k_h, \alpha - \) core parameter, \( b = \pi d_0^2 / (6 \rho) \), \( \rho - \) resistivity, \( d_0 - \) material thickness, \( c - \) empirical parameters.

Then, AC loss of winding is mainly analysed. The eddy current loss of the winding is mainly due to the skin effect and proximity effect of the coil at high frequency.

In engineering, the penetration depth \( \Delta \) (cm) is defined as follows [9]:

\[
\Delta = \left( \frac{1}{\pi f \mu \sigma} \right)^{1/2}
\]

\( \mu - \) permeability of conductor, \( \sigma - \) conductivity of conductor.

Excluding the influence of external magnetic field, the magnetic field energy between two coils per unit length is as follows [10]:

\[
W_m = \frac{\mu_0}{2} H^2 V / l = \frac{\mu_0}{2} \left( \frac{l}{b} \right)^2 b W = \frac{\mu_0 W}{2b} f^2
\]

\( I - \) current; \( H - \) magnetic field strength between the windings; \( b - \) width of the winding.

Therefore, when \( b \) is smaller, the magnetic field energy between the windings is larger. The proximity effect makes the effective cross-sectional area of the winding smaller, resulting in greater winding loss.

2.2. The analysis of leakage inductance
In the winding layer, due to mutual repulsion, the leakage inductance is produced by the leakage flux. Magnetic field and magnetic leakage of single layer double coil window is shown in Figure 1.

![Figure 1. Magnetic field and magnetic flux leakage of single layer double coil window.](image1)

![Figure 2. Magnetic field and magnetic flux leakage of interleaved coils](image2)
The simplified primary leakage inductance is [11]:

\[ L_i = \frac{\mu_0 N_1^2 l_{w} k_{a} \left( c + b + d \right)}{l} \]  \hspace{1cm} (4)

Therefore, the leakage inductance is directly proportional to the square of the primary turns \((N_1)\) and inversely proportional to the window width \((l)\). In addition, in order to reduce leakage inductance, the primary windings and secondary windings can be divided into two sections [12]. Magnetic field and magnetic flux leakage of interleaved coil is shown in Figure 2.

3. The finite element model of transformer

In this section, the finite element model of the transformer is established. Firstly, the advantages of bidirectional mag-thermal coupling are analysed, compared with unidirectional coupling. Then, the paper optimizes the windings and establishes the finite element analysis model.

3.1. The analysis of Bidirectional mag-thermal coupling

ANSYS can be used to study the interaction between two or more physics [13]. The coupling relationship between multiple physical fields is divided into unidirectional coupling and bidirectional coupling.

Unidirectional coupling means that the loss of the electromagnetic field is used as the excitation of the temperature field to obtain the result of the temperature field.

Bidirectional coupling refers to: the loss of electromagnetic field and the heat of the temperature field of the previous cycle are coupled to each other, which are used as the input parameter of the mag-thermal coupling calculation program of the next cycle.

![Flow chart of bidirectional mag-thermal coupling analysis.](image)

Flow chart of bidirectional mag-thermal coupling analysis is shown in Figure 3. During the calculation, the magnetic field and the temperature field influence each other. Moreover, the APDL command flow makes the coupling calculation more convenient. This paper uses bidirectional coupling method to make the transformer simulation results more accurate.

3.2. The finite element model of Optimized winding

According to the cross distribution of windings, the magnetic field energy between coils is reduced, and then the leakage inductance is reduced. In addition, increasing the window width and decreasing spacing...
of coils can also reduce the leakage inductance, resulting in reducing the winding loss and minimizing temperature rise. The initial 1/8 structure of the winding is shown in Figure 4. The winding distribution is P-S₁-S₂, and the window width is 4.8mm. The optimized 1/8 structure is shown in Figure 5. The winding distribution is 1/2P-1/2S₁-1/2P-1/2S₁-S₂, and the winding width is 5.2mm.

The initial 1/8 structure.  Figure 5. The optimized 1/8 structure.

The three-dimensional model of switching power transformer with optimized winding is shown in Figure 6. In order to simplify the simulation calculation, the 1/8 model of the transformer meshed is shown in Figure 7.

The optimized 3D model  Figure 7. The mesh of 1/8 transformer

Material properties are shown in table 1. B-H curve of ferrite is shown in Figure 8. Copper resistivity curve with temperature is shown in Figure 9.

| Table 1. Material properties. |
|--------------------------------|
| Relative permeability          | Resistivity (Ω·m) | Thermal conductivity (W·m⁻¹·C⁻¹) | Density (kg·m⁻³) | Specific heat capacity (J·kg⁻¹·C⁻¹) |
|--------------------------------|-------------------|-----------------------------------|------------------|-------------------------------------|

4
For mag-thermal coupling analysis, parallel boundary conditions of magnetic field and convection boundary conditions of temperature field need to be applied. The convection heat transfer coefficient is 20 W/m². Then applying excitation and determining the solution parameters. Finally, APDL command will be written.

4. Simulation results and analysis

4.1. Steady-state field
The results of the magnetic field and temperature field can be obtained by the bidirectional mag-thermal coupling calculation program. Firstly, the temperature field of transformer before and after optimization is compared, then the flux density vector and Joule heat of optimized transformer are analysed.

The temperature field of transformer before winding optimization is shown in Figure 10, and the maximum temperature is 57.62°C. The temperature field of the transformer after winding optimization is shown in Figure 11, and the maximum temperature is 46.88°C. The optimized temperature is reduced by 10 °C, which proves the cross distribution of windings and bigger windows width can reduce winding loss, and minimizing temperature rise.
The flux density vector of the transformer after winding optimization is shown in Figure 12. Figure 13 shows the Joule heat distribution of the transformer after winding optimization. It can be seen from the figure that the working magnetic density of the core is 0.21T, and the magnetic flux direction is correct. The maximum magnetic density of the core is 0.98T, which appears at the corner of the core. According to the Joule heat distribution of the winding, the primary winding has the most serious heat generation, so the insulating material with higher insulation grade is needed.

4.2. Transient field

The average temperature rise curve of the optimized winding is shown in Figure 14. Within 0-2000s, the temperature rise of transformer is fast, which indicates that the heat production of transformer is more serious in the early stage of operation. After 2000 s, the temperature rise curve tends to be gentle, and the maximum temperature is no more than 50°C, which shows that the optimized winding transformer can operate safely and stably. The comparison of temperature is shown in Table 2. According to the temperature rise data, the maximum temperature of experimental result is 49.67°C, and the maximum temperature of bidirectional coupling is 46.88°C, and the maximum temperature of unidirectional coupling is 44.91°C. Therefore, compared with unidirectional coupling, the optimization algorithm greatly improves the simulation accuracy by 4%.

| Category            | Temperature of winding/°C | Error rate/% |
|---------------------|---------------------------|--------------|
| Unidirectional coupling | 44.91                    | 9.58         |
| Bidirectional coupling     | 46.88                    | 5.62         |
| Experimental result            | 49.67                    | 0            |

The temperature of winding is measured by platinum metal resistance thermometer at room temperature of 25°C. The temperature change curve of the winding is shown in Figure 15. The temperature rise curves obtained by simulation and experiment are basically the same.
5. Conclusion

In this paper, the bidirectional mag-thermal coupling algorithm is used to analyse the steady and transient fields of the switching power transformer. By optimizing the winding size and distribution, the winding loss is reduced and the efficiency is increased by 5%, and the temperature rise of transformer is reduced by 10°C. In addition, the accuracy of the optimization algorithm is verified by the measured temperature curve. Compared with unidirectional coupling, the optimization algorithm greatly improves the accuracy by 4%.

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