TEMPERATURE FIELD SIMULATION RESEARCH ON THE LEAKAGE INDUCTANCE TRANSFORMER

by

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The structural and electrical parameters of leakage inductance transformers can significantly affect the efficiency, noise, and vibration of microwave ovens. The paper proposed a new iron core structure with finite element modeling and simulations of a leakage inductance transformer by both the electromagnetic field and system design simulation software. Different silicon steel sheet models were used for the upper and lower parts of the proposed iron core to reduce the loss and heat of the leakage inductance transformer. The iron core scheme was changed from the traditional E-I type to the E-E type. The feasibility of the new iron core scheme was tested by numerical results which showed that the maximum temperature rise of the leakage inductance transformer decreased significantly.

Key words*: leakage inductance transformer, temperature field simulation, electromagnetical simulation, iron core structure*

Introduction

A leakage inductance transformer (LIT), which often exists in microwave ovens, can not only perform voltage transformation but also stabilize the voltage. The LIT can improve the efficiency, decrease the vibration and noise, and save the energy.

Although the manufacturing of LIT has matured, the power loss and temperature rise are still problems which need to be addressed for the designs and optimizations of LIT. When a LIT operates, the eddy current in the iron core of the LIT can cause iron loss which generates heat in the iron core and increase the temperature of the LIT. When a LIT performs a function of stabilizing voltage, its secondary iron core often works in deep saturation, and the current in the coil is larger than that in a general ideal transformer. The heat produced by electrical currents in the LIT, which is often given in term of copper loss, becomes significant in this situation. Since the typical power efficiency of LIT is about 80-90%, the heat problem of LIT is more serious than general transformers. Electromagnetic noise and vibration can also be produced by the magneto-strictive effect of the iron core material in LIT [1].

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During the progress of traditional transformer structure designs, the approximate structure parameters, the loss and temperature rise of transformers are all calculated based on complex empirical formulas since the exact working situations can not been obtained by experimental tests [2]. That is, the results and conclusions based on these calculations are empirical and limit. Because such empirical method of traditional designs will go through the four phases of design, machining, test and optimization, accuracy of the results is often not high [3]. Due to special functions of LIT, the structures of LIT are often complex. The ability of LIT can not be tested independently since the complex LIT need to be connected with high voltage capacitor and tested in the circuit with magnetrons. Numerical simulations are well known as a kind of numerical experiments. Using numerical experiments can save the cost and time of researching and increase the development efficiency.

Nakata and Takahashi [4] used finite element method (FEM) to numerical simulate the effects of structures and materials of iron cores for electromagnetic characteristics of transformers [4]. Ni [5] used FEM to simulate the leakage inductance magnetic field of transformers and eddy current loss of coils. Enokizono and Soda [6] calculated the iron core loss of transformers by FEM. Kashtiban *et al*. [7] researched the influence of winding modes of transformer coils on leakage flux. Yan *et al*. [8] presented a theoretical analysis and numerical simulations of magnetic field distributions of a 3-phase electric transformer. Silva *et al*. [9] conducted electromagnetic and heat analysis of an electric transformer by FEM. Wei *et al*. [10] simulated the leakage magnetic field of electric transformers and obtained the leakage inductance value by simulations. Zhang *et al*. [11] analyzed the simulation process of compatible magnetic-field for a 3-phase electric transformer by FEM, and verified the simulation results by analytical and experimental results. All these demonstrate that numerical simulations of FEM for analysis of electromagnetic field of transformers are available [10].

On the other hand, Jing [12] obtained the secondary voltage waveform, magnetic field distribution of iron cores, leakage induction distribution of LIT by 2-D coupling numerical simulations. Chen *et al*. [13] presented 3-D simulation models for LIT with considering electric characteristic parameters of medium material. Gu *et al*. [14] presented a model for a high-frequency high-voltage transformer and obtained the leakage induction value of the transformer by the energy conservation and simulation results.

It should be note that most of the existed researches of transformers focused on the electric transformers, while the researches of LIT are relatively rare. The paper established numerical research models to design and optimize LIT. The exact working environment of LIT which can not been obtained by experiments had been obtained based on numerical simulations. The optimization of LIT was also conducted in this paper to make LIT more suitable, efficient and steady for applications in microwave ovens.

Model of the LIT and calculation of the loss

The structure of a LIT for microwave ovens is shown in fig. 1. Here, a leakage branch of the magnetic flux is designed between the primary and secondary coils by using a silicon-steel lamination. The secondary voltage can be stabilized by the characteristic of the main magnetic circuit saturation and non-saturation property of the leakage branch. The iron core structure is E-I type. The structure parameters of the LIT are shown in fig. 2. The electric parameters are shown in tab. 1.

The LIT will operate in deep saturation, and the currents in the primary and secondary coils are huge. The iron loss and copper loss will be significant in such situation. These instant and average loss can be calculated by FEM. Figure 3 showed the circuit diagram of the simula-

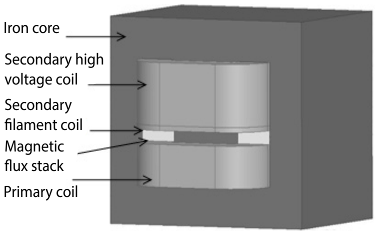

Figure 1. Structure of the LIT for microwave ovens

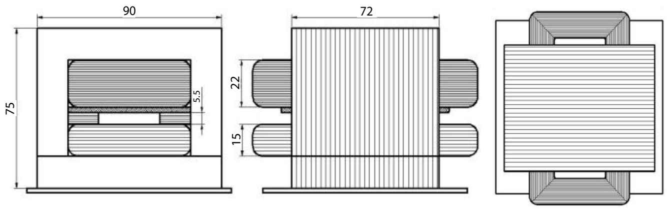

Figure 2. Simplified view of the LIT model

tions when the LIT connected with the magnetron. According to the circuit principle, the exact working process can be obtained.

The instant curves of the iron loss of input voltage 220 V can be obtained as

Table 1. Electrical parameter of the LIT

Parameter	Value	Parameter	Value
Rated power	700W	Primary voltage	AC 190-240 V
Turn of primary coil	230	Secondary voltage	AC 2100 V
Turn of secondary coil	2200	No-load current	2.5 A

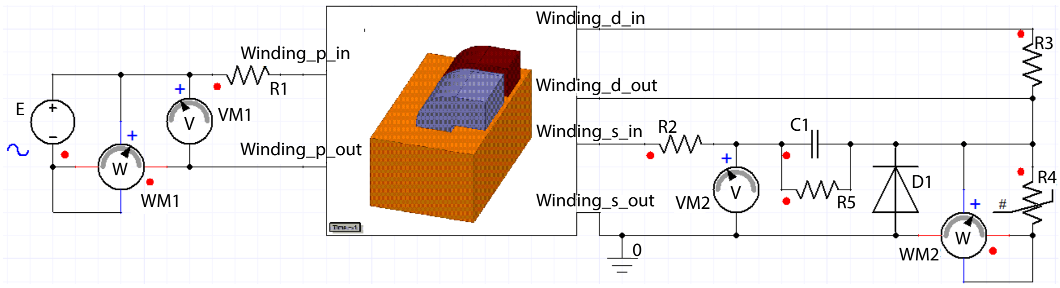

Figure 3. The circuit diagram of the joint simulation of Maxwell and Simplorer

shown in fig. 4. It can be seen that the average iron loss is about 10.69 W. Figure 5 showed the instant curves of the copper loss when the input voltage of the LIT is 220 V. It can be seen that the average copper loss is about 73.76 W.

When the LIT is used in the microwave oven, it can only transfer heat in the way of natural convection of air, and the iron loss and copper loss can make the LIT temperature rising.

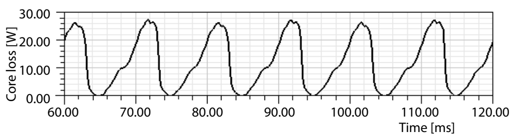

Figure 4. The iron loss of the LIT

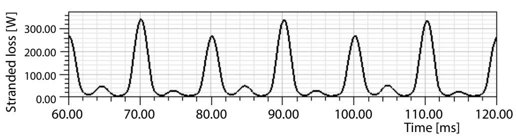

Figure 5. The copper loss of the LIT

Simulation of the temperature field

In order to obtain the temperature distribution of the LIT for microwave ovens, a quarter model was adopted because of the symmetry of the LIT. The convective heat transfer coefficient was set as 20 W/m^{2}K. The room temperature was set as 22 °C. The heat generated by the iron loss and copper loss was directly transferred by air and the iron core. Figure 6 shows the temperature distributions of the LIT after working for 300 seconds. It can be seen that,

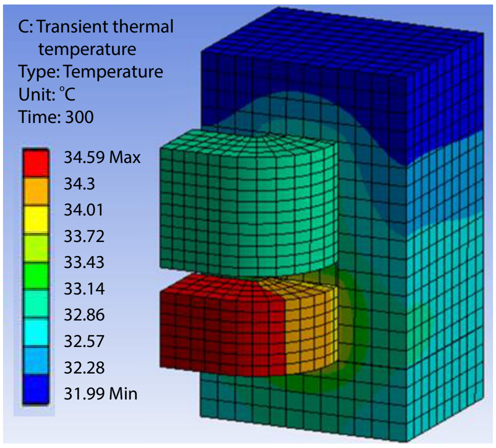

Figure 6. Temperature profile of the LIT at 300 s

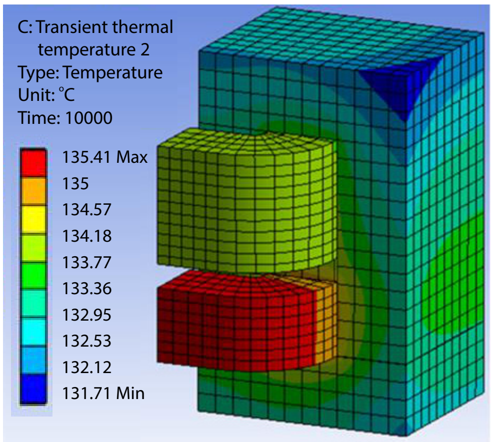

Figure 8. Temperature profile of the LIT at 10000 s

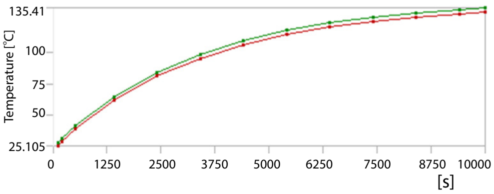

Figure 7. Highest temperature and lowest temperature of the LIT

under the natural convection heat transferring conditions of microwave ovens, the temperature of the windings at primary side reaches 34.59 °C and the maximum temperature rise of the LIT was 12.59 °C.

Figure 7 showed the curves of the highest and lowest temperatures of the working LIT. It can be seen that the temperature of the balanced state was about 135 °C. Figure 8 shows the temperature distribution of the LIT in the balanced state and the maximum temperature was 135.41 °C. The high temperature will cause lower efficiency and high electromagnetic noise.

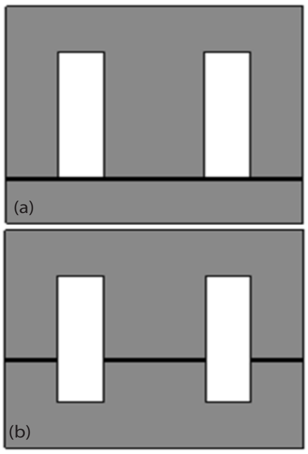

Figure 9. Front view of optimized iron core structure; (a) Original structure of iron core (b) Optimized structure of iron core

Structure optimization of the LIT

In order to improve the efficiency and reduce the noise of the LIT, this paper proposed an E-E type iron core scheme which was shown in fig. 9. The original structure of the E-I type iron core was shown in fig. 9(a), and the optimized E-E type iron core was shown in fig. 9(b). Silicon-steel sheets of different thicknesses and permeability were used for the primary and secondary sides of the new E-E type iron core. The quarter model of the optimized LIT was shown in fig. 10. For the new iron core LIT, the parameters of external circuit and boundary conditions were set as those of the structures before being optimized. The copper loss of the new LIT was calculated and shown in fig. 11. It can be seen that the average value is about 58.33 W which was 15.43 W less than that of the original iron core scheme of the LIT. The iron loss of the new LIT was calculated and shown in fig. 12. The average value of the iron loss was about 6.89 W which was less about 3.8 W than the original structure of the LIT.

Figure 13 showed the variation curves of the highest and lowest temperatures of the working optimized LIT. Figure 14 showed the temperature distribution of the optimized LIT in the balanced state and the maximum temperature was 109.6 °C, which was 25.81 °C below that of the original structure under the same operating conditions. Therefore, heat generated by various losses can be effectively reduced by the optimized iron core structure of the LIT. The maximum temperature was occurred on the primary side of the windings, too.

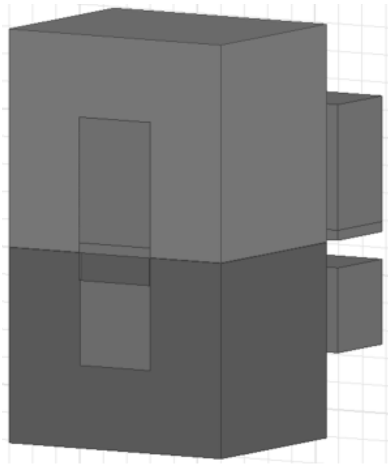

Figure 10. Model of the optimized LIT

Conclusions

The paper presented numerical simulation models to design and optimize LIT for applications in microwave ovens. The exact working environment of LIT, which can not been obtained by experiments, had been obtained by numerical simulations. The optimization of LIT was conducted and an optimized iron core structure was proposed in this paper. Different silicon steel sheet models were used for the upper and lower parts of the proposed iron core. The iron core scheme is changed from the traditional E-I type to the E-E type. The optimized iron core structure can reduce the loss and heat generation of the LIT. The numerical simulation results showed that the maximum temperature rise of the optimized LIT was 25.81 °C below that of the original structure under the same operating conditions.

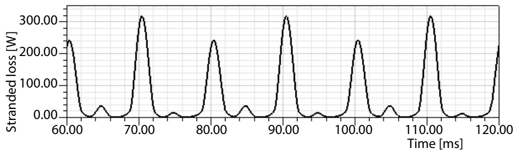

Figure 11. Copper loss of the optimized LIT

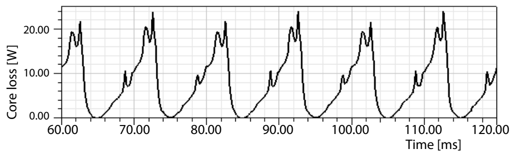

Figure 12. Iron loss of the optimized LIT

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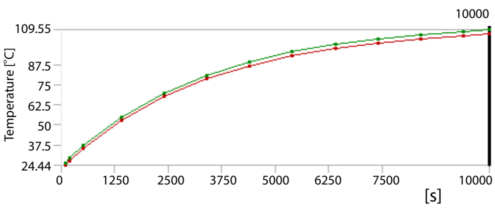

Figure 13. The highest temperature and lowest temperature of the optimized LIT

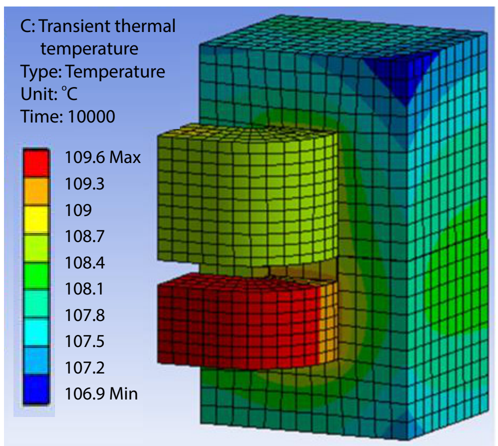

Figure 14. Temperature profile of the optimized LIT

References

[1] Jiang, C., Zhu, B., Analysis of Transformer Noise and its Reduction (In Chinese), *Journal of Nanjing Normal University*, *18* (1995), 2, pp. 19-21
[2] Zhang, Z., *The Principle and Application of the Transformer* (In Chinese), Chemical Industry Press, Beijing, China, 2007
[3] Jin, C., Design of Magnetic Leakage Transformer, *Power Supplies Technology*, *5* (2001), 11, pp. 35-36
[4] Nakata, T., Takahashi, N., Finite Element Analysis of Transformer Cores, *Memoirs of the School of Engineering*, *18* (1984), 1, pp. 1-31
[5] Ni, G., *et al.*, FEM Analysis of 3-D Transformer Leakage Field and Eddy Current Loss in the Windings, *IEEE Transactions on Magnetiics*, *28* (1992), 2, pp. 1382-1385
[6] Enokizono, M., Soda, N., Core Loss Analysis of Transformer by Improved FEM, *Journal of Magnetism & Magnetic Materials, 196-197* (1999), 1, pp. 910-912
[7] Kashtiban, A. M., *et al*., Investigation of Winding Type Effect on Leakage Flux of Single Phase Shell Type Transformer Using FEM, *Proceedings,* 8th Electrical Machines and Systems Conf., Nanjing, China, 2005, Vol. 3, pp. 1755-1758
[8] Yan, X. Q., *et al*., Study on Simulation of the Core Magnetic Field and Leakage Field in Power Transformer Based on Ansys (In Chinese), *Journal of Xinjiang University*, *22* (2005), 3, pp. 361-364
[9] Silva, J. R. D., *et al*., Using FEM for Power Transformer Electromagnetic and Thermal Analysis, *Proceedings*, Computational Electromagnetics Conf., Aachen, Germany, 2006, pp. 1-2
[10] Wei, G., Wang, X., Calculation of Leakage Inductance in Transformer Based on ANSYS (In Chinese), *Journal of Shantou University*, *23* (2008), 3, pp. 63-68
[11] Zhang, T., Zhou, K., *et al*., The Analysis of Three Dimensional Magnetic Field for a Power Transformer based on ANSYS (In Chinese), *Journal of Xihua University*, *27* (2008), 5, pp. 7-16
[12] Feng, J., Simulation and Calculation of ANSYS-based Magnetic Leakage Transformer, *Modern Electronics Technique*, *34* (2011), 6, pp. 181-184
[13] Chen, Y. X., *et al*., Simulation Match of Electromagnetic Fielding Microwave Oven, *Material Review*, *27* (2013), 3, pp. 132-135
[14] Gu, X. T., *et al*., The Leakage Inductance Study of High-Frequency High-Voltage Transformer Based on ANSYS, *Electronic Design Engineering*, *22* (2014), 4, pp. 112-114

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