

Simulation Study of PFC Inductor for Inverter Air Conditioner: Postprint

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Abstract

To address the local overheating and high temperature rise issues in the inductor of power factor correction (PFC) circuits for variable frequency air conditioners during operation, this paper employs electromagnetic-thermal coupling simulation for optimization design. Through finite element analysis, a three-dimensional electromagnetic-thermal field simulation model for the PFC inductor is established. The power loss of the PFC inductor is calculated via electromagnetic simulation and utilized as a heat source for thermal field simulation. By varying the winding turns and magnetic core dimensions, four distinct design schemes are simulated, with magnetic field-thermal coupling analysis performed for each, from which an optimized design scheme is proposed. Practical operation demonstrates that the optimized PFC inductor effectively reduces temperature rise and losses, and the design methodology holds reference value for the design of other inductive devices.

Full Text

Simulation Study of PFC Inductor for Variable Frequency Air Conditioner

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Abstract: In view of the local overheating and elevated temperature rise observed in the inductor of the power factor correction (PFC) circuit for inverter air conditioners during operation, this paper employs electromagnetic-thermal coupling simulation to optimize its design. Through finite element analysis, a three-dimensional electromagnetic-thermal field simulation model of the PFC inductor is established. The power loss of each inductor component is calculated via electromagnetic simulation and utilized as the heat source for thermal field simulation. By varying the number of winding turns and magnetic core dimensions, four distinct design schemes are simulated and subjected to magnetic-thermal coupling analysis, yielding an optimized design solution. Actual operational results demonstrate that the optimized PFC inductor effectively reduces temperature rise and losses, providing a valuable reference for the design of other inductive devices.

Keywords: Variable frequency air conditioner, power factor correction inductor, finite element analysis, electromagnetic-thermal field

1 Introduction

With the advancement of power electronics technology and the improvement of living standards, variable frequency air conditioners have gradually secured a dominant position in the air conditioning market. Compared with conventional fixed-frequency air conditioners, variable frequency systems offer significant advantages including high efficiency, energy savings, and quiet operation, making them increasingly popular among consumers [1]. To mitigate harmonic pollution from variable frequency air conditioners to the power grid, power factor correction (PFC) circuits are typically integrated into these systems. The PFC inductor serves as a critical component within the PFC circuit, and optimizing its magnetic core structure and electrical parameters is essential, as improper design can result in excessive local temperature rise and potential system damage.

Regarding PFC inductor design, literature [2] proposed a hybrid magnetic circuit topology where each material leverages its respective strengths to balance the magnetic circuit while reducing high-frequency losses. Literature [3] introduced a patch-coupled inductor design where the magnetic fluxes of two reverse-coupled windings cancel each other, significantly decreasing ferrite flux and improving the power inductor's saturation current. Literature [4] conducted a detailed analysis of amorphous magnetic PFC inductor design, with experimental results confirming that iron-based amorphous magnetic materials exhibit high saturation flux density and excellent temperature stability.

2 Numerical Analysis of Electromagnetic-Thermal Coupling Field for PFC Inductor

2.1 Mathematical Model for Electromagnetic Field Calculation

Under normal operating conditions, PFC inductor losses primarily comprise copper loss and iron loss. Copper loss refers to the ohmic loss in the winding coils, while hysteresis loss constitutes the main component of iron loss [5]. The overall loss can be expressed as the sum of copper loss and iron loss. The Joule loss induced by non-eddy current regions in the PFC inductor can be derived from electromagnetic field analysis, with eddy current loss determined through magnetic field and eddy current field calculations. The switching frequency is denoted as f_s .

2.3 Electromagnetic-Thermal Coupling Field Calculation

In analyzing the electromagnetic-thermal coupling field behavior and operation of the PFC inductor, eddy current loss and Joule heating generated in the coil represent the primary causes of temperature rise in various components. The eddy current loss produced by the inductor can be obtained through magnetic field and eddy current field analysis.

The governing equation for the thermal field is: $\nabla \cdot (\lambda \nabla T) + P = 0$

2.2 PFC 电感的温度场计算数学模型

热传导、热对流和热辐射是 PFC 电感正常运行中产生损耗主要的途径。考虑到 PFC 电感内部空气对流较为缓慢且热辐射较弱, 在热损耗分析时仅考虑 PFC 电感的热传导方式。

在计算温度场时, 热传导方程为 $\nabla \cdot (\lambda \nabla T) + P = 0$ where ρ is density (kg/m^3), C_p is specific heat capacity ($\text{J}/(\text{kg} \cdot \text{K})$), T is temperature ($^\circ\text{C}$), k is thermal conductivity ($\text{W}/(\text{m} \cdot \text{K})$), and P is the heat generation rate (W/m^3).

The boundary conditions for heat dissipation at the outer surfaces of the PFC inductor in contact with air are expressed as: $\lambda \nabla T \cdot \mathbf{n} = 0$ 式中, R 为线圈的电阻 (Ω); I 为通入线圈的电流有效值 (A)。) = 0

3 PFC 电感的电磁热耦合场建模

式中, σ 为电导率 (S/m); μ 为磁导率 (H/m); V 为标量电位 (V); \mathbf{A} 为矢量磁位; t 为时间。非涡流区的控制方程为

3.1 变频空调用 PFC 的电路拓扑

变频空调用 PFC 电路如图 1 [Figure 1: see original paper] 所示。电感 L 为 PFC 电感, 工频 AC220V 输入经整流、PFC 功率因数校正电路后为变频电路供电 [6]。PFC 电感 L 在充放电过程中, 因设计不当, 容易出现温升过高, 从 $I = 0.2I_{pk} = 0.2 \times 14.14\text{A} = 2.8\text{A}$ 而降低了空调的可靠性。(3) 计算输入电压峰值的占空比 D 。

AC220V 图 1 变频空调用 PFC 电路 Fig.1 PFC circuit for variable frequency air conditioner

3.1.1 PFC 电路的工作参数

设通过 PFC 电感 L 的电流为 I_d , 电容 C 的电压为 U_d , 输入电流为 i_2 。交流输入电压 U_i : 220VAC, 50Hz。额定输出电压 U_o : 380V。输入功率 P_{in} : 2.2kW。开关频率: $f_s = 40\text{kHz}$ 。

3.1.2 电感量的计算

(1) 计算最大峰值线电流 I_{pk} 。 $I_{pk} = \frac{U_o}{U_{in}} \cdot I_{in} = \frac{380}{220} \cdot 14.14\text{A} = 24.14\text{A}$ (4) 电感量计算。

$U_{in} = 220\text{V}$, $D = 0.18$, $f = 40000\text{Hz}$, $L = 2.8\text{H}$ # 5" 10\$\$\$ where h is the surface heat transfer coefficient ($\text{W}/(\text{m}^2 \cdot \text{K})$), T_b is the temperature of the heating body ($^\circ\text{C}$), and T_a is the ambient temperature ($^\circ\text{C}$).

This study focuses on the PFC inductor for variable frequency air conditioners, employing a consistent inductor model while selecting four different magnetic core structures for simulation-based design. Finite element software is utilized to conduct separate magnetic field and temperature field simulations, obtaining specific iron loss and copper loss values. Through comparative analysis, a design scheme with reduced temperature rise is identified.

3 Electromagnetic-Thermal Coupling Field Modeling

3.2 Magnetic Material Selection

In magnetic device research, material selection is critical. Based on coercivity characteristics, magnetic materials can be classified as soft magnetic or permanent magnetic materials. This paper initially evaluated six candidate materials, and considering the properties summarized in Table 1, atomized Fe-Si-Al produced by Qingdao Yunlu Advanced Materials Company was selected for its low cost and minimal losses.

For winding conductor selection, enameled flat copper wire was chosen. Compared with traditional round copper wire, flat copper wire enables automated machine winding while maintaining equivalent electrical characteristics, eliminating manual winding time.

3.3 Electromagnetic-Thermal Coupling Field Modeling

This paper employs electromagnetic-thermal field simulation software and the finite element method to perform transient magnetic field analysis and transient thermal field temperature distribution analysis for the PFC inductor. The simulation process begins with magnetic field analysis to obtain iron loss and copper loss curves, which serve as the heat source for the thermal analysis module. This approach is termed the load transfer method.

The coupling analysis flow chart is illustrated in Figure 2 [Figure 2: see original paper]. Initially, material parameters and properties of the magnetic core and windings are input, current density is applied, and electromagnetic field calculations are performed according to equations (2) through (4) to obtain the heat source required for temperature field analysis—namely, the heat generation rate P . Subsequently, temperature field analysis is conducted based on equations (5) and (6) [8].

In the inductor design optimization process, multiple parameters must be considered, including design parameters and process parameters. Design parameters primarily encompass inductor volume and geometry, number of coil turns, and winding configuration, while process parameters include substrate resistivity and metal thickness. Since process parameters cannot be arbitrarily modified, this paper focuses on optimizing the more readily adjustable design parameters for the PFC inductor [9].

Theoretical analysis demonstrates that PFC inductor losses are closely related to core size and winding turns. According to the “thermal circuit” Ohm’s law, $\Delta T = R_{th} \cdot P$, where R_{th} represents the external thermal resistance from the inductor surface to the environment ($W/^\circ C$), temperature rise is directly proportional to power loss.

Table 2 presents the magnetic core specifications for the four schemes. Scheme 1 represents the enterprise’s original PFC inductor design, which exhibited excessive temperature rise during testing. Elevated temperature rise reduces the saturation magnetic flux density of the PFC inductor, affecting normal charge-discharge processes, and causes local overheating, accelerated aging, increased losses, and reduced system efficiency. Based on Scheme 1, while maintaining the initial inductance value and meeting actual circuit design requirements, three additional inductor specifications were developed by varying magnetic core dimensions and coil turns for comparative evaluation.

4 Simulation Analysis and Optimization Design of PFC Inductor

4.1 Magnetic Flux Density Simulation of Four Schemes

Following simulation, the magnetic flux density distribution nephograms for the four PFC inductor schemes are presented in Figures 5 [Figure 5: see original paper] through 8 [Figure 8: see original paper]. The magnetic field simulation employs the aforementioned atomized Fe-Si-Al core material. The figures reveal that due to differing geometric dimensions of the magnetic cores, their magnetic reluctance and air gap cross-sectional areas vary, resulting in different magnetic flux density distributions. All four schemes exhibit vertically symmetric magnetic flux density distributions, with stronger magnetic flux density observed at the magnetic core locations adjacent to the windings.

Scheme 1 exhibits magnetic flux density distribution ranging from 7.7×10^{-4} to

8.5×10^3 T, Scheme 2 from 1.0×10^3 to 7.4×10^3 T, Scheme 3 from 7.5×10^3 to 5.1×10^3 T, and Scheme 4 from 2.0×10^3 to 5.1×10^3 T. Notably, Scheme 4 demonstrates significantly lower magnetic flux density than the other schemes, indicating its inductor structure is less susceptible to saturation. This improvement indirectly reflects that Scheme 4 has mitigated local overheating compared with the first three schemes, enhancing system reliability [11].

4.2 Temperature Distribution Simulation of Four Schemes

The temperature distribution nephograms for the four schemes are presented in Figures 9 [Figure 9: see original paper] through 12 [Figure 12: see original paper]. The temperature distributions show similar patterns across all schemes. Scheme 1 exhibits temperature distribution from 96.7 to 99.7°C, Scheme 2 from 113.5 to 114.6°C, Scheme 3 from 85.7 to 86.9°C, and Scheme 4 from 83.5 to 84.5°C. Consequently, Scheme 4 achieves the lowest maximum temperature with a significantly reduced temperature gradient compared to the other three schemes, demonstrating effective temperature rise reduction.

4.3 PFC Inductor Loss Analysis

The magnetic flux density and temperature field simulations indicate that Scheme 4's inductor structure effectively reduces temperature rise and improves system efficiency. This paper further analyzes and calculates specific iron loss and copper loss values for the four inductor structures to enable direct comparison. The copper loss curves for one operating cycle are shown in Figures 13 [Figure 13: see original paper] through 16 [Figure 16: see original paper].

Figure 13 shows Scheme 1's maximum copper loss as 6.68 W. Based on the magnetic field simulation results, step 35 to step 65 is selected for iron loss calculation at 40 kHz, yielding 1.9 W. Similar simulations and calculations are performed for Schemes 2, 3, and 4.

Through consistent simulation analysis and calculation, the copper loss, iron loss, and temperature rise data for all four schemes are obtained and summarized in Table 3.

Table 3 Comparison of Four Schemes [Table content with columns: Highest Temperature/°C, Room Temperature/°C, Copper Loss/W, Iron Loss/W]

The results show temperature rise ranking from lowest to highest as: Scheme 4 < Scheme 3 < Scheme 1 < Scheme 2, and total loss ranking as: Scheme 3 < Scheme 4 < Scheme 1 < Scheme 2. Therefore, Schemes 3 and 4 outperform Schemes 1 and 2. Further analysis of Figures 5 through 12 reveals that while Schemes 3 and 4 exhibit similar loss characteristics, Scheme 3's higher maximum temperature and temperature gradient indicate inferior overall thermal performance and potential local overheating issues. Thus, Scheme 4 represents the optimal solution.

4.4 Experimental Verification

Figure 17 [Figure 17: see original paper] shows the actual inductor model manufactured by Qingdao Yunlu Company. At an ambient temperature of 21°C, measured peak coil temperatures are 101°C for Scheme 1, 118°C for Scheme 2, 94°C for Scheme 3, and 92°C for Scheme 4. The experimental results demonstrate good correlation with simulation trends, confirming Scheme 4's lowest temperature rise.

5 Conclusion

Comparative analysis of the electromagnetic-thermal field simulations for the four PFC inductor schemes demonstrates that Scheme 4 achieves lower magnetic flux density, making it less susceptible to saturation. Scheme 4 also exhibits the lowest simulated maximum temperature with relatively small copper and iron losses, validated through experiments. While maintaining the initial inductance value, Scheme 4's design incurs minimal cost increase compared with traditional schemes but significantly reduces core loss and optimizes temperature rise performance. Therefore, Scheme 4 effectively reduces losses and temperature rise, prevents local overheating, and improves overall system efficiency, providing a theoretical basis for mass production.

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Note: Figure translations are in progress. See original paper for figures.

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