

Simulation Study on PFC Inductor for Inverter Air Conditioners (Postprint)

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Abstract

Aiming at the local overheating and high temperature rise issues of the inductor in Power Factor Correction (PFC) circuits for inverter air conditioners during operation, this paper employs electromagnetic-thermal coupling simulation for its optimized design. Through Finite Element Analysis, a three-dimensional electromagnetic-thermal field simulation model of the PFC inductor is established; the power loss of the PFC inductor is calculated using electromagnetic simulation and employed as a heat source for thermal field simulation. By varying the number of winding turns and magnetic core dimensions, four different design schemes are simulated, each undergoing magnetic field-thermal coupling analysis, from which an optimized design scheme is presented. Practical operation demonstrates that the optimized PFC inductor effectively reduces temperature rise and losses, and the design methodology offers reference value for the design of other inductive components.

Full Text

Preamble

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 was established. The power losses of each component of the inductor were calculated via electromagnetic simulation and applied as heat sources for thermal field simulation. By varying the number of winding turns and magnetic core dimensions, four distinct design schemes were simulated and subjected to magnetic-thermal coupling analysis, from which an optimized design was identified. Actual operation demonstrates that the optimized PFC inductor effectively reduces temperature rise and losses, and the proposed design methodology offers 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 become mainstream in the air conditioning market. Compared with traditional fixed-frequency air conditioners, variable frequency air conditioners offer numerous advantages such as high efficiency, energy savings, and quiet operation, making them increasingly popular among users [1]. To reduce harmonic pollution to the power grid from variable frequency air conditioners, power factor correction (PFC) circuits are typically incorporated. The PFC inductor is a critical component in the PFC circuit, and the optimal design of its magnetic core structure and electrical parameters is essential. Improper design can lead to excessive local temperature rise and even damage to the air conditioner.

Regarding PFC inductor design, literature [2] proposes a hybrid magnetic circuit PFC inductor where each material can leverage its strengths to balance the magnetic circuit and reduce high-frequency losses. Literature [3] presents a design scheme for patch-coupled inductors, where the magnetic fluxes of two reverse-coupled windings cancel each other out, significantly reducing flux in the ferrite and increasing the saturation current of the power inductor. Literature [4] provides a detailed analysis of amorphous magnetic PFC inductor design, with experimental results demonstrating that iron-based amorphous magnetic

materials feature high saturation flux density and excellent temperature stability.

This paper focuses on the PFC inductor for variable frequency air conditioners, adopting the same inductor model and selecting four different core structures for simulation design. Using finite element software, magnetic field and temperature field simulations were conducted separately to obtain specific values for iron loss and copper loss. Through analysis and comparison, a design scheme with lower temperature rise was identified.

2 Numerical Analysis of PFC Inductor Electromagnetic-Thermal Coupling Field

2.1 Mathematical Model for PFC Inductor Electromagnetic Field Calculation

Under normal operating conditions, the losses generated in PFC inductors primarily include copper loss and iron loss. Copper loss generally 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:

$$P = P_{Cu} + P_{Fe}$$

The governing equations are:

$$\langle MATH_0001 \rangle$$

where ρ is density (kg/m^3), C_p is specific heat capacity ($\text{J}/(\text{kg} \cdot \text{K})$), θ 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).

For the boundary conditions of heat dissipation, which correspond to the outer surface of the PFC inductor in contact with air, the formula is expressed as:

$$\langle MATH_0002 \rangle$$

where α is the surface heat transfer coefficient ($\text{W}/(\text{m}^2 \cdot \text{K})$), θ_0 is the temperature of the heating body ($^{\circ}\text{C}$), and θ_f is the ambient temperature ($^{\circ}\text{C}$).

2.3 Electromagnetic-Thermal Coupling Field Calculation for PFC Inductor

When analyzing the electromagnetic-thermal coupling field calculation and operation process of PFC inductors, eddy current losses and Joule heat generated

in the coils are the primary causes of temperature rise in various components. Based on magnetic field and eddy current field analysis, the eddy current loss generated by the inductor can be determined. The Joule loss caused by non-eddy current regions in the PFC inductor can be derived from the following formula:

$$P_{Cu} = RI^2$$

where f_s is the switching frequency.

Therefore, from equations (11) to (13), when the current ripple coefficient is controlled at 0.2, an inductance value of 500 H is appropriate.

3 Electromagnetic-Thermal Coupling Field Modeling

3.2 Magnetic Material Selection

In magnetic device research, magnetic material selection is a crucial aspect. Based on differences in coercivity, magnetic materials can be categorized as soft magnetic materials or permanent magnetic materials. This paper initially selected six materials for comparison. Considering the characteristics of the six materials listed in Table 1, atomized Fe-Si-Al produced by Qingdao Yunlu Advanced Materials Company was selected for its low cost and small losses.

For winding wire selection, this paper chose enameled flat copper wire. Compared with traditional round copper wire, flat copper wire enables automated winding, eliminating manual winding time while maintaining equivalent electrical characteristics.

3.3 Electromagnetic-Thermal Coupling Field Modeling

This paper utilizes electromagnetic-thermal field simulation software and the finite element method to conduct transient magnetic field analysis and transient thermal field temperature distribution analysis for PFC inductors. The simulation software first performs magnetic field analysis to obtain iron loss and copper loss curves, which are then applied as heat sources for the thermal analysis module. This method is called the load transfer method. The coupling analysis flowchart is shown in Figure 2 [Figure 2: see original paper].

First, material parameters and properties of the magnetic core and windings are input. Current density is loaded, and electromagnetic field calculations and analysis are performed according to equations (2) to (4) to obtain the heat generation rate P required for temperature field analysis. Subsequently, temperature field analysis is conducted based on equations (5) and (6) [8].

When analyzing different fields, the results from one field analysis can be applied as loads to other fields, thereby achieving coupling between the fields [7].

4 PFC Inductor Simulation Analysis and Optimization Design

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

Theoretical analysis shows that PFC inductor losses are closely related to core dimensions and winding turns. According to the “thermal circuit” Ohm’s law:

$$\Delta T = R_{th} \cdot P$$

where R_{th} is the external thermal resistance from the inductor surface to the external environment (W/°C). Temperature rise is directly related to losses.

Table 2 presents the specifications of the inductor magnetic cores for the four schemes. Scheme 1 represents the company’s original PFC inductor design, which exhibited excessive temperature rise during testing. Excessive temperature rise leads to decreased saturation magnetic flux density of the PFC inductor, affecting normal charging and discharging processes. The direct consequence of excessive temperature rise is local overheating, accelerated aging, increased losses, and reduced system efficiency. Based on Scheme 1 and under the premise of maintaining the initial inductance value and meeting the design requirements for actual circuit implementation, three additional inductor schemes with different core dimensions and coil turns were designed for comparison.

4.1 Magnetic Flux Density Simulation of Four PFC Inductor Schemes

A three-dimensional nonlinear mathematical model of the PFC inductor was built in the simulation software using atomized Fe-Si-Al for the core as mentioned previously. To make the experimental results more closely approximate real-world conditions, the model was created according to the actual inductor dimensions. The main view and cross-section of the inductor core are shown in Figure 3 [Figure 3: see original paper].

In the four schemes, Scheme 1 uses 0.4×4 mm enameled flat copper wire with 36 turns × 2 series; Scheme 2 uses 0.4×4 mm enameled flat copper wire with 45 turns × 2 series; Schemes 3 and 4 use 0.4×4 mm enameled flat copper wire with 50 turns × 2 series.

Since actual current waveforms cannot be directly implemented in the simulation software, the current waveform was sampled at 100 time points for simulation.

The current value reaches its maximum at time 0.005006 s with step 50 [10]. The simulated current waveform is shown in Figure 4 [Figure 4: see original paper].

The magnetic flux density distribution nephograms for the four schemes are shown in Figures 5 [Figure 5: see original paper] through 8 [Figure 8: see original paper]. Due to different geometric dimensions of the PFC inductor cores in the four schemes, their magnetic reluctance and cross-sectional area at the air gap differ, resulting in different magnetic flux density distribution values. The magnetic flux density distribution is symmetric vertically, with stronger magnetic flux density at the inductor winding core. Scheme 1 exhibits magnetic flux density distribution from 7.7×10^{-3} 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. Scheme 4 shows significantly lower magnetic flux density than other schemes, indicating its inductor structure is less prone to saturation and suggesting improved local overheating conditions for enhanced system reliability [11].

4.2 Temperature Distribution Simulation of Four PFC Inductor Schemes

The temperature distribution nephograms for the four schemes are shown in Figures 9 [Figure 9: see original paper] through 12 [Figure 12: see original paper]. Scheme 1 shows 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. Scheme 4 exhibits the lowest maximum temperature and significantly reduced temperature gradient distribution compared to the other three schemes, demonstrating that the Scheme 4 inductor structure effectively reduces PFC inductor temperature rise.

4.3 PFC Inductor Loss Analysis

Based on the magnetic field and temperature field simulations, Scheme 4 effectively reduces temperature rise and improves system efficiency. This paper also specifically analyzes and calculates the iron loss and copper loss values for the four inductor structures to more intuitively compare their losses and temperature rise. The copper loss curves for one cycle of the four schemes are shown in Figures 13 [Figure 13: see original paper] through 16 [Figure 16: see original paper].

Figure 13 shows Scheme 1 has a maximum copper loss of 6.68 W. Based on the magnetic field simulation results from step 35 to step 65, iron loss was calculated at 40 kHz as 1.9 W. Similar simulation, analysis, and calculations were performed for Schemes 2, 3, and 4.

Through simulation analysis and calculations following the same process as Scheme 1, the copper loss, iron loss, and temperature rise data for the four schemes were obtained, with results presented in Table 3.

The comparison shows temperature rise ranking from lowest to highest: Scheme 4 < Scheme 3 < Scheme 1 < Scheme 2. The sum of iron loss and copper loss ranking from lowest to highest: Scheme 3 < Scheme 4 < Scheme 1 < Scheme 2. Therefore, Schemes 3 and 4 outperform Schemes 1 and 2. Analysis of Figures 5 through 12 reveals that while the inductor losses of Schemes 3 and 4 are very close, their different magnetic circuit structures result in Scheme 3 having higher maximum temperature and temperature gradient distribution than Scheme 4. The excessively high maximum temperature in Scheme 3 could lead to local overheating issues. Therefore, Scheme 4 is identified as the optimal solution.

While maintaining the initial inductance value, Scheme 4's design shows minimal cost increase compared to the traditional scheme but features relatively lower core loss and significantly optimized temperature rise characteristics. Thus, Scheme 4 effectively reduces losses and temperature rise, avoids local overheating, and improves overall system efficiency, providing a theoretical basis for mass production.

4.4 Experimental Validation

Figure 17 [Figure 17: see original paper] shows the actual inductor model manufactured by Qingdao Yunlu Company. At an ambient temperature of 21°C, testing revealed maximum coil temperatures of 101°C for Scheme 1, 118°C for Scheme 2, 94°C for Scheme 3, and 92°C for Scheme 4. The actual test results show similar trends to the simulations, with Scheme 4 exhibiting the lowest temperature rise.

5 Conclusion

Through comparative analysis of electromagnetic-thermal field simulations for the four PFC inductor schemes, Scheme 4 demonstrates lower magnetic flux density than other schemes, making it less susceptible to saturation. Additionally, Scheme 4 shows the lowest maximum temperature in simulations with relatively small copper and iron losses, which has been validated experimentally. Under the premise of maintaining the initial inductance value, Scheme 4 provides an optimized design that effectively reduces temperature rise and losses, enhancing system reliability.

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