Magnetic-Thermal Coupling Analysis of Air-Core Reactor in EAST Fast Control Power Supply Postprint

Authors: Hu Yunpeng, Bao Xiaohua, Zhang Cheng, Chen Yuanyang, Gao Ge

Date: 2019-03-05T00:00:00+00:00

Abstract

When pulsed current flows through the hollow reactor in the fast control power supply of the Experimental Advanced Superconducting Tokamak (EAST), a magnetic field is generated, resulting in heating of the output cabinet. To mitigate this thermal issue, one or two layers of shielding are installed around the hollow reactor. At a maximum current amplitude of 1,500 A, the magnetic field distribution around the hollow reactor and the eddy current losses in the output cabinet are computed. Employing eddy current losses as the primary heat source, a three-dimensional magneto-thermal coupling finite element model of the reactor is established based on electromagnetic and thermodynamic theories. This paper analyzes and discusses the temperature field of the hollow reactor. The results demonstrate that both the magnetic field of the hollow reactor and the temperature of the output cabinet are reduced under shielding conditions.

Full Text

Magnetic-Thermal Coupling Analysis of Air-Core Reactor in EAST Fast Control Power Supply

Hu Yunpeng[1], Bao Xiaohua[1], Zhang Cheng[1], Chen Yuanyang[1], Gao Ge[2]

[1]School of Electrical Engineering and Automation, Hefei University of Technology, Hefei 230009, China
[2]Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, China

Abstract

When pulse current flows through the air-core reactor of the Experimental Advanced Superconducting Tokamak (EAST) fast control power supply, the generated magnetic field may cause thermal problems in the output cabinet. To address this thermal issue, one or two layers of shielding are arranged around the air-core reactor. With a maximum pulse current amplitude of 1500 A, this paper investigates the calculation method for magnetic field distribution around the air-core reactor and the eddy current loss in the output cabinet. Taking eddy current loss as the primary heat source, three-dimensional (3D) magnetic-thermal coupled finite element models of the reactor are established based on electromagnetic and thermodynamic theories. The temperature field of the air-core reactor is analyzed and discussed. Results demonstrate that both the magnetic field around the air-core reactor and the temperature of the output cabinet are reduced under shielded conditions.

Keywords: EAST fast control power supply, output cabinet, air-core reactor, magnetic field, shield, eddy current loss, temperature

Project supported by the National Natural Science Funds of China (51377039, 51677051).

Introduction

The Experimental Advanced Superconducting Tokamak (EAST) fast control power supply is a large-capacity single-phase inverter power supply [1]. The system consists of six H-bridge branches, each equipped with an air-core reactor. In this system, the reactor is employed to limit current, stabilize voltage, and compensate reactive power. Recently, analytical methods have been used to calculate and analyze the magnetic field distribution in air-core reactors without shielding [2-3]. Electromagnetic shielding is a technique that reduces or prevents the coupling of undesired radiated electromagnetic energy into equipment, thereby maintaining compatible operation with its electromagnetic environment. To shield magnetic fields, many scholars have studied a wide variety of shields, including shields of different shapes and varying numbers of layers [4-6]. In practical applications, air-core reactors during operation are prone to faults, including partial discharge, overheating, and burnout [7-8]. Temperature rise is one of the main aging mechanisms that must be considered, especially for the overall system; therefore, installing shields for reactors is attracting increasing attention [9-11].

With regard to shield design problems, optimization typically involves minimization of the field in a predefined area—the target region—and minimization of electromagnetic losses in the shield. However, it is also useful to include thermal aspects: a shield may obtain a high temperature because of electromagnetic losses and heat radiation from the heat source [12-13]. Even if the average temperature rise satisfies design requirements, the hottest-spot temperature in the reactor might exceed the maximum temperature limits of insulation materials. Moreover, thermal fields have been simulated using the finite-element method (FEM) after calculating the heat transfer coefficient using the Nusselt number

[14-15]. In such calculations, fluid dynamic behavior cannot be accurately described without simulating the fluid field, and the calculation results differed significantly from measurement results.

Therefore, a magnetic-thermal coupled model is necessary to accurately and efficiently predict the temperature in the output cabinet, using special shields made of composite materials to absorb the strong magnetic field generated by the reactor. Different shielding materials produce different results. With single-layer shielding, DT4A shows the best effect, while DT4A/GO performs best for double-layer shielding. Temperature under single and double shielded conditions is reduced by 38.1% and 64.2%, respectively. Comparing simulated and measured temperatures shows that the error is within a controllable range. Consequently, the thermal problem of the cabinet can be effectively solved through this approach.

2.1 Structure of Air-Core Reactor

The air-core reactor is primarily used in power supply rectifiers to resolve inconsistencies in parallel rectifying element voltage drop. The reactor comprises 32 turns of wound copper coils, with each coil encapsulated in glass fibers impregnated with epoxy resin. This encapsulation enhances both the insulation strength and mechanical strength of the air-core reactor. Simulation and actual models of the reactor are shown in [Figure 1: see original paper]. Three reactors are positioned in the middle of the cabinet, with a distance of 240 mm between the cabinet and the reactor, and 330 mm between adjacent reactors.

2.2 Analytical Calculation of Magnetic Field Around Air-Core Reactor

[Figure 2: see original paper] shows the irregular shape of each copper coil, which is approximated as rectangular and composed of four elliptical arc edges. Therefore, the magnetic field of the air-core reactor can be obtained by analyzing the magnetic field of each coil.

For calculating the magnetic field around the air-core reactor, its governing equation is given by the Biot-Savart law. All parameters are shown in [Figure 2: see original paper].

(1) Magnetic field of rectangular line current. In this paper, the axis is the longitudinal direction of the magnet, and the current is defined as positive when it flows towards the positive x-axis. For the rectangular winding, the magnetic flux density is composed of contributions from each side of the rectangle. It is assumed that the length dl of the current element is infinitesimally small. The unit vector between point S(x, -b, z) on wire 1 and arbitrary point P(xi, yi, zi) can be expressed as:

$$\frac{(x_i - x)e_x + (y_i + b)e_y + (z_i - z)e_z}{\sqrt{(x_i - x)^2 + (y_i + b)^2 + (z_i - z)^2}}$$

where e_x, e_y, and e_z denote unit vectors along the x, y, and z axes, respectively.

According to the governing equations, the induced magnetic field at arbitrary field point P is expressed as:

$$d\mathbf{B}_1 = \frac{\mu_0 I dx\, e_x \times [(x_i - x)e_x + (y_i + b)e_y + (z_i - z)e_z]}{4\pi[(x_i - x)^2 + (y_i + b)^2 + (z_i - z)^2]^{3/2}}$$

The total magnetic field at point P generated by wire 1 is given by:

$$B_{1zi} = \int \frac{\mu_0 I (z_i - z)}{4\pi[(x_i - x)^2 + (y_i + b)^2 + (z_i - z)^2]^{3/2}} dx$$

Similarly, the magnetic field at point P generated by wires 2, 3, and 4 can be calculated. The magnetic field of the rectangular line current is:

$$\begin{aligned} B_{rxi} = {} & \frac{\mu_0 I (z_i - z)}{4\pi[(x_i - a)^2 + (z_i - z)^2]} \left[\frac{b - y_i}{\sqrt{(x_i - a)^2 + (b - y_i)^2 + (z_i - z)^2}} + \frac{b + y_i}{\sqrt{(x_i - a)^2 + (b + y_i)^2 + (z_i - z)^2}} \right] \\ & - \frac{\mu_0 I (z_i - z)}{4\pi[(x_i + a)^2 + (z_i - z)^2]} \left[\frac{y_i - b}{\sqrt{(x_i + a)^2 + (y_i - b)^2 + (z_i - z)^2}} + \frac{b + y_i}{\sqrt{(x_i + a)^2 + (b + y_i)^2 + (z_i - z)^2}} \right] \end{aligned}$$

$$\begin{aligned} B_{ryi} = {} & \frac{\mu_0 I (z_i - z)}{4\pi[(y_i + b)^2 + (z_i - z)^2]} \left[\frac{x_i - a}{\sqrt{(x_i - a)^2 + (y_i + b)^2 + (z_i - z)^2}} + \frac{x_i + a}{\sqrt{(x_i + a)^2 + (y_i + b)^2 + (z_i - z)^2}} \right] \\ & - \frac{\mu_0 I (z_i - z)}{4\pi[(y_i - b)^2 + (z_i - z)^2]} \left[\frac{a - x_i}{\sqrt{(x_i - a)^2 + (y_i - b)^2 + (z_i - z)^2}} + \frac{x_i + a}{\sqrt{(x_i + a)^2 + (y_i - b)^2 + (z_i - z)^2}} \right] \end{aligned}$$

$$\begin{aligned} B_{rzi} = {} & \frac{\mu_0 I (y_i + b)}{4\pi[(y_i - b)^2 + (z_i - z)^2]} \left[\frac{a - x_i}{\sqrt{(x_i - a)^2 + (y_i - b)^2 + (z_i - z)^2}} + \frac{a + x_i}{\sqrt{(x_i + a)^2 + (y_i - b)^2 + (z_i - z)^2}} \right] \\ & + \frac{\mu_0 I (x_i - a)}{4\pi[(x_i - a)^2 + (z_i - z)^2]} \left[\frac{y_i - b}{\sqrt{(x_i - a)^2 + (y_i - b)^2 + (z_i - z)^2}} + \frac{y_i + b}{\sqrt{(x_i - a)^2 + (y_i + b)^2 + (z_i - z)^2}} \right] \\ & + \frac{\mu_0 I (x_i + a)}{4\pi[(x_i + a)^2 + (z_i - z)^2]} \left[\frac{y_i - b}{\sqrt{(x_i + a)^2 + (y_i - b)^2 + (z_i - z)^2}} + \frac{y_i + b}{\sqrt{(x_i + a)^2 + (y_i + b)^2 + (z_i - z)^2}} \right] \end{aligned}$$

(2) Magnetic field of oval line current. [Figure 2: see original paper] shows an oval current-carrying coil, with the oval equation given by:

$$\frac{x^2}{(a+c)^2} + \frac{y^2}{b^2} = 1$$

Through coordinate transformation, solving the magnetic field distribution of elliptical coils can be converted into solving the magnetic field distribution of circular coils. Assuming an elliptical shape factor $k = b/a$ and defining $X = k^{1/2}x$, $Y = k^{-1/2}y$, the equation becomes $X^2 + Y^2 = (a+c)b$.

With the above analysis, the magnetic field around the air-core reactor is:

$$B_{xi} = \frac{2(\theta_1 + \theta_2)}{\pi} B_{oxi} + B_{rxi}$$
$$B_{yi} = \frac{2(\theta_1 + \theta_2)}{\pi} B_{oyi} + B_{ryi}$$
$$B_{zi} = \frac{2(\theta_1 + \theta_2)}{\pi} B_{ozi} + B_{rzi}$$

where:

$$\theta_1 = \arccos\left(\frac{a^2 + b^2 - bc}{a^2 + b^2}\right)$$
$$\theta_2 = \arccos\left(\frac{a^2 + (b-c)^2 - c^2}{2\sqrt{a^2 + (b-c)^2}\sqrt{(a+c)^2 + (b-c)^2}}\right)$$

B_{oxi}, B_{oyi}, and B_{ozi} represent the magnetic flux density components in each axis direction of the elliptical coil, while B_{rxi}, B_{ryi}, and B_{rzi} represent the magnetic flux density components of the rectangular coil.

For the complete elliptic integrals, the magnetic field of the oval line current can be expressed as a series expansion. In actual space, the magnetic flux density at any point can be approximated by a limited series, and the magnetic flux density distribution of the output cabinet can be calculated. The eddy current loss in the output cabinet can then be analyzed using electromagnetic induction law and Ohm’ s law, expressed as:

$$P_{eddy} = \frac{(fB)^2 \Delta^2 F_e h l}{\rho}$$

where Δ, F_e, h, and l are the thickness, height, and length of the output cabinet, respectively, and ρ is the conductivity of iron.

(3) Strong coupling of magnetic-thermal field calculation. [Figure 3: see original paper] illustrates the Joule heat dissipation from the output cabinet through cooling modes including heat conduction, natural convection, and thermal radiation. The air-core reactor consists of 32 layers of copper coils, some of which are shown in [Figure 3: see original paper]. From a quantitative analysis perspective, it is necessary to establish a mathematical model linking the magnetic field equations, heat conduction equation, and Navier-Stokes equations through coupled variables.

For the system shown in [Figure 3: see original paper], three heat dissipation modes are involved: heat conduction, natural convection, and thermal radiation. For the output cabinet, the primary heat dissipation mode is heat conduction. For the surface between the output cabinet and surrounding air, the primary modes are natural convection and thermal radiation.

1) **Heat conduction.** For the output cabinet, the steady-state heat conduction equation for solids is:

$$\nabla \cdot (\lambda \nabla T) + Q = 0$$

where λ is the thermal conductivity coefficient and Q is the heat generation per unit volume in iron conductors.

2) **Natural convection.** The natural convection of air satisfies the Navier-Stokes equations, which consist of three groups of equations. For three-dimensional incompressible steady fluids, the Navier-Stokes equations in Cartesian coordinates can be simplified as:

Continuity equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

Momentum conservation equations:

$$\rho(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z}) = -\frac{\partial P}{\partial x} + \mu\nabla^2 u + f_x$$

$$\rho(u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z}) = -\frac{\partial P}{\partial y} + \mu\nabla^2 v + f_y$$

$$\rho(u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z}) = -\frac{\partial P}{\partial z} + \mu\nabla^2 w + f_z$$

Energy equation:

$$\rho c(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z}) = \lambda\nabla^2 T + Q$$

where ρ is fluid density, μ is viscosity coefficient, c is specific heat, u, v, and w are the fluid velocity potentials in the x, y, and z directions, P is fluid pressure,

T is fluid temperature, and f_x, f_y, and f_z are source terms in the respective directions.

3) **Thermal radiation.** For a system of two surfaces (surface i and j) radiating to each other, the heat transfer rate between surfaces i and j is:

$$Q_{ij} = \sigma \epsilon_i \beta_{ij} A_i (T_i^4 - T_j^4)$$

where σ is the Stefan-Boltzmann constant, ϵ_i is the effective emissivity of surface i, β_{ij} represents the radiation view factor between surfaces i and j, A_i is the area of surface i, and T_i and T_j represent the absolute temperatures of surfaces i and j.

---

3. Calculations of an Air-Core Reactor

(1) Analysis of shielding thickness. To limit the leakage magnetic field inside the shield and use shielding materials efficiently, the shield thickness must be considered. The penetration depth of the shield is expressed as:

$$\delta = \sqrt{\frac{2}{\omega \mu \sigma}}$$

where ω is angular frequency, μ is permeability, and σ is conductivity of the conductor.

Taking a reference line through the shield, the shield depth is based on the magnetic density of this reference line. Where the magnetic flux is high, the magnetic field passes through. This distance is the penetration depth of high magnetic flux. [Figure 4: see original paper] shows the penetration depth and magnetic flux density of the shield when the AC amplitude and frequency are 1500 A and 100 Hz, respectively. Obviously, the penetration depth of the magnetic field shield does not exceed 20 mm. The equation shows that penetration depth increases as frequency decreases. To ensure that the magnetic field does not penetrate the shield, the shield thickness is selected as 20 mm.

A shield is a metallic partition placed between two regions of space, used to control the propagation of electromagnetic fields from one region to the other. The shield changes not only the magnitude of magnetic flux density but also the direction of the magnetic field. [Figure 5a: see original paper] shows the magnetic flux density distribution in the no-shielded condition. It can be seen that the magnetic field around the four corners of the reactor is strongest, while the center is weakest, because magnetic lines form loops from inside to outside. The magnetic flux densities around the output cabinet in single-shielded and double-shielded conditions are shown in [Figure 5b: see original paper] and [Figure 5c: see original paper], respectively. Obviously, magnetic flux density is reduced under shielded conditions, and this reduction is more pronounced with double-layer metal plate shields. When using the double shielding metal plate DT4A/GO (DT4A is closer to the field source), the shielding effect is better.

(2) The influence of shield. [Figure 6: see original paper] represents the schematic drawing of the simulation setup for an air-core reactor shielding system. The reactor is surrounded by a shield positioned between the reactor and output cabinet. The reference point is taken from the coordinate origin, and multiple sets of data can be obtained from this point to evaluate shield performance. The shield can be placed at any position between the reactor and output cabinet, allowing the distance between shield and reference point to be varied.

Magnetic field was measured from the reference point on the output cabinet. The relationship between the cabinet and resultant magnetic field with shields shows linear behavior. The shielding materials evaluated were grain-oriented electrical steel (GO), electrical pure iron (DT4A), and 1008 steel. All materials are 20 mm thick, with a current amplitude of 1500 A flowing through the air-core reactor. As a measure of shielding performance, shielding factor (SF) is used, defined as the ratio of shielded to unshielded magnetic field:

$$\mathrm{SF} = 20\log_{10}\left(\frac{B_{\mathrm{unshielded}}}{B_{\mathrm{shielded}}}\right)$$

Among the three materials, DT4A shows the best shielding effect with a maximum SF_1 of 105 dB, while 1008 steel shows the worst performance with a maximum SF_1 of 54.3 dB. The shielding factor of DT4A is 48.2% higher than that of 1008 steel. The greater the SF value, the better the shielding effect. Considering all aspects, DT4A demonstrates the most effective shielding performance.

For magnetic fields generated by the reactor, the variation of shielding factor as a function of distance is shown in [Figure 7a: see original paper]. The reference point is fixed, and the metal plate moves toward the z-axis at 20 mm intervals. A noticeable reduction of magnetic fields by the shields is observed when current (1500 A, 30 kHz) flows through the reactor. [Figure 7b: see original paper] shows the relationship between SF_2 (double-layer shielding factor) and distance. When the distance between the double-layer shield and reference point varies, SF_2 changes accordingly. SF_2 is inversely proportional to distance: the smaller the distance, the greater the SF_2. Although six combinations yield similar results, the shielding effect of DT4A/GO (DT4A is closer to the field source) is superior. Therefore, DT4A/GO is more appropriate as a shielding material.

EAST fast control power supply provides current with a frequency range of 100 Hz to 30 kHz. [Figure 8a: see original paper] and [Figure 8b: see original paper] show the single and double-layer shielding factors at different frequencies, respectively. In all cases, SF_1 and SF_2 gradually increase with frequency. Among these groups, DT4A/GO exhibits the best shielding effect, reaching a maximum shielding factor of 121.45 dB. The performance of 1008 steel is the worst, with a maximum shielding factor of 72 dB. The double-layer shielding method is more effective for shielding electromagnetic fields across frequency variations.

This result demonstrates that closely adjacent layers act as a single body under the shunt mechanism of magnetic shielding. For example, SF of closely adjacent DT4A/GO depends simply on an averaged permeability of DT4A and GO. On the other hand, DT4A effectively reduces the strong magnetic field first, and then the GO sheet effectively shields the weakened field. In the case of the 1008 steel/GO pair, shielding performance was not improved since the strong magnetic field near the source was too high to be effectively shielded by 1008 steel. From the above analysis, DT4A is the best material in terms of both distance and frequency factors.

(3) Temperature and eddy current loss of output cabinet. The temperature and eddy current loss of the output cabinet can be simulated using ANSOFT and ANSYS Workbench. First, the eddy current density of the cabinet is calculated. Then, these results are imported into ANSYS Workbench. Finally, temperature distribution is obtained by combining the two software packages and adding material properties.

In the no-shielded condition, the eddy current loss and temperature are 1225.2 W and 68.5°C. shows the eddy current loss and temperature of the output cabinet under different shielding materials when pulse current flows into the air-core reactor. It can be seen that temperature under shielded conditions is reduced by 64.2% compared to the no-shielded condition.

The eddy current loss and temperature of the output cabinet under different shielding materials

Material	Eddy current loss (W)	Temperature (°C)
1008 steel	[value]	[value]
DT4A/GO	[value]	[value]
...	...	...

The temperature distributions of the cabinet in shielded (DT4A/GO) and no-shielded conditions are compared in [Figure 9a: see original paper] and [Figure 9b: see original paper]. As can be seen from the temperature distribution diagram, the four sides have relatively high temperatures, which corresponds exactly to the distribution of flux density. Simulation errors for temperature in no-shielded and shielded conditions are 4.5% and 2.2%, respectively. Comparing measured and simulated data demonstrates that the thermal problem can be effectively solved by using shields to absorb strong magnetic fields.

5. Conclusion

In this paper, the magnetic field and thermal field are analyzed through experiment and FEM. Magnetic shielding performances of three shielding materials have been evaluated. In single-layer shielding, DT4A shows the best shielding performance. DT4A/GO is the most effective shield for double-layer configurations. In summary, the minimum temperature of the cabinet dropped to 24.5°C through this measure, effectively solving the thermal problem.

References

[1] Huang Haihong, Wang Haixin, Gao Ge, et al. Application of phase-shift PWM in EAST fast control power supply[J]. IEEE Transactions on Applied Superconductivity, 2010, 20(3): 1671-1674.

[2] Yu Qin, Sebo S A. Calculation accuracy of the planar filament current loop stack model of large air-core reactor coils[J]. IEEE Transactions on Magnetics, 1997, 33(5): 3313-3315.

[3] Yu Qin, Sebo S A. Accurate evaluation of the magnetic field strength of large substation air-core reactor coils[J]. IEEE Transactions on Power Delivery, 1998, 13(4): 1114-1119.

[4] Sergeant P, Dupre L, Melkebeek J. Active and passive magnetic shielding for stray field reduction of an induction heater with axial flux[J]. IEE Proceedings-Electric Power Applications, 2005, 152(5): 1359-1364.

[5] Bavastro D, Canova A, Giaccone L. Numerical and experimental development of multilayer magnetic shields[J]. Electric Power Systems Research, 2014, 116(11): 374-380.

[6] Su Y P, Liu Xun, Hui S Y R. Mutual inductance calculation of movable planar coils on parallel surfaces[J]. IEEE Transactions on Power Electronics, 2009, 24(4): 1115-1123.

[7] Yoshizawa K, Noguchi S, Igarashi H. Influence of planar magnetic property of ferromagnetic shield on high field magnet analysis[J]. IEEE Transactions on Applied Superconductivity, 2011, 21(3): 2088-2091.

[8] Ranran Lin, Haavisto A, Arkkio A. Analysis of eddy-current loss in end shield and frame of a large induction machine[J]. IEEE Transactions on Magnetics, 2010, 46(3): 942-948.

[9] Sergeant P, Hectors D, Dupre L, et al. Thermal analysis of magnetic shields for induction heating[J]. IET Electric Power Applications, 2009, 3(6): 543-550.

[10] Ho S L, Li Y, Lin X, et al. A 3-D study of eddy current field and temperature rises in a compact bus duct system[J]. IEEE Transactions on Magnetics, 2006, 42(4): 987-990.

[11] Ho S L, Li Y, Lin X, et al. Calculations of eddy current, fluid, and thermal fields in an air insulated bus duct system[J]. IEEE Transactions on Magnetics, 2007, 43(4): 1433-1436.

[12] Sergeant P, Adriano U, Dupre L, et al. Active and passive magnetic shielding for stray field reduction of an induction heater with axial flux[J]. IEEE Transactions on Magnetics, 2004, 40(2): 675-678.

[13] Oktem M H, Saka B. Design of multilayered cylindrical shields using a genetic algorithm[J]. IEEE Transactions on Electromagnetic Compatibility, 2001, 43(2): 170-176.

[14] Oktem M H, Saka B. Design of multilayered cylindrical shields using a genetic algorithm[J]. IEEE Transactions on Electromagnetic Compatibility, 2001, 43(2): 170-176.

[15] Ho S L, Li Y, Lin X, et al. Calculations of eddy current, fluid, and thermal fields in an air insulated bus duct system[J]. IEEE Transactions on Magnetics, 2007, 43(4): 1433-1436.

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