Electromagnetic-Thermal-Fluid Coupled Simulation of Variable Impedance Energy-saving Transformer

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New-type power transformer possessing variable impedance and energy-saving is proposed to limit the fault current. A numerical simulation method considered the interaction of electromagnetic, thermal and fluid is applied to calculate the temperature distribution of variable impedance and energy-saving transformer when the three-phase short-circuit fault which has a higher contribution for transformer instabilities occurs at the location of the termination of medium-voltage winding. Based on steady-state coupled field calculation which the temperature not longer rises and the balance of heat production and dissipation at the same time, as the initial value of transient coupled field, thus the transient temperature distribution is calculated. The nonlinear characteristics of material properties depended on temperature are considered in steady-state and transient coupled field calculation. Researches indicated that the transient temperature distribution of variable impedance transformer not exceed its maximum specified limits, meets the requirements of thermal stability.

***Index Terms*—Current-limiting reactor, electromagnetic-thermal-fluid, temperature distribution, thermal stability.**

I. Introduction

NEW-TYPE OF variable impedance and energy-saving transformer was proposed to reduce the impact of fault current in transformer simultaneously [1]. The current limiting ability and overvoltage of transformer possessing variable impedance have been analyzed to assess their potential benefit, whereas other important properties such as mechanics and thermal properties have yet to be analyzed. The temperature rise in the core, the winding of transformer and coils of current-limiting reactor directly influences the durability and lifetime of variable impedance transformer after the fault happened. Meanwhile insulation aging caused by thermal effects in large-scale transformers is one of significant factors which have a negative effect on operation stability. Up to now, the empirical formula and thermal circuit model method are extensively applied to investigate the hot-spot temperature in earlier numerous studies [2]. However there is lack of research on the nonlinear characteristics along with temperature of transformer oil and copper winding, and impossible to determine the location of the maximum temperature. Thus, an electromagnetic-thermal-fluid coupled method is applied to calculate the temperature rise of variable impedance transformer when three-phase short-circuit fault occurs by using numerical simulation method. At the same time, the nonlinear properties of materials depended on the temperature are considered, include the viscosity, thermal conductivity, specific heat capacity of oil and the electrical conductivity of the winding.

II. Mathematical Model

A. Principle of Variable Impedance Transformer

The integration of the current limiting device and traditional transformer constituted the variable impedance transformer can realize impedance of autonomic regulation along with the different working conditions, the principle of variable impedance transformer as shown in fig.1. Current-limiting reactor is short circuit by high-speed switch under normal circumstances. However, high-speed switch opens meanwhile current-limiting reactor is connected to the power system when the fault occurs. The coupled field simulation models of transformer and current-limiting reactor show in fig.2.

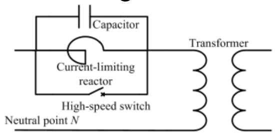

Fig. 1 Principle of variable impedance transformer

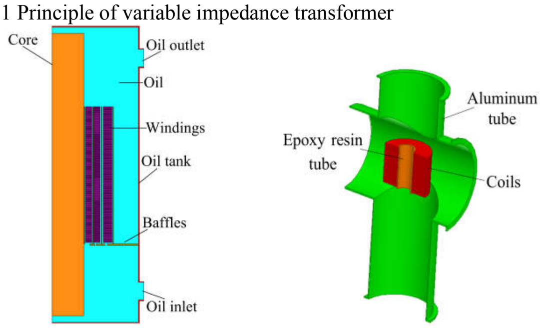

Fig. 2 (a) 2-D model of transformer and (b) 3-D model of current-limiting reactor

B. Magnetic Field Equations

The heat source insides the transformer mainly comes from the core, the windings, aluminum tube and the coil of current-limiting reactor. The transient electromagnetic field of variable impedance transformer observes the Maxwell's equations, can be described as follows.

$$\nabla \times \frac{1}{\mu}(\nabla \times \boldsymbol{A}) = \boldsymbol{J}_s - \sigma \frac{\partial \boldsymbol{A}}{\partial t}$$

where μ, σ, $\boldsymbol{A}$ and $\boldsymbol{J_s}$ are the relative permeability, electrical conductivity, magnetic potential and source current density.

C. Thermal Field Equations

Compared with heat conduction and heat convection, the thermal radiation can be ignored, thus only considering the heat convection and heat conduction in the calculation of temperature field [2].

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \boldsymbol{w} \cdot \nabla T + \nabla \cdot (-k \nabla T) = Q$$
$$q = hS(T - T_{amb})$$

where ρ, C_p, T, $\boldsymbol{w}$, k, Q, h, S and T_{amb} are density, specific heat capacity, temperature, velocity, thermal conductivity, electromagnetic heating, convective coefficient of heat transfer, surface area and environmental temperature.

D. Fluid Field Equations

The properties of transformer oil are slow speed and high viscosity, so the laminar flow model was adopted, considering oil flow influence on the temperature field distribution. The simulation applied finite element method to solve the mass conservation equation, momentum conservation equation and energy conservation equation, described as follows.

$$\begin{cases} \nabla \cdot \rho \boldsymbol{w} = 0 \\ \rho \dfrac{\partial \boldsymbol{w}}{\partial t} = \boldsymbol{F} - \nabla p + u \nabla^2 \boldsymbol{w} \\ \rho C_p \boldsymbol{w} \cdot \nabla T = \nabla \cdot (k \nabla T) + Q \end{cases}$$

where $\boldsymbol{w}$, $\boldsymbol{F}$, p, u *and* Q are velocity, volume force, pressure, viscosity and volume heat source.

III. Method of Electromagnetic-Thermal-Fluid Coupled

Fig. 3 shows the method of the coupling simulation of the electromagnetic, thermal, and fluid fields. First of all, the temperature field of thermal equilibrium state is calculated in steady field, which contributes to obtain the initial value of the transient coupled field. Then the electromagnetic heat generated in the transient electromagnetic field is transferred to the thermal field and fluid field, respectively. The temperature field is calculated to modify material properties that are dependent on temperature accordingly, considering the temperature influence on the velocity simultaneously. Research on the thermal effect of the transformer under short circuit conditions, the computation time is 2s. Considering the interaction between field and field is the superior characteristic of this coupling method. Furthermore, it can be more accurate than weak coupling method.

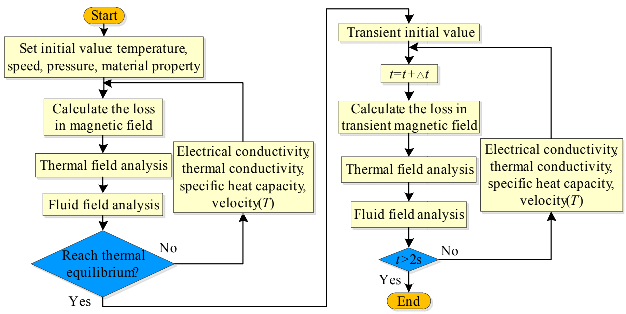

Fig. 3 Flowchart of electromagnetic-thermal-fluid coupled

IV. Result And Discussion

A. Temperature Field of Transformer

Fig. 4 shows magnetic flux density, current density and temperature field at different time, respectively. The eddy current mainly concentrated in the surface of the core. In addition, between high voltage and medium voltage winding is the major distribution area of magnetic flux density. The temperature distribution of thermal equilibrium state is calculated by the steady coupling field. The initial temperature is 313.15K and the maximum of windings is 359.55K locates at the low winding close to the upper. Then the overall temperature distribution with higher shows the tendency of increase when the short-circuit fault occurs at 2s. While for transformer cores and windings, the maximum temperature are 389.49K and 404.47K, respectively, meets the requirements of thermal stability.

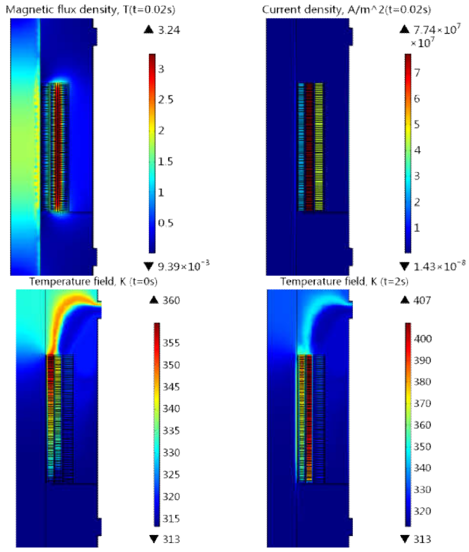

Fig. 4 Magnetic flux density, current density and temperature distribution at different time

B. Temperature Field of Current-limiting Reactor

The coils of current-limiting reactor using epoxy resin casting are placed within the aluminum tube to prevent electromagnetic effects of reactor from the traditional transformer. Fig. 5 shows the magnetic flux density, current density, electromagnetic heat and temperature distribution, respectively. The initial temperature is 273.15K on account of the reactor is not work under normal condition. The current density and electromagnetic heating mainly distributed in copper coils and the surface of aluminum tube contribute to the distribution of temperature. The maximum of aluminum tube and coils are 487.25K and 392.95K, not exceed its maximum specified limits, meet the requirements of thermal stability.

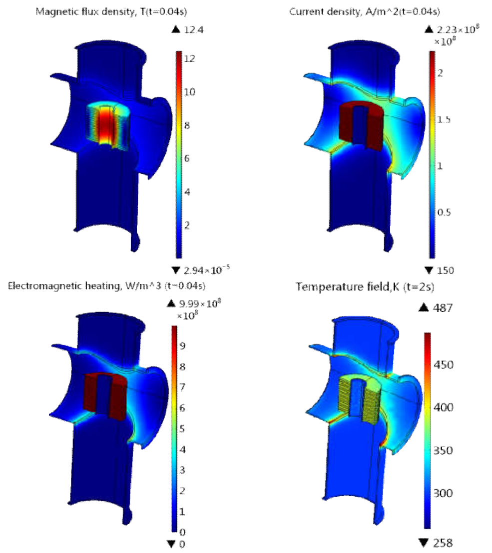

Fig. 5 Magnetic flux density, current density, electromagnetic heating and temperature distribution of current-limiting reactor

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