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Oil Movement In Closed Environment Of Distribution Transformer Tank Problem Simulation

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A B S T R A C T

The objective of the study is to solve the general equation of transformer cooling oil movement inside the tank in the form, suitable for further use as algorithmic mathematical model and implementation of thermo-convective method for determination the initial value of oil velocity in one of its movement sections and application of which improves existing method of distribution transformers project synthesis at the level of solving the magnetic circuit and windings thermal state calculation problem. The mathematical model of natural movement of oil in the distribution transformer tank in the form of Navier - Stokes differential equation with assumptions that formed its basis in software environment COMSOL Multiphysics Femlab 3.0 in the Fluid Dynamics - Incompressible Navier - Stokes section is considered. For non-zero initial independent value of cooling substance speed obtaining as an annex to the Navier - Stokes equation, the results of experimental tests of cooling agents massive expenditure in a separate section of its movement circuit in a sealed system using thermoconvective method were utilized. Thermo-convective method application for determining the non-zero initial value of oil velocity in the radiator pipe section - along the contour of its movement is substantiated. The velocity calculation of transformer oil which cools the active part of the transformer, with sources of heat flux in the magnetic circuit and windings is performed. The obtained equations and results from the use thermoconvective method will be useful for solving of engineering problems in the field of electromechanical engineering and thermal calculations which are based on the calculation results of moving environment speed.

Key words: *Simulation; Distribution Transformer; Oil Velocity; Thermo-convective method; magnetic circuit*

Introduction

Design synthesis of distribution transformers with the capacity of 25...1000 kWA, as a solution of subordinate problems set while performing electromagnetic calculation on determined complex optimality criterion at the level of thermal calculation is based on the necessity of taking into account the velocity of cooling oil movement and emergence of heat exchange by convection inside the leakproof tank, the source of which is the active power losses in the magnetic circuit and windings.

The existing approach Gresho & Sani, (2000); Pironneaute, (1989); Rose, et al., (2000) to determination of the thermal load of transformers is focused on the past experience of their operation, or, in some cases, on the calculation of the transformer thermal state on the basis of the method of equivalent thermal schemes of its replacement.

This method is very approximate because empirically it takes into account not only the speed of the oil on the important directions of motion in the artificially formed hydraulic system but also heat transfer by convection between the complex configuration of the active part of transformer with oil which cools it in the leakproof tank and in coolers - radiators. The method does not take into account the pressure of oil circulation in the internal volume of the tank and, especially in certain areas of the circuit of its movement which have non- identical hydraulic resistances.

The aim of the study is to solve the general equation of transformer cooling oil movement inside the tank in the form, suitable for further use as algorithmic mathematical model and implementation of thermo-convective method for determination the initial value of oil velocity in one of its movement sections and application of which improves existing method of distribution transformers project synthesis at the level of solving the magnetic circuit and windings thermal state calculation problem. The urgency of the problem is related to the production of modern distribution transformers in which the capacity ratio to weight of active materials is crucial.

It is known that reliability and regulatory insulation durability, and therefore regulated by the transformer manufacturer operating conditions, in general, depends on the exact choice of the transformer electromagnetic load in terms of current density in the windings and magnetic induction in the magnetic circuit.

The topological analysis of the distribution transformer with flat bladed structure of magnetic circuit indicates that the location of its phase windings relative to the upper yoke is not similar. To the vertical movement of oil along the side surfaces of windings, especially in the middle phase B, the magnetic circuit yoke prevents twice and, therefore, presumably it will have a greater temperature than phases A.C that are partially protruding from the yoke.

If proceed from approximate equation for determining expiration date of Class A isolation according to the expression

$$\tau = 7{,}15 \cdot 10^4 \cdot e^{-0{,}088\vartheta}$$

where ϑ - insulation temperature, it is clear that overheating even on a separate section of the winding reduces the useful life of the transformer as a whole.

Materials And Methods

Differential equation of oil movement

To consider the generalized differential Navier-Stokes equation with assumptions that are embodied into its mathematical model, the analysis of oil natural movement in the transformer tank closed environment is usually applied, Godina, R. et al. (2015). It is known that the presence of internal sources of heat flow in the windings and magnetic circuit the temperature field distribution $T_{i,j,k} = f(\upsilon_{i,j,k}; \partial\upsilon_{i,j,k} / \partial\tau)$ is determined by the thermodynamic oil pressure p and by the dynamics of its flux, where -$T_{i,j,k}$ $\upsilon_{i,j,k}$ - oil temperature and velocity, τ - cooling time. The viscosity γ as oil thermo-physical property is a non-linear temperature dependence. It influences the oil movement speed and acceleration $(\upsilon_{i,j,k}; \partial\upsilon_{i,j,k} / \partial\tau) = f(\gamma)$ because they depend on it.

, solving the problem of movement and transfer of heat by oil convection reduces to the iterative solution of nonlinear problem, namely cooling substance field velocities at a constant its viscosity $\gamma = const$ determination; calculation according to its parametrsof the substance temperature field; viscosity specification. Solving of the problem is repeated in iterative cycle, but on condition of simulation results convergence obtaining, and ends in terms of relative difference of temperature values obtained in previous and subsequent iterations.

Ttransfer of heat by oil is determined by conservation laws of mass, momentum and energy and has the form of differential equations, which are adapted to the elementary volume of the environment through the surface of which the movement is taking place. Solving differential equations by means of their integration allows to determine the exchange of heat by convection and are usually carried out variational methods or numerically - by the finite elements method, Reddy, (2006); Zienkiewicz, et.al. (2005); Bathe, (2006), which applies the transformation of differential equations into matrix of their algebraic counterparts. Each cell formed in a grid should be characterized by physical and functional properties of substance, should have a certain size and be connected with neighboring cells by boundary conditions.

For obtaining the generalized equation of oil motion with density ρ, through area of surface S, which limits the certain fixed volume V, we consider the equation of its mass preservation in a small period of time dτ and, if relevant, the formation of additional mass by inside source, namely in the form of component $\frac{d}{d\tau}\left(\int_V \rho dV\right)$ (in closed volume there is no additional mass). Considering that oil transfer is made up by the chaotic movement of its molecules and, at the same time, by the movement of all oil by convection, the transfer of molecules is estimated by their density $\vec{J}_\rho$ directed on the normal $\vec{n}$ to the isoconcentration surface S of the elementary volume V, and by convection – on the substance flow density $\vec{\upsilon}\rho$, where $\vec{\upsilon}(u, v, z)$ - linear oil velocity in three coordinates.

Thus, through elementary surface dS of elementary volume dV, by both types of substance mass transfer its leakage of total weight $\left[-\int_S \vec{J}_\rho \cdot \vec{n} dS - \int_S \rho(\vec{\upsilon} \cdot \vec{n}) dS\right]$ is carried out. If inner source of oil is available its amount $\int_V I_\rho dV$ is supplied to the volume, where - I_ρ capacity of the substance source. Making the transition from surface integrals to integrals on the volume (Ostrogradskii - Gauss Theorem) and applying conservation of substance mass in volume law, we obtain balance equation in the expression

$$\frac{d}{d\tau}\int_V \rho dV = -\int_V \nabla \cdot (\rho\vec{\upsilon}) dV - \int_V \nabla \cdot \vec{J}_\rho dV + \int_V I_\rho dV, \qquad (1)$$

where gradient vector $\nabla = \vec{i}\,\frac{\partial}{\partial x} + \vec{j}\,\frac{\partial}{\partial y} + \bar{k}\,\frac{\partial}{\partial z}$, and set $\nabla \cdot \vec{\upsilon}$ - is the divergence of oil speed.

Since the integration in the equation is carried out on the joint volume, it is simplified to general integral:

$$\int_V \left(\frac{d\rho}{d\tau} + \nabla \cdot (\rho\vec{\upsilon}) + \nabla \cdot \vec{J}_\rho - I_\rho \right) dV = 0. \qquad (2)$$

After integration of the equation (2), it transforms to

$$\frac{d\rho}{d\tau} + \nabla \cdot (\rho\vec{\upsilon}) = -\nabla \cdot \vec{J}_\rho + I_\rho. \qquad (3)$$

The resulting oil mass balance equation in transformer shows that in the case of ignoring the movement of its molecules $(\vec{J}_\rho = 0)$ and at the absence of inner sources of oil $(I_\rho = 0)$, it is simplified to

$$\frac{d\rho}{d\tau} + \nabla \cdot (\rho\vec{\upsilon}) = 0. \qquad (4)$$

When examining sustainable mode of oil movement the local derivative $\frac{d\rho}{d\tau} = 0$ and equation (4) is simplified to

$\nabla \cdot (\rho\vec{\upsilon}) = 0$ or

$$\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho k)}{\partial z} = 0. \qquad (5)$$

Because the liquid oil does not compress, and thus its density is $\rho = const$, the equation (5) is simplified to $\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial k}{\partial z} = 0$, that is adequate even in the case of oil transfer with minor modifications of its temperature and pressure in the enclosed volume of the tank.

Equation (5) indicates that for taking into consideration the oil mass movement it is necessary to know its speed, and therefore, the next stage of the one-component substance movement problem formalization is to solve the differential equation of power impulse κ or momentum transfer. Differential equation of power impulse transfer is derived from the expression (4), if the mass of a substance that is transferred is associated with the amount of its movement (power impulse) per volume unit proceeding from Newton's second law

$$m\vec{a} = m\frac{d\vec{\upsilon}}{d\tau} = \frac{d(m\vec{\upsilon})}{d\tau} = \frac{d\vec{\kappa}}{d\tau} = \vec{F}. \qquad (6)$$

In respect that oil density gradient is proportional to the divergence of its speed $\vec{\rho} \equiv \rho\vec{\upsilon}$, the total change of momentum in the volume will match to the power which force on the elementary volume. Thus, the speed of power impulse change will be determined by the sum of: the surface integral from flux momentum density that is transferred by substance convection via boundaries of specified elementary volume; the surface integral of the mechanical stress tensor (Cauchy problem) - normal and tangential that attributes on three orthogonal planes of the volume and is specified by mass force vector $\vec{F}_{i,j,k}$ acting on oil mass unit, i.e. as $\bar{\sigma}_{i,i} = \frac{dF_{i,j,k}}{dS_i}$, and volume integral of the full vector of gravitational force.

To the surface forces that arise under the action of neighboring elementary volumes with oil correspond the stresses acting on six surfaces of the defined cubic volume. Thus the expression (1) as for transfer of substance momentum will look like

$$\frac{d(\rho\vec{\upsilon})}{d\tau} + \nabla \cdot (\rho\vec{\upsilon}\vec{\upsilon}) = -\nabla \cdot \bar{\bar{\sigma}} + \rho\vec{F}, \qquad (7)$$

but in this case $\vec{J}_\rho = \bar{\bar{\sigma}}$, a $I_\rho = \rho\vec{F}$, where $\bar{\sigma}$ - stress tensor.

Performing substitution of stress tensor $\bar{\bar{\sigma}}$ by the sum of spherical tensor associated with the change of the elementary volume under the substance thermodynamic pressure p and stress deviator (viscosity stress tensor) associated with the change of elementary volume form because of its deformation under the influence of substance γ viscosity change, therefore its flux, i.e. in the form $\overline{\overline{\sigma}} = p\overline{\overline{\delta}} + \overline{\overline{\gamma}}$, we get the differential equation of force impulse transfer in the form

$$\frac{d(\rho\vec{\upsilon})}{d\tau} + \nabla \cdot (\rho\vec{\upsilon}\vec{\upsilon}) = -\nabla p - \nabla \cdot \overline{\overline{\gamma}} + \rho\vec{F} \ . \qquad (8)$$

In the equation $\overline{\overline{\delta}} = 1$ is Kronecker delta tensor (the sum of two variables - the identity and diagonal sparse matrix). The left side of (8) raises the sum of local change of momentum in time and as a consequence of heat transfer by convection. The right side considers change of momentum influenced by changes in pressure, internal friction from substance viscosity change and by external forces action (gravity in the case under consideration).

Equation (8) is not self-sufficient to solve, because it has two unknown quantities - the substances velocity vector $\vec{\upsilon}$ and stress tensor or molecular flow viscosity, which is taken into consideration by viscosity γ.

Based on the assumption that the oil is isotropic substance that is with the linear law of transfer of impulse forces, to reduce the number of unknowns in differential equation rheological equation is used that establishes the relationship between of stress deviator $\nabla \cdot \overline{\overline{\gamma}}$ (tensor of viscous stresses) and strain velocity tensor of elementary volume $\nabla \cdot (\rho\vec{\upsilon} \cdot \vec{\upsilon})$. In rheological equation the stress tensor of viscous isotropic liquid flows is considered as the sum of two components - isotropic and non-isotropic and with their relationship in expression (9) as one to two thirds

$$\overline{\overline{\sigma}} = [p - \varphi(\nabla \cdot \vec{\upsilon})]\overline{\overline{\delta}} + \overline{\overline{\gamma}} \ , \qquad (9)$$

where φ - volumetric viscosity of cooling oil, which is usually neglected due to small values. In laminar flow of oil, as in the transformer tank, its viscosity is associated with velocity by Newton's law in the form $\gamma = -\eta \frac{\partial \upsilon}{\partial n}$, in which η - oil dynamic viscosity; υ - oil velocity in the direction of momentum; n - normal to the direction of velocity. For the general case the rheological equation is used in the form

$$\overline{\overline{\gamma}} = -\eta\left[\nabla \cdot \vec{\upsilon} + (\nabla \cdot \vec{\upsilon})^T\right] + \frac{2}{3}\eta(\nabla \cdot \vec{\upsilon})\overline{\overline{\delta}} \ , \qquad (10)$$

where $(\nabla \cdot \vec{\upsilon})^T$ - tensor, adjoint from tensor $\nabla \cdot \vec{\upsilon}$ (transpose).

Taking into consideration (10), the differential Navier-Stokes equation which arises from the equation of force impulse transfer (8) gets the form

$$\frac{d(\rho\vec{\upsilon})}{d\tau} + \nabla \cdot (\rho\vec{\upsilon}\vec{\upsilon}) = -\nabla p + \nabla \cdot \left\{\eta\left[\nabla \cdot \vec{\upsilon} + (\nabla \cdot \vec{\upsilon})^T\right]\right\} - \nabla \frac{2}{3}\eta(\nabla \cdot \vec{\upsilon}) + \rho\vec{F} \ . \qquad (11)$$

Because the oil does not compress, its density $\rho = const$, velocity of divergence $\nabla \cdot \vec{\upsilon} = 0$, and therefore equation (11) simplifies to

$$\frac{d(\rho\vec{\upsilon})}{d\tau} + \nabla \cdot (\rho\vec{\upsilon}\vec{\upsilon}) = -\nabla p + \nabla \cdot \left\{\eta\left[\nabla \cdot \vec{\upsilon} + (\nabla \cdot \vec{\upsilon})^T\right]\right\} + \rho\vec{F}, \qquad (12)$$

but if examining the sustainable process of substance movement, for which local derivative $\frac{d\upsilon}{d\tau} = 0$, it takes the final form (13)

$$\nabla \cdot (\rho\vec{\upsilon} \cdot \vec{\upsilon}) = -\nabla \cdot p + \nabla \cdot \left\{\eta\left[\nabla \cdot \vec{\upsilon} + (\nabla \cdot \vec{\upsilon})^T\right]\right\} + \rho\vec{F} \qquad (13)$$

or as Navier - Stokes equation

$$\rho(\nabla \cdot \vec{\upsilon})\vec{\upsilon} = \nabla \cdot \left[-p + \eta\left(\nabla \cdot \vec{\upsilon} + (\nabla \cdot \vec{\upsilon})^T\right]\right] + \rho\vec{F} \ . \qquad (14)$$

Dynamic viscosity η, which appears in the Navier - Stokes equation in the case of isothermal flow is an unvariable parameter and generally depends on the temperature and composition of oil. In fact, in physics, Navier - Stokes vector equation is a system of three scalar equations with three variables of velocity that are determined and pressure. To solve the problem, additional – the fourth equation of mass conservation law - the equation of continuity is used, which in the case of oil, that is not compressed, has the form $\nabla \cdot \vec{\upsilon} = 0$. As initial conditions the equation $\vec{\upsilon}(\vec{x}) = \vec{\upsilon}^0(\vec{x})$ is used, in which $\vec{\upsilon}^0(\vec{x})$ - is the assigned smooth vector-function that responds the equation of no-dissociation $\nabla \cdot \vec{\upsilon}^0 = 0$.

So, considering the transformer with cooling by means od oil movement we should treat it as a hydraulic system that requires numerical analysis at design level by solving Navier - Stokes equation.

Results And Discussion

Method of oil movement velocity initial value determination

Mass flow of oil along the ring contour of its cooling –is a very important parameter in hydrodynamics, and one that is associated with its movement under the influence of formed internal forces - pressure difference in height of the transformer tank or on some of its sites, and force of gravity. The hydrodynamic coolant flow pattern and heat transfer phenomenon when it moves in the radiator (tube) is difficult. The impact of the physical process of braking that occurs when the coolant contacts with the wall due to viscous forces gradually extends to the whole cross section of the pipe, which leads to uneven distribution of velocity and temperature of the coolant in section of pipe (parabolic in laminar flow). For the experimental determination of the mass flow of a substance flowmeters are used. The lineup of flow meters includes: mechanical meters; lever-pendulum; pressure difference transducers (Venturi effect); optical; ultrasonic; electromagnetic; coriolis; vortex; label and heat. The selection of the necessary flowmeter is carried out taking into condideration the operational conditions of the investigating device, the requirements for precision of carrying measurements and the possibility of its use without direct intervention into closed sealed system. The implication of this is that the most practical are the heat flowmeters, namely their modification – thermo-convective samples. Additionally, they are divided into quasi-calorimetric (flow temperature difference or heating power of thermal element is measured) and the thermal boundary layer (flow temperature difference or heating power is measured). Thermal flowmeters are distinguished by: a method of heating; heater location (outside or inside the pipeline); the nature of the functional relationship between the mass flow of moving substance and the measured value.

The most widely spread value at assessment of expenditures is volumetric flow of substance, as a product of the substance flow average velocity υ on active cross-sectional area of the pipeline S , i.e. in the form $G = \upsilon S$. Together with it, the concept of mass flow $G_m = \rho G,$ is used, where $\rho -$ density of substance. To the composition of thermoconvective device two temperature gauges (sensors) are included, which are installed along the direction of the oil – before and after the thermal element – heat insulated spiral of heater.

If we will ignore the loss of heat formed by thermal element into the environment – air, thermal conductivity of which is two thousand times lower than the conductivity of radiator steel pipe, the heat balance equation between formed heat thermal element and given to the oil flow in the pipeline, will be the following

$$q_t = k_0 G_m c_p \Delta t, \qquad (15)$$

where k_0 – amendment that takes into account the uneven temperature distribution in the useful cross section the pipeline; c_p – specific heat of transformer oil, which ranges between 1,5…2,5 к/J/(kg·ºC) – at constant oil pressure and known temperature – 35…135°C); $\Delta t = t_1 - t_2$ – difference of temperature gauges – sensors readings , where t_1 and t_2 - temperatures before and after the thermal element along the flow of oil in the pipe, ºC.

Typically the thermal element is electrical heater (coil of 10 turns of nichrome) in which the power of heat flow, at the direct current power supply is

$$q_t = I^2 R, \qquad (16)$$

where I - operating amperage of power source, A; R - active resistance of thermal element spiral segment, Ω. Joint solution of the equations (15) and (16) provides static characteristic of thermoconvective device transformation, which connects the gauges temperature difference with mass flow in the oil radiator pipe in the form of expression

$$G_m = \frac{I^2 R}{k_0 c_p \Delta t} \ . \qquad (17)$$

From (17) follows that the oil velocity in the radiator pipe is

$$\upsilon = \frac{G_m}{\rho S}, \qquad (18)$$

and its value can be applied initial speed (independent non-zero initial condition) in the Navier - Stokes equation of gas dynamics, i.e. as $\vec{\upsilon}^0(\vec{x})$.

The executed numerical simulation of the Navier - Stokes equation and proposed for its applying thermo-convective method for determining the initial value of the velocity along the circuit of cooling substance in a sealed environment, where the movement of heat is taking place, allows close approach to the calculation of the thermal state of various electromagnetic devices - transformers, electrical machines etc. Velocities of the coolant movement, obtained by using these equations, and on their (velocities) basis, temperature fields at the most critical according to the temperature areas of electromagnetic devices in the future should be laid as the basis of electromagnetic calculations, namely when selecting linear loads - magnetic induction, currents density and so on. Such approach improves the adequacy of devices electromagnetic calculation, and in the conditions of their variable load during operation - has no alternative. For the first time it is proposed to consider the electromagnetic devices on the example of distribution transformer as a system composed of three sub semi-systems - hydraulic, thermal and electromagnetic.

Conclusion

The detailed description of obtaining of mathematical model of cooling substances movement –oil in the distribution transformer tank enclosed volume - has been completed. Its full convergent with the Navier - Stokes equation which is applied in COMSOL software environment, in particular, in its section - fluid dynamics has been proved.

For non-zero initial independent value of cooling substance speed obtaining as an annex to the Navier - Stokes equation, the results of experimental tests of cooling agents massive expenditure in a separate section of its movement circuit in a sealed system using thermoconvective method were utilized.

The obtained equations and results from the use thermoconvective method will be useful for solving of engineering problems in the field of electromechanical engineering and thermal calculations which are based on the calculation results of moving environment speed.

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