Analyses of Three-Dimensional Eddy Current Field and Thermal Problems in an Isolated Phase Bus

S. L. Ho, Y. Li, Edward W. C. Lo, J. Y. Xu, and X. Lin

***Abstract*—In this paper, a three-dimensional eddy current field model to calculate the eddy current losses in an isolated phase bus (IPB) is proposed. The rise in temperature of the conductors and enclosures in the IPB are evaluated using the proposed set of thermal equations. Computation results of a 20-kV/12.5-kA IPB scheme are reported to validate the algorithm. The withstand voltage ability and short-circuit stress of the IPB are also verified. The agreement between the computation and test results confirm that the design scheme being studied is successful and practical.**

***Index Terms*—Eddy currents, electromagnetic fields, isolated phase bus (IPB), thermal problem.**

I. Introduction

THE MODULAR noncontinuous isolated phase buses (IPBs) are busbars in which the consecutive sections of the enclosure surrounding the conductors of the same phase are electrically insulated from each other. Sections of the enclosures encompassing the three different phases are cross connected to each other at the extremities of the section. With this arrangement, the induced current is unable to flow longitudinally across the enclosure joints. Moreover, each enclosure section is connected to a ground bus at one point only [1]. Such IPB arrangements are commonly used to carry large currents from the generator in a power station to the distribution transformer. The conductors and enclosures of the IPB are usually made of inexpensive aluminum [2]. Because the IPB carries large electric current with high voltage, it is important to address the problems of induced magnetic heating and induced circulating current in the enclosures [1], [2]. In other words, it is important to determine the main dimensions such as the diameter and wall thickness of the bus conductors and enclosures. In the past, the main design and calculating method is to use lumped circuits together with empirical curves [1]–[3]. Recently, the two-dimensional finite element method (FEM) has been used to calculate and analyze the magnetic field distribution in IPB [4]. However, the IPB design is a three-dimensional (3-D) problem with eddy current field, induced magnetic heating, thermal behavior of the conductors, withstand voltage, and short-circuit force. A thorough investigation of these problems is, thus, important in the optimization studies of IPBs in industry. In this paper, a 3-D eddy current field model to calculate the eddy current losses is described. The temperature rises of conductors and enclosures in the IPB are determined by solving the thermal equations. A good 20-kV/12.5-kA IPB bus scheme is studied and described. The withstand voltage ability and short-circuit stress of the IPB are also verified. The results of computation and test show that the design scheme presented in this paper is practical and successful.

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S. L. Ho and E. W. C. Lo are with the Department of Electrical Engineering, Hong Kong Polytechnic University, Kowloon, Hong Kong (e-mail: eeslho@polyu.edu.hk; eewclo@ polyu.edu.hk).

Y. Li is with the Shenyang Polytechnic University, Shenyang, China (e-mail: liyanty@yahoo.com).

J. Y. Xu and X. Lin are with the Department of Electrical Engineering, Shenyang Polytechnic University, Shenyang, China (email: syxjy@sohu.com; xuzhaoy@mail.sy.ln.cn).

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II. Formulations

A. 3-D Eddy Current Field Model

To analyze the losses and thermal problem in the IPB, the 3-D open boundary eddy current field satisfying the following equations have to be evaluated first [5]–[7]:

$$\nabla \times \nu \nabla \times \mathbf{A} = -\sigma \frac{\partial \mathbf{A}}{\partial t} - \sigma \nabla \phi \tag{1}$$

$$\nabla^2 \phi + \frac{\partial}{\partial t} \nabla \times \mathbf{A} = 0. \tag{2}$$

Introducing the Coulomb gauge condition and assuming the conductivity is constant, (1) and (2) can be written as

$$\nabla \times \nu \nabla \times \mathbf{A} = -\sigma \frac{\partial \mathbf{A}}{\partial t} + \mathbf{J}_s. \tag{3}$$

Assuming that the current is sinusoidal, the following equations can be obtained:

$$\nabla \times \nu \nabla \times \dot{\mathbf{A}} = \dot{\mathbf{J}}_s - j\omega\sigma\, \dot{\mathbf{A}}. \tag{4}$$

The boundary conditions are

$$\begin{aligned} s_1 &: \dot{\mathbf{A}} = \dot{\mathbf{A}}_0 \\ s_2 &: \mathbf{n} \times \nu \nabla \times \dot{\mathbf{A}} = \mathbf{0}. \end{aligned} \tag{5}$$

The weighted residue equation can be written as

$$\int_\Omega \left[\dot{\mathbf{W}} \cdot (\nabla \times \nu \nabla \times \dot{\mathbf{A}}) + \dot{\mathbf{W}} \cdot j\omega\sigma\, \dot{\mathbf{A}} - \dot{\mathbf{W}} \cdot \dot{\mathbf{J}}_s \right] d\Omega = 0 \tag{6}$$

where W is the weighted function. Using integration by parts and the Galin transfer formula, the following is obtained:

$$\int_\Omega \left[\dot{\mathbf{W}} \cdot (\nabla \times \nu \nabla \times \dot{\mathbf{A}}) \right] d\Omega = \int_\Omega \nu \nabla \times \dot{\mathbf{W}} \cdot \nabla \dot{\mathbf{A}} d\Omega + \int_S \dot{\mathbf{W}} \cdot (\mathbf{n} \times \nu \nabla \times \dot{\mathbf{A}}] ds = 0. \tag{7}$$

Introducing the boundary condition, (7) can be expressed in the following form:

$$\int_\Omega \left[\dot{\mathbf{W}} \cdot (\nabla \times \nu \nabla \times \dot{\mathbf{A}})\right] d\Omega + \int_\Omega j\omega\sigma \mathbf{W} \cdot \dot{\mathbf{A}} d\Omega = \int_\Omega \dot{\mathbf{W}} \cdot \dot{\mathbf{J}}_s] d\Omega. \quad (8)$$

With a total of n nodes in the solved area when FEM is used, one can define a function W which is the primary function along the x, y, z directions and the corresponding $3n$ order equations can then be derived. By solving the equations, the magnetic flux, eddy current, and losses can be calculated.

B. Thermal Equilibrium Equations

After the losses of the conductors and enclosures are found, their corresponding temperature rises can be computed by solving the following thermal equilibrium equations [2]:

$$P_M = Q_{MF} + Q_{MD} \quad (9)$$
$$P_K + P_M = Q_{KD} + Q_{KF} \quad (10)$$

where P_M and P_K are the power losses in Joule per meter in, respectively, the phase conductor and the phase enclosure. Q_{MF} and Q_{MD} are, respectively, the heat losses from the conductor to the enclosure by radiation and heat exchange. Q_{KD} and Q_{KF} are, respectively, the heat loss from the enclosure to the surrounding air by radiation and heat exchange. Radiation heat loss per single phase conductor per meter is

$$Q_{MF} = C_0 \varepsilon_n \pi D_M \left[\left(\frac{273+\theta_M}{100}\right)^4 - \left(\frac{273+\theta_K}{100}\right)^4\right] \quad (11)$$
$$\varepsilon_n = \frac{1}{\frac{1}{\varepsilon_M} + \frac{D_M}{d_K}\left(\frac{1}{\varepsilon_K} - 1\right)} \quad (12)$$

where C_0 is the radiation factor, D_M is the conductor outside diameter, θ_M is the calculated temperature of conductor in degrees Celsius, θ_K is the computed temperature of the enclosure in degrees Celsius, d_K is the enclosure inside diameter, ε_n is the emissivity of the system, and ε_M and ε_K are, respectively, the emissivity of the conductor outside surface and enclosure inside surface.

The convection heat loss per meter of single phase conductor is

$$Q_{MD} = \frac{\theta_M - \theta_K}{\frac{1}{2\pi\lambda_e} \ln \frac{D_K - 2c_K}{D_M}} \quad (13)$$

and λ_e is the equivalent heat coefficient

The radiation heat loss per meter per single phase of the enclosure is

$$Q_{KF} = \varepsilon_K C_0 \pi D_K \left[\left(\frac{\theta_K+273}{100}\right)^4 - \left(\frac{\theta_0+273}{100}\right)^4\right] \times \left(1 - b\, \sin^{-1} \frac{D_K}{2S}\right) \quad (14)$$

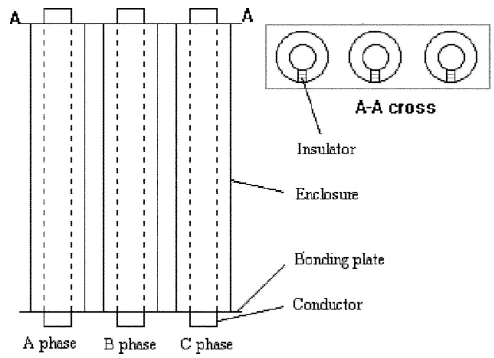

Fig. 1. Structure of an IPB.

TABLE I
MAIN DESIGN SIZE AND CALCULATED RESULTS IN A 20-kV/12.5-kA IPB

Layout arrangement scheme	1	2	3	4	5
Rated current I (kA)	12.5	12.5	12.5	12.5	12.5
Outside diameter of bus conductor D_m (mm)	500	500	500	500	500
Conductor wall thickness C_m (mm)	16	16	16	16	16
Enclosure outside diameter D_k (mm)	900	900	950	1000	1050
Enclosure wall thickness C_k (mm)	9	7	7	6	5
Space of conductor center lines S (mm)	1400	1400	1400	1400	1400
Loss in conductor P_m (W per meter per phase)	271.7	273	272.4	272.7	272.6
Loss in enclosure P_k (W per meter per phase)	216.4	273.4	257.9	285.6	326.1
Total Loss in bus P (W per meter per phase)	488.1	546.4	530.3	568.3	598.7
Temperature in conductor Θ_m (°C)	78	80	79	79	79
Temperature in enclosure Θ_k (°C)	59	60	59	60	60
Appraisal of the scheme	Fair	Good	Fair	Fair	Fair

Note: conductor and enclosure are both fabricated with aluminum

where ε_K is the emissivity of the enclosure outside surface covered by oil paint and, hence, the corresponding ε_K is assumed to be 0.85. θ_0 is the ambient temperature in degrees Celsius and b is the correction radiating coefficient.

The natural convection heat loss per meter per single phase of the enclosure is

$$Q_{KD} = \alpha_{KD} \pi D_K (\theta_K - \theta_0) \quad (15)$$

where α_{KD} is the convection heating coefficient.

III. DESIGN OF A 20-kV/12.5-kA IPB

A typical 20-kV/12.5-kA IPB structure as shown in Fig. 1 has been designed. Its eddy current field, losses, and temperatures are computed using the proposed algorithm. Since the hot spots usually appear in the middle phase conductor and its nearby enclosure, the middle phase bus is selected as the model being studied. Table I gives the losses as well as the temperatures of the conductor and enclosure in different conductor layout schemes. Note that the layout Scheme 2 is the best arrangement which is commonly used in the industry. With a maximum ambient

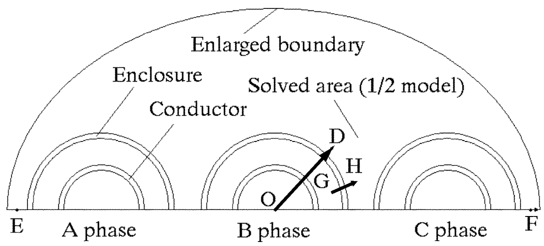

Fig. 2. Diagrammatic sketch of the cross section of the IPB.

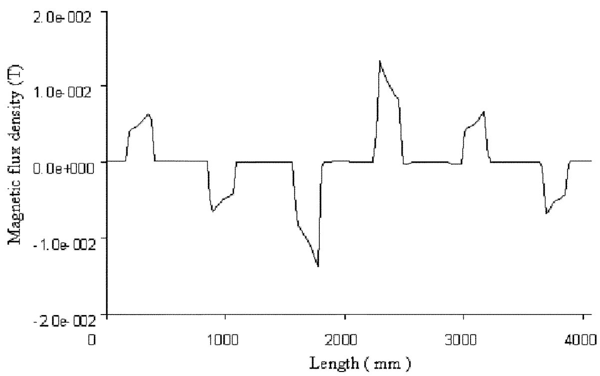

Fig. 3. Distribution of the magnetic flux density along the EF path in the three phase buses when $\omega t = 90°$.

temperature of 40 °C, the maximum temperature limit of the hottest spot in the enclosure and conductor is 70 °C and 90 °C, respectively.

It is assumed the currents flowing in the conductor in the selected design are $i_a = 17.675 \sin(\omega t + 60°)$ kA, $i_b = 17.675 \sin(\omega t + 0°)$ kA and $i_c = 17.675 \sin(\omega t - 60°)$ kA.

The computed induced currents in the corresponding enclosures of the three phases are $i_a = 17.634 \sin(\omega t - 60.7°)$ kA, $i_b = 17.646 \sin(\omega t + 181.6°)$ kA and $i_c = 17.50 \sin(\omega t + 58.88°)$ kA.

Apart from a reversal in phase, the currents in the enclosures are approximately equal to those in the phase conductors.

Fig. 2 gives the diagrammatic sketch of the cross section of an IPB. With Fig. 2 as the reference, Fig. 3 gives the distribution of the magnetic flux density along the electric field (EF) path in the three phase buses at $\omega t = 90°$ when the current in the B Phase reaches its instantaneous maximum. It is found that the maximums magnetic flux densities in every phase bus are on the outside surface of the conductors. The maximum magnetic flux density in the B Phase bus is about 0.014 T and the distributions of magnetic flux density in Phases A and C are almost the same with a maximum of about 0.007 T.

Fig. 4 illustrates the distribution of the current density along the GH path in the B Phase enclosure, as shown in Fig. 2. Curve 1 shows the magnitude of current with a maximum value 0.78MA/m^2, Curves 2 and 3 give the currents of the B Phase enclosure when $\omega t = 0°$ and $\omega t = 90°$, respectively.

Figs. 5 and 6 illustrate the distribution of the magnetic flux density in the bus and the current density distribution in the three-phase enclosures.

In order to check whether the IPB complies with the design, a prototype that is shorter than the real bus is built and tested. The results of the test indicate that the average temperature in all the measured points in the bus conductor is 79.04 °C which agrees with the calculated result. The average temperature in all the measured points in the enclosures is 59.13 °C which again agrees with the predicted value.

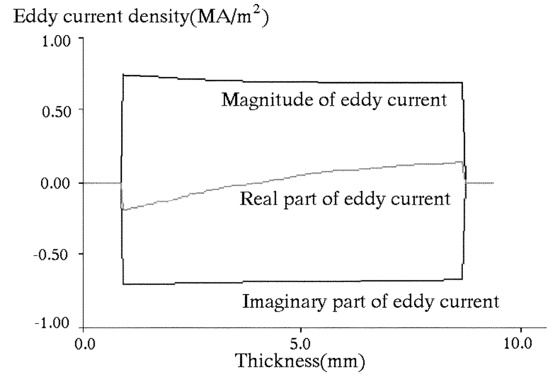

Fig. 4. Distribution of current density in the enclosure wall.

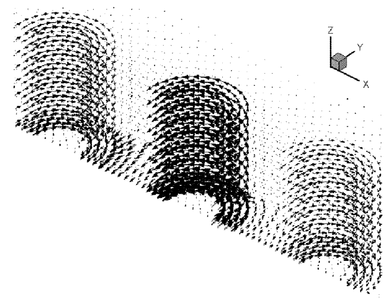

Fig. 5. Distribution of magnetic flux density in the three phase buses at $\omega t = 90°$.

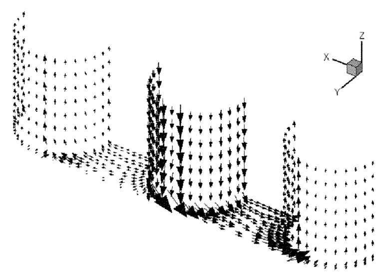

Fig. 6. Distribution of current density in the three-phase enclosures at $\omega t = 90°$.

IV. Verification of Design Scheme

In the design of the IPB, a three-insulator support structure is adopted. In order to study the withstand voltage performance, the EF intensity distribution in the bus with power frequency voltage as well as with an impulse voltage must be calculated. Fig. 7(a) gives the sketch map of an IPB with three support insulators. The calculated area includes the neighborhood area of one insulator. FEM is used to compute the field.

For the object being studied, one can define the exterior surface of the conductor as Boundary 1 where the voltage U is applied. The inner surface of the earthed enclosure is Boundary 2. The area from the exterior surface of conductor to the inner surface of the enclosure is chosen as the area being studied. Due

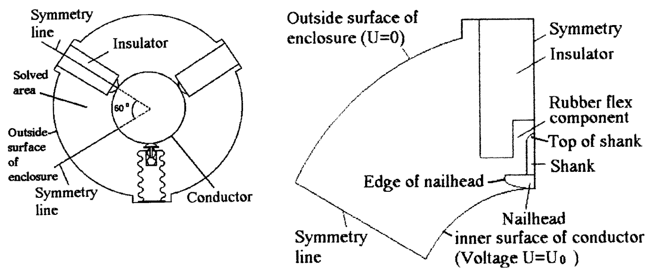

Fig. 7. EF computation model in an IPB. (a) Cross section of single phase bus. (b) Solved area of EF.

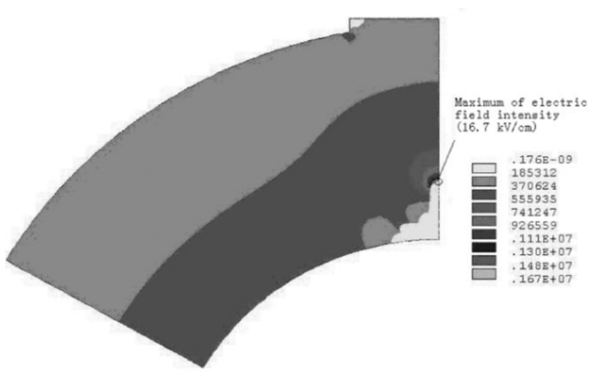

Fig. 8. The distribution of EF intensity in the solved area.

to the structural and electric symmetry of the model, the final solved area is given in Fig. 7(b).

A. Verification of Withstand Power Frequency Voltage Capability

According to the design specification of the IPB being reported in this paper, the withstanding voltage of the 20-kV IPB is 75 kV. Based on the experimental data, the breakdown EF intensity in air between cylinders in the same axis is 30 kV/cm (maximum). The breakdown EF intensity along the porcelain surface in air is 21.6 kV/cm (maximum). The corresponding EF intensity distribution in the solved area is calculated by using FEM and the results are shown in Fig. 8. The part below the top of the nailhead and shank are circular to minimize the sharp edges. For the case being studied, the maximum EF intensity at the top of the shank which touches the rubber flex component is 28.6 kV/cm which is considered marginally excessive. When the shape of the nailhead was made ellipsoidal, the EF becomes 16.5 kV/cm which is lower than the power frequency breakdown EF intensity in either air or along the path on the porcelain surface. Hence, the design is considered acceptable.

B. Verification of Withstand Impulse Voltage Capability

In order to study the lightning surge withstanding voltage in the IPB, the impulse voltage test is carried out. The breakdown EF intensity along the porcelain surface in air is found to be 70.8 kV/cm. Computation shows that the maximum EF intensity is 36.4 kV/cm at the top of the metal shank. As such a value is less than the breakdown value of 400 kV for a 20-kV IPB, the design is considered satisfactory.

C. Stress Verification of Bus Conductor

By calculating the magnetic field of the IPB, the electromagnetic force of the conductor can be computed based on the current flowing in the busbars. For the IPB with three insulators, only the bus conductor stress needs to be verified. The stress of the insulator and rubber flex component cannot be verified because they are subject to axial press forces when the friction forces are ignored. For the bus conductor, the maximum stress is

$$\sigma_{x\,\max} = \frac{k f_{\max} l^2}{W}$$
$$W = 0.1\frac{D_M^4 - d_M^4}{D_M} \qquad \text{(for tube conductor)} \qquad (16)$$

where $f_{\max}$ is the maximum force of the bus conductor (N/m); l is span of the bus conductor (m); W is the section factor of the bus conductor (m^3) and k is a constant.

The maximum short-circuit force is 901 N/m. Assuming the bus conductor is a state beam model, then the maximum stress $\sigma_{x\,\max} = 279\,310\ \mathrm{N/m^2}$. Noting the allowed stress of aluminum is generally between 5×10^7 to $7\times10^7\ \mathrm{N/m^2}$, the calculated stress is lower than the maximum allowable stress. Hence, one could conclude that the enclosure design is also satisfactory.

V. Conclusion

Unlike other research results presented before, a 3-D eddy current field method has been described for calculating the eddy current losses in an IPB in this paper. By solving the thermal equations, the temperature of the bus as well as the main size of the bus conductor and enclosure are determined. By comparing several schemes as reported, a good design scheme has been identified and described. In order to verify the validity of the design and calculation in terms of EF intensity and short-circuit stress of the bus, a prototype was built and tested. The calculated and tested results show that the proposed IPB scheme complies with the practical requirements of the engineering industry.

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