IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received December 4, 2020, accepted January 5, 2021, date of publication January 14, 2021, date of current version January 21, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3051241

The Electromagnetic-Fluid-Temperature Field Analysis of Loss and Heat of Self-Cooling Separate-Phase Enclosed Bus of Large Generator

ZHEN-NAN FAN[1], ZU-YING BIAN[1], KE XIAO[1], JING-CAN LI[2], BING YAO[1], AND XUE-GUI GAN[1]

[1]Key Laboratory of Fluid and Power Machinery, Ministry of Education, Xihua University, Chengdu 610039, China

[2]State Key Laboratory of Power Transmission Equipment & System Security and New Technology, Chongqing University, Chongqing 400030, China

Corresponding author: Zhen-Nan Fan (fanzhennan@126.com)

This work was supported in part by the National Natural Sciences Fund Youth Fund of China under Grant 51607146, in part by the Sichuan Science and Technology Program under Grant 2018GZ0391, and in part by the the Sichuan Hydropower Energy and Power Equipment Technology Engineering Research Center, Xihua university, Chengdu, China, under Grant SDNY2020-001.

ABSTRACT The loss and heat of a self-cooling enclosure-isolated phase bus of large generator are studied by establishing the electromagnetic-fluid-temperature field model of the bus using the finite element method. Factors such as skin effect and eddy loss, the electro-conductivity temperature effect, gas flow, and gravity are considered. The compositive calculation and analysis of the loss and temperature of the self-cooling enclosure-isolated phase bus of a 600 MW generator are conducted, and the data are compared with the test. The results show that the current and loss distribution in the conductor and sheath of the horizontal bus correlate with skin effect. The distribution of the bus temperature around the vertical center axis is symmetric, but the temperature of the top bus is higher than the bottom. If the influence of the acceleration of gravity and heat radiation is not considered, the result will become unreasonable.

INDEX TERMS Electromagneti-fluid-temperature field, self-cooling separate-phase enclosed bus, loss, heat.

I. INTRODUCTION

With the gradual development of power grids to high-voltage and large-generators in China, using the self-cooling separated-phase enclosed busbar has become increasingly widespread in the large generator [1]–[5]. However, because of the large current, good sealing, and limited volume of this type of bus, the overheat faults directly affect the safety of the generator and power grid. The design, manufacture, operation, and maintenance level must be improved to eliminate overheat defects and avoid similar malfunctions. This improvement requires a comprehensive grasp of the heat source and the temperature distribution of this type of bus. Therefore, accurate calculation and analysis of loss and heat are essential for performance.

For the loss calculation on the large-current enclosed bus, it is challenging to solve the loss of the bus conductor and metal shell using the traditional circuit analysis method because of the skin effect, induced eddy current, conductivity temperature effect, and other factors. Regarding temperature calculation, because of the constraints of material properties, geometric shapes, placement ways, gravitational acceleration, surface radiation, and ambient temperature, analyzing gas flow and heat dissipation or experimental determination also becomes challenging, significantly affecting the accuracy of temperature calculation. In recent years, researchers have made some outstanding achievements in the temperature analysis of enclosed bus [6]–[9], but the coupling analysis of multi physical fields for the loss and heat of self-cooling separate-phase enclosed bus of large generator still needs to be further carried out.

In view of these facts, this study uses the self-cooling separated-phase enclosed busbar of a 600 MW generator as an example. By comprehensively considering the mentioned effects, we established a loss and heat finite element model by combining the electromagnetic field with flow field methods. Furthermore, this study calculated and analyzed the distribution of the current, loss, and temperature of this type of

The associate editor coordinating the review of this manuscript and approving it for publication was Wei Xu.

TABLE 1. Basic parameters of bus.

Parameter	Value
Shell Outer diameter (mm)	1450
Shell thickness (mm)	10
Distance between phases (mm)	1800
Conductor current (A)	23000
Conductor outer diameter (mm)	900
Conductor thickness (mm)	15
Ambient temperature (℃)	40
Placement method	Horizontally

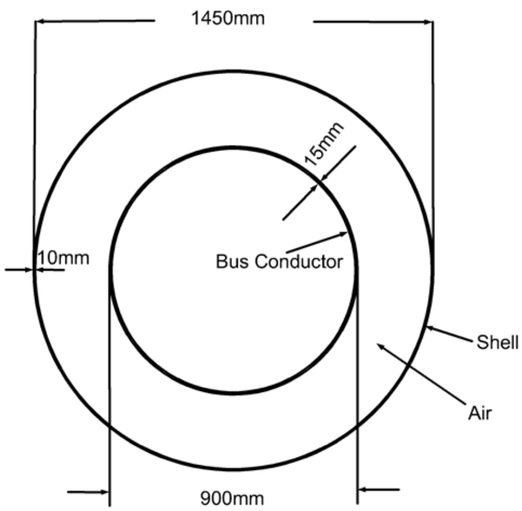


FIGURE 1. Schematic diagram of the cross-section of the bus.

bus. We then discussed the influence of the two principal heat dissipation ways (convection and radiation) on the calculated results of loss and heat.

II. LOSS HEATING CALCULATION MODEL

Table 1 shows the basic data of the bus in this paper.

Fig.1 shows the cross-sectional structure of the bus. In the annular closed space between the bus conductor and metal shell,the filling gas is air.

A. ELECTROMAGNETIC FIELD BOUNDARY VALUE PROBLEM

The electromagnetic field governing equation in the bus area is [10]

$$\nabla \times (\nu \nabla \times \mathbf{A}) = \mathbf{J} \tag{1}$$

In the solution of the two-dimensional electromagnetic field, the vector magnetic potential and current density only have the z-axis component, which is Ax = Ay = 0 and Jx = Jy = 0. Equation (1) can be transformed into

$$\frac{\partial}{\partial x}(\nu \frac{\partial A_z}{\partial x}) + \frac{\partial}{\partial y}(\nu \frac{\partial A_z}{\partial y}) = -J_z \tag{2}$$

However,

$$J_z = J_{sz} + J_{cz} \text{ and} \tag{3}$$

$$J_{cz} = -\sigma \frac{\partial A_z}{\partial t} \tag{4}$$

where v is the reluctivity, Jsz is the source current density, Jcz is the current density induced by the magnetic field change in the conductive region, and σ is the conductivity of the conductive region.

For the two-dimensional sinusoidal time-varying electromagnetic field, the governing equation is changed to

$$\frac{\partial}{\partial x}(\nu \frac{\partial A_z}{\partial x}) + \frac{\partial}{\partial y}(\nu \frac{\partial A_z}{\partial y}) = -J_{sz} + j\omega\sigma A_z \tag{5}$$

The Coulomb norm $\nabla \cdot A = 0$ and the far-region boundary condition set as A = 0 at a far from the shell constitutes a sinusoidal time-varying electromagnetic field boundary value problem of a closed bus.

B. CALCULATION OF LOSS

Through finite element post-processing, the current and loss of an element can be obtained from

$$I_e = \iint_{\Delta e} J_{ze} dxdy \text{ and} \tag{6}$$

$$P_e = I_e^2 \frac{L_{ef}}{\sigma \Delta_e} \tag{7}$$

where Jze is the current density of an element in the conductive area, Δe is the area of the element, and Lef is the axial length of the busbar calculation area.

Therefore, the expression of loss in this area is

$$P_c = \sum_{e=1}^{k} P_e \tag{8}$$

where k is the total number of elements in the area.

Therefore, the calculated loss in the bus conductor and metal shell can be calculated as the heat source for the temperature field calculation.

C. FLUID-TEMPERATURE FIELD CALCULATION MODEL

For the self-cooling separated-phase enclosed bus, the heat source dissipates heat by convection and radiation.

In the solution of the two-dimensional temperature field, the heat conduction differential equation of the bus in the rectangular coordinate system is

$$\frac{\partial}{\partial x}(\lambda \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(\lambda \frac{\partial T}{\partial y}) = -q_V \tag{9}$$

where λ is the thermal conductivity of the medium, T is the temperature to be calculated, and qV is the heat source density obtained from the loss calculation mentioned earlier.

Equations (10)–(13) can express the steady-state natural convection of air [11].

Mass conservation equation

$$\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} = 0 \tag{10}$$

Momentum conservation equations

$$\rho\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=-\frac{\partial P}{\partial x}+\frac{\partial}{\partial x}(\eta\frac{\partial u}{\partial x})+\frac{\partial}{\partial y}(\eta\frac{\partial u}{\partial y}) \quad (11)$$

$$\rho\left(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{\partial P}{\partial y}+\frac{\partial}{\partial x}(\eta\frac{\partial v}{\partial x})+\frac{\partial}{\partial y}(\eta\frac{\partial v}{\partial y})+g\beta\rho\Delta T \quad (12)$$

Energy conservation equation

$$\rho cu\frac{\partial T_q}{\partial x}+\rho cv\frac{\partial T_q}{\partial y}=\frac{\partial}{\partial x}(\lambda\frac{\partial T_q}{\partial x})+\frac{\partial}{\partial y}(\lambda\frac{\partial T_q}{\partial y})+q_V \quad (13)$$

where ρ is the gas density, P is the gas pressure, η is the gas kinematic viscosity coefficient, and u and v are the components of the gas velocity in the x and y axes, respectively. g is the acceleration of gravity, β is the thermal expansion coefficient, ΔT is the temperature difference between the hot and cold surfaces, Tq is the gas temperature, and c is the specific heat capacity.

By ignoring the temperature difference between the inner and outer walls of the metal shell and considering the influence of radial heat dissipation, the boundary conditions for the outer surface of the bus conductor are

$$-\lambda_1\frac{\partial T}{\partial n}=\alpha_{in}\left(T_1-T_2\right)+\varepsilon_{in}\sigma_b(T_1^4-T_2^4) \quad (14)$$

For the outer wall of the metal shell, the boundary conditions are

$$-\lambda_2\frac{\partial T}{\partial n}=\alpha_{out}\left(T_2-T_f\right)+\varepsilon_{out}\sigma_b(T_2^4-T_f^4) \quad (15)$$

where λ1 and λ2 are the thermal conductivity of the bus conductor and metal shell, respectively. α in and α out are the convection heat dissipation coefficients of the outer surface related to the gas flow condition and geometric parameters of the bus. ε in and ε out are the equivalent emissivity of the outer surfaces of the bus conductor and metal enclosure, respectively. The equivalent emissivity is related to the emissivity of the painted surface and geometric parameters of the bus. T1, T2, and Tf are the temperature of the conductor and shell outer surfaces and the outer environment of the cylinder, respectively. σb is the Stefan-Boltzmann constant.

The air far away from the outer surface of the shell is unaffected by the heat source. It is used as the far-region boundary of the flow field calculation, and the temperature is set to the ambient temperature of 40°C.

D. DETERMINATION OF CONDUCTIVITY IN THE CONDUCTIVE AREA

The conductive area includes the bus conductor and metal shell, and its conductivity value directly affects the accuracy of the loss and temperature calculation. This study considers the temperature influence on conductivity by adopting the iterative trial method to determine its conductivity. For each conductive area, first, assume an average initial temperature t1 to obtain its corresponding conductivity. Then, calculate its loss and average temperature t2 using electromagnetic field and temperature field calculations. Finally, use t2 as the average initial temperature and repeat the above calculation until t1 is close to t2.

III. CALCULATION RESULTS AND ANALYSIS

By using the above model, this study has analyzed the distribution law by calculating the bus current, loss, and temperature. Then,combined with the bus temperature measurement results, the influence of two principal heat dissipation ways (convection and radiation) on the loss and heat calculation results is studied and discussed.

A. TEMPERATURE MEASUREMENT TEST

In order to verify the accuracy and rationality of the calculation results in the following discussion, the temperature measurement experiment of the bus is described as follows:

The temperature measurement test of the bus samples is carried out in accordance with the requirements of the Chinese National Standard "GB2706-1989 Test Method for Dynamic Thermal Stability of AC High Voltage Electrical Apparatus" and "GB763-1990-Heating of AC High Voltage Electrical Apparatus in Long-term Work". This requires to specially manufacture a set of three-phase prototype test section whose structure and size parameters are the same as those of the actual product. The length of each phase is not less than 3 to 4 times of its cross-sectional size, and at least one detachable connector.

The results showed that: when the ambient temperature is 40°C, the average temperature rise of measuring points of the conductor is 44.04°C (allowable temperature rise is 50°C), that is, the measured average temperature of the conductor is 84.04°C. The average temperature rise of measuring points of the shell is 24.13°C (allowable temperature rise is 30°C), that is, the measured average temperature of the shell is 64.13°C. The relevant measurement results, together with the calculation results, are listed in the TABLE 2 and TABLE 3.

B. ONLY CONSIDERATION ON CONVECTION HEAT DISSIPATION

When setting the boundary conditions of the temperature field, set the emissivity of the busbar conductor and metal shell outer surfaces to 0 to simulate the heat dissipation by air convection alone.

Fig.2 shows the obtained current and loss density distribution curves along the thickness. Fig.3 and Fig.4 show the temperature distribution and airflow, respectively. TABEL 2 shows the calculated values of loss and temperature.

Fig.2 shows that in the bus conductor and metal shell, the current density distribution shows an obvious skin effect. In the bus conductor, the current density near the outer surface is higher than near the inner surface. However, in the metal shell, the current density near the inner surface is higher than the outer surface. Therefore, the loss density is distributed by the same law. Note that to ensure the accuracy of the calculation, the skin effect must be considered in the loss solution.

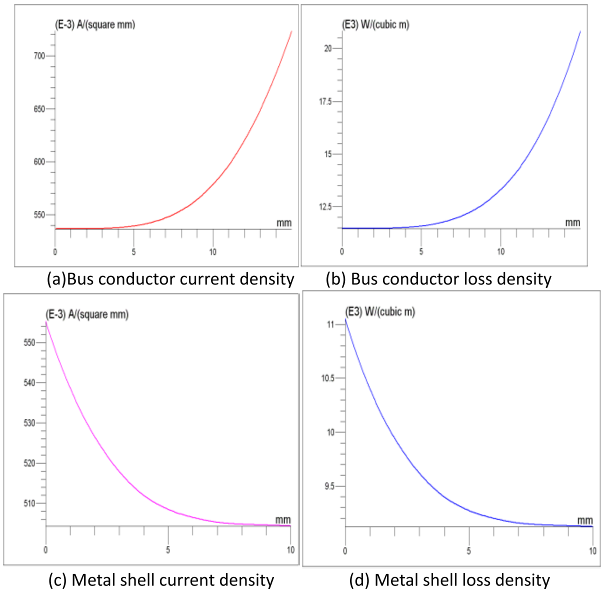


FIGURE 2. Current and power density distribution curves when ignoring radiation heat.

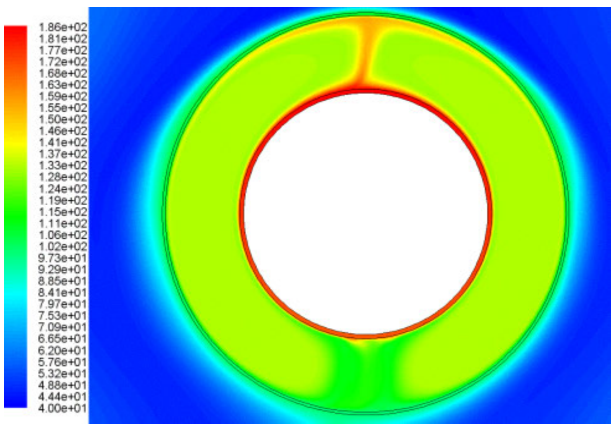


FIGURE 3. The temperature distribution of the bus when ignoring radiation heat dissipation.

Fig.3 shows that the temperature distribution of the bus correlates with the symmetrical geometric law and the upper part is higher than the lower part. Whether it is a bus conductor or a metal shell, the highest temperature is at the top and the lowest temperature at the bottom, predominantly because of the gas velocity vector distribution shown in Fig.4. Because of the symmetrical geometric construction of the bus, the gas flow and heat dissipation conditions are the same on the left and right, making the temperature distribution symmetrical. Moreover, because of the influence of gravitational acceleration on the gas flow, the vertical temperature distribution of the bus indicates that the upper parts are higher than the lower parts.

However, regarding specific temperature calculation values, TABLE 2 shows that when only convection heat is considered, although the calculated average temperature differs from the preset value by only 1 °C, it is far from the actual

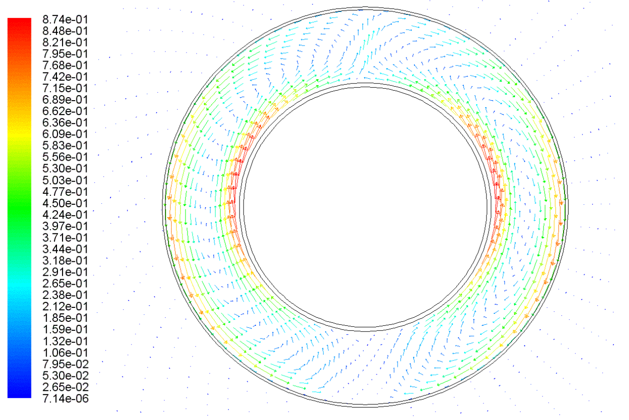


FIGURE 4. Vector diagram of airflow when ignoring radiation heat dissipation.

TABLE 2. Loss and heat calculation results when ignoring radiation heat dissipation.

	Bus conductor	Metal shell
Loss (W/m)	557	433
Preset conductivity ((Ω−1.m−1) × 107)	2.54	2.79
Preset average temperature t1 (℃)	177	87
The highest calculated temperature Tmax (℃)	186	95
The lowest calculated temperature Tmin (℃)	170	81
The average calculated temperature t2 (℃)	178	88
Measured average temperature Tavm (℃)	84.04	64.13
Average temperature calculation error	112%	37%

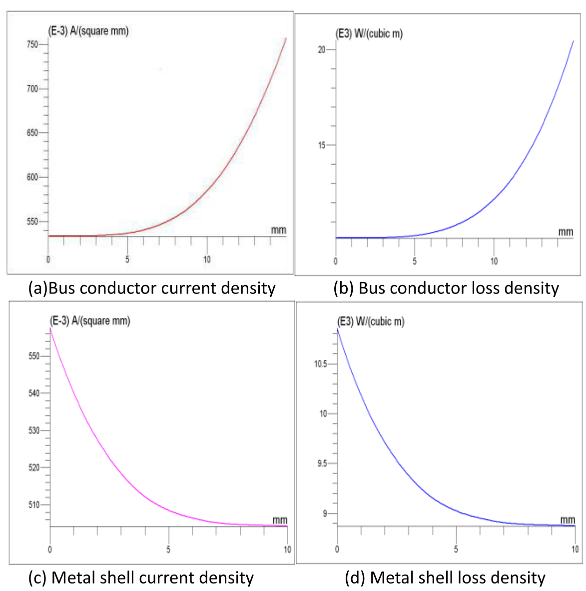


FIGURE 5. Current and power density distribution curve when considering radiation heat dissipation.

measured value. The calculated average temperature of the bus conductor is 2.11 times the measured value, with an error of 112%. The outer surfaces of the bus conductor and metal shell are painted with black or light gray paint, and its emissivity is between 0.8–0.96. Therefore, they have a strong radiation heat dissipation capacity. Ignoring radiation heat

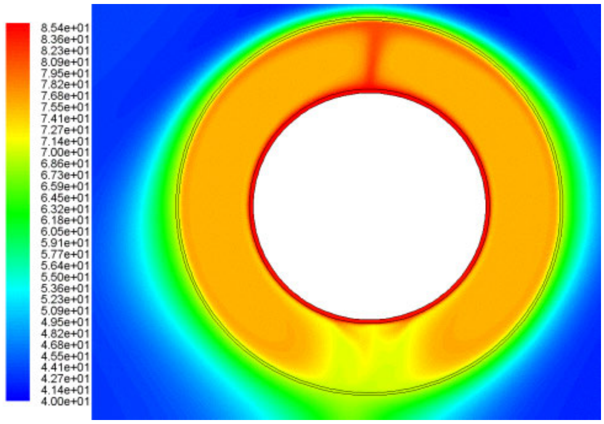


FIGURE 6. The temperature distribution of the busbar when considering radiation heat dissipation.

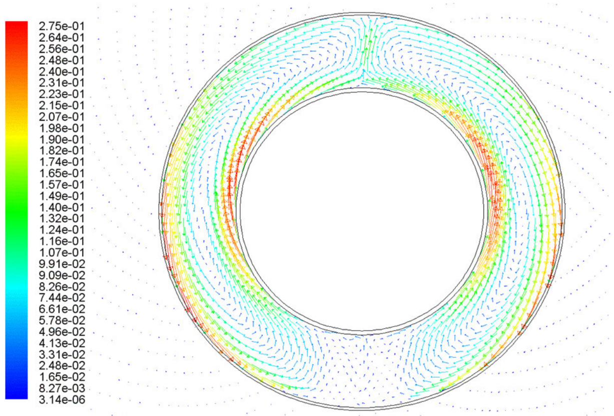


FIGURE 7. The airflow vector diagram of the busbar when considering radiation heat dissipation.

dissipation in the temperature field modeling calculation does not conform to the actual physical conditions. It will cause large errors in the temperature calculation results.

C. COMPREHENSIVE CONSIDERATION OF TWO HEAT DISSIPATION METHODS: CONVECTION AND RADIATION

When setting the boundary conditions of the temperature field, the emissivity of the surface painting of the bus conductor and metal shell are taken as 0.9 to consider the influence of radiation heat dissipation. Fig.5 shows the obtained distribution curves of the current and power density along the thickness direction. Fig.6 and Fig.7 show the temperature distribution and airflow condition, respectively. TABLE 3 shows the calculated values of loss and heating.

TABLE 3 shows that after considering the radiation heat dissipation, the calculated temperature of the bus conductor and metal shell is reduced to approximately half than when ignoring radiation. Compared with the measured data, the calculation error of the average temperature is only 1%. The calculation accuracy is much better than when radiation is neglected and satisfies engineering accuracy. Because the shape of the air convection path is unchanged, the temperature distribution of the bus is a symmetrical geometric shape,

TABLE 3. The calculated results of heat loss when considering radiation heat dissipation.

	Bus conductor	Metal shell
Loss (W/m)	511	420
Preset conductivity ((Ω−1.m−1) × 107)	2.8	2.86
Preset average temperature t1 (℃)	85	65
The highest calculated temperature Tmax (℃)	85.4	64.6
The lowest calculated temperature Tmin (℃)	84.3	63.8
The average calculated temperature t2 (℃)	84.85	64.2
Measured average temperature Tavm (℃)	84.04	64.13
Average temperature calculation error	1%	1%

which is similar to that without radiation (Fig.6 and Fig.7). However, the maximum temperature difference in the upper and lower parts is reduced significantly from 14 °C–16 °C to ∼1 °C.

Regarding the calculated loss value, temperature affects both conductivity and loss. In the iterative trial of loss and heat calculation, after considering radiation heat dissipation, the final value of conductivity increases as the calculated temperature decreases, reducing the loss of the bus conductor and metal shell. However, Fig.5 shows that in the bus conductor and metal shell, the current and loss density distribution still exhibits the skin effect.

Radiant heat dissipation significantly influences the value and accuracy of the loss and temperature calculations. In addition to the influence of convective heat dissipation on the calculated values of losses and temperature, the airflow path also causes the upper part temperature of the bus to be higher than the lower part. Only by comprehensively considering the effects of radiation and convection can the actual physical conditions of loss and heat be simulated and correct and reasonable calculation results obtained.

IV. CONCLUSION

(1) For a horizontally separated closed bus, whether it is in the bus conductor or metal shell, the current, loss, and temperature distribution are not uniform. The distribution of current and loss embodies the skin effect, whereas the temperature is symmetrical, and the upper part temperature is higher than the lower part state.

(2) In the loss and heating modeling calculation, ignoring the radiation heat dissipation could cause large calculation errors. Moreover, when considering convection heat dissipation, the influence of gravitational acceleration on gas flow should be considered, otherwise, it is challenging to obtain a reasonable temperature distribution law. Only by comprehensively considering the effects of convection and radiation can the calculation results conform to the actual physical conditions and engineering accuracy.

(3) Compared with the conventional circuit-heat circuit calculation model, the calculation model in this study is based on the numerical calculation of electromagnetic-fluid-temperature field. It gives more consideration to the skin effect, eddy current loss, convection and radiation heat dissipation, gravitational acceleration, conductance rate

temperature effect, and other factors. Therefore, a more accurate quantitative calculation and analysis of the loss and heat of the self-cooling high-current separated-phase enclosed bus can be performed. Furthermore, the distribution and change laws of various electromagnetic and thermal physical quantities in the operation of the bus can be better theoretically revealed, and it provides a useful reference for the operation, maintenance, design, and manufacture of this kind of bus.

REFERENCES

[1] L. J. Wu, *Theoretical Basis and Design of High-Current Bus*. Beijing, China: Hydropower Force Press, 1985.

[2] Z. L. Yang, "Development and design of fully connected isolated-phase enclosed bus for 600MW unit," *China North Electr. Power Technol.*, vol. 2, pp. 5–9, Feb. 1998.

[3] B. Liang, X. Zhao, and B. J. Yi, "Selection of the high-current isolated-phase enclosed busbar of the three gorges power station," *People's Yangtze River.*, vol. 10, pp. 50–52, Dec. 2000.

[4] W. L. Kang and F. C. Wu, "Research on isolated-phase closed bus of 1000MW unit," *North China Electr. Power Technol.*, vol. 4, pp. 4–13, Apr. 2006.

[5] Q. M. Liu and M. D. Zhao, "Design and development of self-cooling separated phase enclosed bus for 1000MW unit," *Electr. Power Equip.*, vol. 8, pp. 44–46, Jan. 2007.

[6] S. W. Kim, H. H. Kim, S. C. Hahn, B. Y. Lee, K. Y. Park, Y. J. Shin, W. P. Song, J. B. Kim, and I. H. Shin, "Coupled finite-element-analytic technique for prediction of temperature rise in power apparatus," *IEEE Trans. Magn.*, vol. 38, no. 2, pp. 921–924, Mar. 2002.

[7] J. Kyoung Kim, S. Chin Hahn, K. Yop Park, H. Kyu Kim, and Y. Ho Oh, "Temperature rise prediction of EHV GIS bus bar by coupled magnetothermal finite element method," *IEEE Trans. Magn.*, vol. 41, no. 5, pp. 1636–1639, May 2005.

[8] X. W. Wu, N. Q. Shu, L. Li, H. T. Li, and H. Peng, "Finite element analysis of thermal problems in gas-insulated power apparatus with multiple species transport technique," *IEEE Trans. Magn.*, vol. 50, no. 2, pp. 321–324, Feb. 2014.

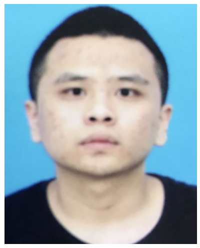
[9] X. W. Wu, N. Q. Shu, H. T. Li, and L. Li, "Contact temperature prediction in three-phase gas-insulated bus bars with the finite-element method," *IEEE Trans. Magn.*, vol. 50, no. 2, pp. 277–280, Feb. 2014.

[10] J. N. Sheng, *Numerical Analysis of Engineering Electromagnetic Field*. Xi'an, China: Xi'an Jiaotong Univ. Press, 1991.

[11] W. Q. Tao, *Numerical Heat Transfer Version 2*. Xi'an, China: Xi'an Jiaotong Univ. Press, 2001.

ZHEN-NAN FAN was born in Longchang, China, in 1981. He received the Ph.D. degree in electrical engineering from Chongqing University, Chongqing, China, in 2013. He is currently an Associate Professor with Xihua University. His research interests include magnetic and thermal field calculation of generators, electrical machinery, and motor drives.

ZU-YING BIAN was born in Fuzhou, China, in 1996. He is currently pursuing the M.Sc. degree with Xihua University. His research interests include magnetic and thermal field calculation of generators, electrical machinery, and motor drives.



KE XIAO was born in Xuanhan, China, in 1992. He graduated from Xihua University. His research interests include magnetic and thermal field calculation of generators, electrical machinery, and motor drives.

JING-CAN LI received the Ph.D. degree in electrical engineering from Chongqing University, Chongqing, China, in 2011. He is currently a Lecturer with Chongqing University. His research interests include magnetic and thermal field calculation of generators, electrical machinery, and motor drives, and the control of electrical machine.

BING YAO was born in Sichuan, China, in 1981. He received the M.Sc. degree from Xihua University, Chengdu, China, in 2010. He is currently a Lecturer with Xihua University. His research interests include magnetic and thermal field calculation of generators, electrical machinery, and motor drives.

XUE-GUI GAN was born in Zizhong, China, in 1997. He is currently pursuing the M.Sc. degree with Xihua University. His research interests include magnetic and thermal field calculation of generators, electrical machinery, and motor drives.