Simulation of Electric and Thermal Fields of High Voltage Interrupter Vacuum Chamber

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Abstract - In this study 3D model of electric field and thermal field distributions of high voltage vacuum chamber is developed. The coupled electric-thermal field problem is formulated and finite element method is applied to calculate the electric field and temperature distributions in vacuum chamber. The heat sources are obtained by electric field analysis. The electric arc discharge conductivity is nonlinearly related to the electric field intensity and arc temperature. The temperature of the interrupter contact system surface has been used to study the operational characteristics of the vacuum chamber.

Keywords - Electrical arc discharge; coupled field analysis; finite element method; electric field; temperature field; vacuum interrupter

I. INTRODUCTION

High Voltage (HV) vacuum interrupters are widely used in the electric power system. Service life of vacuum interrupter is much longer than other types of circuit breaker. They characterize with improved constructions, lightweight, efficient, quiet running, without presence of dangerous and flammable substances, increased switching capability, and operational reliability as well as a reduced maintenance cost. Electrical arc extinguishing becomes very successful in high vacuum $10^{-4}\text{Pa}$. [1-2].

Physical arc models are based on the equations of fluid dynamics and obey the laws of thermodynamics in combination with Maxwell’s equations. Modeling of vacuum interrupter electrical and thermal field could be used to optimize the design, functionality of the interrupters and to reduce the time for development and manufacturing of vacuum interrupter [1-10].

In this paper coupled electric-thermal fields model has been developed in order to give a better understanding of the process which goes with electric arc burning in switching mode. This model combines the expression of electric arc conductivity with the electric potential and equations of electric and thermal fields.

II. VACUUM CHAMBER

Vacuum chamber of HV interrupter is modeled and analyzed. The construction of the chamber is shown in Fig.1(a) and its dimensions in Fig. 1(b). The rated voltage is 12 kV and rated current is 400 A.

![Vacuum Chamber Diagram](image)

Electrical contact system is made of oxygen-free high thermal conductivity (OFHC) copper. Isolation of the chamber is Al$_2$O$_3$ ceramic. Inner chamber pressure is less than $10^{-6}\text{Pa}$.

III. ELECTRIC FIELD MODELING

The governing equation for electric field distribution is governed by Laplace equation [1]

$$\nabla(\sigma(E,T) \nabla V) = 0, \quad (1)$$

where $\sigma(E,T)$ is the electrical conductivity of media between the electrodes, i.e. the electric arc conductivity, and $V$ is electric scalar potential.

The electric field intensity $E$ [1] is determined by

$$E = -\nabla V. \quad (2)$$

Determination of the electric scalar potential $V$ using equation (1) allows to adjust the vacuum interrupter current $I$. 

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This is done by setting the electric potential distribution $V$ with constant value $V = 0$ at the fixed contact and $V_{HV} = U$ at the moveable contact in contact system of the vacuum chamber, where $U$ is total voltage drop.

The electric arc conductivity $\sigma$ [3] is defined by

$$\sigma = n e \mu_e = \frac{n e^2}{m_e v_m},$$  \hspace{1cm} (3)

where $n$ is electron density, $m_e$ is electron mass, $v_m$ is charge flow velocity, $\mu_e$ is electron mobility and $e$ is elementary electron charge. The physical constants are in SI units, where $n \leq 10^{19}$ m$^{-3}$, $m_e = 9.109 \times 10^{-31}$ kg, $e = 1.602 \times 10^{-19}$ As.

Charge flow velocity is determined by

$$v_m = -\frac{e}{m_e v_d} E,$$ \hspace{1cm} (4)

where $v_d$ is thermal velocity called drift velocity dependent on discharge temperature [4]. The electric arc discharge conductivity is nonlinearly related to the electric field intensity and arc temperature.

IV. THERMAL FIELD MODELING

The thermal field is governed by

$$\lambda \frac{\partial T}{\partial n} = \beta k_B (T^4 - T_0^4),$$  \hspace{1cm} (8)

where $\beta$ is emissivity coefficient, and $k_B$ is Boltzmann constant, where $k_B = 1.3806488 \times 10^{-23}$ J/K. Emissivity for contact parts is $\beta = 0.15$ and for the electrical arc $\beta = 1$ used as for ideal black body.

The initial condition according to the temperature is $T = T_0$, where $T_0$ is initial model temperature, set to 20°C.

V. COUPLED FIELD PROBLEM

The coupled field electric-thermal problem is formulated and Finite Element Method (FEM) is used to obtain the electric and thermal field distributions. The heat sources are determined by electric field analysis. Thermal simulations of the HV vacuum chamber were performed to study the influence of rising temperature in chamber constructive elements. The electric field distribution in vacuum chamber is calculated and analyzed for various position of the contact system.

Coupling between electric and thermal fields is realized in order to analyze the processes and phenomena during the current interruption. The coupled equations set is

$$\nabla (\sigma(E,T) \nabla V) = 0$$

and

$$\frac{\nabla^2 T - \gamma_c}{\lambda} \frac{\partial T}{\partial t} = \frac{Q}{\lambda},$$  \hspace{1cm} (10)

The heat source depends on the results of the electric field analysis. The solution of the electric field problem is used to define heat sources for thermal field solution. The thermal field is governed by the heat equation.

For better computational accuracy the electric arc domain is represented by especially created for that purpose block with separated mesh. Each mesh element of that block is with different material properties which are calculated according to electric field intensity and temperature distribution.

<table>
<thead>
<tr>
<th>Chamber part</th>
<th>material</th>
<th>$\sigma$ (S/m)</th>
<th>$\varepsilon_r$</th>
<th>$\gamma$ (kg/m$^3$)</th>
<th>$c$ (kJ/kg K)</th>
<th>$\lambda$ (W/mK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inside enviroment</td>
<td>Vacuum</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Movable conductor</td>
<td>OFHC copper</td>
<td>5.9x10$^7$</td>
<td>-</td>
<td>8.940</td>
<td>385</td>
<td>401</td>
</tr>
<tr>
<td>Fixed conductor</td>
<td>OFHC copper</td>
<td>5.9x10$^7$</td>
<td>-</td>
<td>8.940</td>
<td>385</td>
<td>401</td>
</tr>
<tr>
<td>Ceramic insulator</td>
<td>Al$_2$O$_3$</td>
<td>10$^{-14}$</td>
<td>9.1</td>
<td>3.95</td>
<td>1050</td>
<td>26</td>
</tr>
</tbody>
</table>
Physical properties of vacuum interrupter chamber materials and electric arc discharge are used to calculate the realistic simulation as shown in Table 1. The electric arc is modeled as a perfect black body.

The coupled electric-thermal field FEM model is implemented and analyzed in ANSYS environment. [12]

VI RESULTS

Electric potential and field intensity distributions in vacuum interrupter are illustrated in Fig. 3. The presented results correspond to the different distances of contact system of the chamber from 1 to 8 mm. The results are calculated as sequence of electrostatic models for different distances between contact parts and for the peak value of supplied voltage. Thus the heaviest switching conditions for current interrupting are modelled and simulated.

Results are obtained for peak value of the supply voltage of 12 kV. Electric field distributions, shown on the left sides of Fig. 3, correspond to electric potential distribution along the contact system. The right side of the chamber illustrates electric field intensity which expresses the electric arc appearance. At 1 mm between contacts the electric field intensity is greater than the intensity at larger distances. The field intensity starts to dissipate increasing of the distance from 1mm to 8mm. Electric potential is with relatively constant spatial distribution for each distance because of the fixed supply voltage. For distance of 1 mm, at presence of electric arc, maximum field intensity is about $12.2 \times 10^9$ V/m and its average value is approximately $4 \times 10^9$ V/m. For 8 mm of the contact system the field intensity is with maximum value of $7.9 \times 10^9$ V/m and average one of $3.5 \times 10^9$ V/m.

Fig. 4 and Fig. 5 illustrate current density and temperature for distances between contact parts for 1 mm and 8 mm. The greater values of the current density are in the parts with smaller cross section and in the electric arc domain. In opening of the contact system the arc current density decreases progressively with distance to disappearing of the electric arc. The current density inside the contacts should stay sufficiently low to prevent the conductor from fast heating up and melting, which is related with system electrical properties variation.

The contact system temperature (Fig.4 and Fig.5) depends on current density and electric arc conductivity. The surfaces of the contact elements are more heated because of the arc heating power. The temperature of contact elements is around 40÷80°C along them at the time of arc burning.
3D model of HV vacuum interrupter chamber is developed. The coupled electric-thermal field problem is formulated and finite element method is applied to calculate the electric field and temperature distributions in the vacuum chamber. The electric arc discharge conductivity in the model is nonlinearly related to the electric field intensity and arc temperature. Investigation is made for fixed value of the supply voltage to obtain the results for the heaviest switching conditions. Electric and temperature distributions for different distances in switching mode of the chamber are obtained. The temperature of the contact system surface has been used to study the operational conditions of the vacuum interrupter chamber. The formulated model and calculated results could be used for observing and estimating some of the major phenomena at plasma high temperature conditions. Also the time of arc extinguishing could be determined for HV switching devices. Developed model is suitable for vacuum chamber design and constructive optimization. Future investigations will be focused on experimental verification of the results.

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REFERENCES