Thermal Analysis of Hybrid Excitation Generator for Distributed Generation Applications

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Abstract. This paper presents a general thermal calculation method to analyze the thermal behaviors of hybrid excitation generators for distributed generation applications. The three-dimensional (3D) finite element method was adopted to calculate the temperature field of the air-cooled generator. The steady-state heat transfer mathematic and physical models were established, and hypothetical conditions were presented, together with boundary conditions and loads were calculated. The temperature field distributions under different operation conditions were achieved. The temperature field of a 12kW, 100rpm prototype was calculated, and the calculation results were compared with experimental data to verify the accuracy of the thermal calculation results.

Introduction

With the consumption of traditional fossil energy and the enhancement of public’s consciousness of environmental protection, the wind energy has been paid more attention to as a kind of vast and clean renewable energy all around the world. At present, in wind power system, electrically excited synchronous generator has a good magnetic field regulating ability. However, because of the existence of brush and collector ring, it does not be applied in harsh environments. Permanent magnet generator (PMG) is widely applied with higher efficiency and higher reliability in the field of wind power, but the air-gap magnetic field of PMG is determined by permanent magnets and the permeance of magnetic circuit. It is very difficult to control the fixed excitation provided by the permanent magnets. In order to make up for the shortcomings, hybrid excitation generator is introduced into distributed generation system. Permanent magnets have temperature sensitive properties, they can lose partially or completely their magnetic characteristics when they are submitted to high temperatures. It can entail a risk of demagnetization which damages the generator. The electrical insulation also has a temperature limit, so an accurate simulation of the thermal behavior of the hybrid excitation generator is necessary.

In this paper, a natural convection air-cooling system for hybrid excitation generators is introduced. The configuration of the hybrid excitation generator is shown in Figure 1.

![Figure 1. Configuration of the hybrid excitation generator.](image)
A 3D finite element model is established to analyze the temperature rise of the generator key parts, such as the AC winding and DC winding that always are the hottest parts in air-cooled hybrid excitation generators. The calculation results can give a clear picture of temperature distribution and hottest spot. The temperature field distributions under different operation conditions were analyzed. Finally, the temperature rise experimental results of a 10kW prototype were obtained, and compared with the calculated values to verify the feasibility of the calculation method.

**Cooling System and Thermal Analysis Parameters**

**Cooling System of the Hybrid Excitation Generator**

In order to make full use of the natural wind and simplify the cooling structure, the hybrid excitation wind generator is cooled directly by natural wind blowing through the surface of frame. There are no heat ribs on the surface of the generator. The cooling air and generator frame exchange heat, dissipating the heat.

**Thermal Analysis Parameters**

The heat sources in the hybrid excitation generator are including AC winding copper losses, DC excitation winding copper losses, iron losses and stray losses. The most significant of these is the copper losses which are generated due to the flow of current through the resistance of the windings. In the finite element model, the copper loss is applied as a volumetric heat generation imposed uniformly over the wingding volume. The iron losses are obtained from magnetic circuit and the stray losses is assumed to be 0.5% of the rated power, and evenly distributed between teeth and pole shoes’ surface. The values of heat sources are shown in Table 1.

Thermal conductivities for the solids used in wind generator can be considered to be constants with respect to the temperature. The thermal conductivity of air depends strongly on the temperature. Table 2 gives some typical values for the thermal conductivities of materials used in this paper.

<table>
<thead>
<tr>
<th>Heat sources position</th>
<th>Maximum magnetizing status (kW/m³)</th>
<th>No DC excitation (kW/m³)</th>
<th>Maximum demagnetizing status (kW/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>stator AC winding</td>
<td>66.282</td>
<td>265.129</td>
<td>265.129</td>
</tr>
<tr>
<td>DC winding(kW/m³)</td>
<td>87.942</td>
<td>1.676</td>
<td>157.561</td>
</tr>
<tr>
<td>stator core(kW/m³)</td>
<td>11.157</td>
<td>16.489</td>
<td>31.652</td>
</tr>
<tr>
<td>pole shoe(kW/m³)</td>
<td>0.878</td>
<td>0.878</td>
<td>0.878</td>
</tr>
</tbody>
</table>

**Table 1. Heat sources distributions.**

<table>
<thead>
<tr>
<th>Material</th>
<th>X (W/m/K)</th>
<th>Y (W/m/K)</th>
<th>Z (W/m/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>stator core</td>
<td>39</td>
<td>39</td>
<td>4.43</td>
</tr>
<tr>
<td>air (90°C)</td>
<td>0.0305</td>
<td>0.0305</td>
<td>0.0305</td>
</tr>
<tr>
<td>copper</td>
<td>385</td>
<td>385</td>
<td>385</td>
</tr>
<tr>
<td>pm</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>pole shoe</td>
<td>39</td>
<td>39</td>
<td>4.43</td>
</tr>
<tr>
<td>slot wedge</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
</tbody>
</table>

**Table 2. Thermal conductivities of materials used in the hybrid excitation generator.**

3-D Finite Element Model

**Mathematic Model**

Steady heat conduction equation of anisotropic solid material with inner heat sources can be written as
\[
\frac{\partial}{\partial x} (\lambda_x \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y} (\lambda_y \frac{\partial T}{\partial y}) + \frac{\partial}{\partial z} (\lambda_z \frac{\partial T}{\partial z}) = -q_v
\]
(1)

where \(q_v\) is heat generation in unit volume, \(T\) is temperature of solid and \(\lambda\) is thermal conductivity of solid.

There are three kinds of common boundary conditions in thermal calculation, two of them can be written as:

1) **Heat Flow Boundary Condition**

\[
\lambda \frac{\partial T}{\partial n} \bigg|_{S_1} = 0
\]
(2)

2) **Convection Boundary Condition**

\[
-\lambda \frac{\partial T}{\partial n} \bigg|_{S_2} = \alpha (T - T_0), \quad \alpha
\]
(3)

where \(T_0\) is ambient temperature that surrounds surface \(S_1\), and \(\alpha\) is heat transfer coefficient of surface \(S_2\).

**Thermal Analysis Assumptions and Model Simplification**

In order to simplify the calculation, some assumptions are given as follows:

- The temperature distribution in the circumferential direction is symmetric, so a model which includes half of the axial length, one third of the circumferential direction, is obtained as shown in Figure 2. The finite element model is shown in Figure 3.
- The copper for both left winding and right winding are considered as one isothermal conductor respectively, and the insulations including material of the impregnation, residual air as another which equivalent thermal conductivity is 0.26W/mK\(^5\). The model of stator winding is shown in Figure 4.
- Use an equivalent thermal conductivity for the airgap to replace the radiation and convection phenomena\(^6\).
- Simplify the structure of the AC end windings as straight line sections having equivalent lengths.

**Calculation Results under Rated Condition**

Before calculation, the boundary conditions have to be applied to the model. One of the most important boundary conditions for this generator is heat transfer coefficient of the frame. It can be calculated as follows\(^5\)

\[
\alpha = \alpha_0 \left[ 1 + k \sqrt{U} \right]
\]
(4)

where \(\alpha_0\) is heat transfer coefficient in calm air, \(k\) is coefficient of efficiency and \(U\) is air velocity.

Heat transfer coefficient of end winding can be written as

\[
Re = \frac{Ud}{\nu}
\]
(5)

\[
Nu = 0.456 Re^{0.6}
\]
(6)
\alpha = \text{Nu} \lambda / d \quad (7)

where Re is Reynolds number, \( d \) is equivalent fluid diameter and Nu is Nusselt number.

Based on the analysis stated above, a 3D finite element model is calculated by Ansys software. Temperature distributions are attained in Figure 5 - Figure 7.

As can be seen from Figures 5-7, the hotshot of the 12kW hybrid excitation generator locates in the AC winding with the temperature rise of 41.9K, and the average temperature rise of AC winding is 38.7K which is pretty safe. The maximum temperature rise of PM is 19.2K which is far away from danger.

Table 3. Calculated value of the temperature rise under rated condition.

<table>
<thead>
<tr>
<th>Hottest spot</th>
<th>Maximum pm temperature rise(K)</th>
<th>Maximum AC winding temperature rise(K)</th>
<th>Average AC winding temperature rise(K)</th>
<th>Average stator core temperature rise(K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC winding</td>
<td>19.2</td>
<td>41.9</td>
<td>38.7</td>
<td>31.0</td>
</tr>
</tbody>
</table>

**Calculation Results under Different Excitation Conditions**

The calculation results of the hybrid excitation generator under different excitation conditions are shown in Figure 8, Figure 9 and Table 4.
Table 4. Calculation results of maximum temperature rise (/K).

<table>
<thead>
<tr>
<th>Status</th>
<th>AC winding</th>
<th>DC winding</th>
<th>Stator teeth</th>
<th>Stator yoke</th>
<th>Permanent magnet</th>
</tr>
</thead>
<tbody>
<tr>
<td>maximum magnetizing</td>
<td>20.6</td>
<td>27.4</td>
<td>18.0</td>
<td>17.9</td>
<td>11.3</td>
</tr>
<tr>
<td>maximum demagnetizing</td>
<td>64.4</td>
<td>68.9</td>
<td>53.9</td>
<td>53.4</td>
<td>32.7</td>
</tr>
</tbody>
</table>

As can be obviously seen from Table 4, the DC winding has the maximum temperature rise under both maximum magnetizing status and maximum demagnetizing status due to large excitation current and poor cooling condition. The assembly clearance between the stator frame and the DC winding is inevitable, which affects the heat dissipation of DC winding seriously.

**Experimental Validation**

To verify the feasibility of the technique, an experiment is conducted on a 12kW hybrid excitation generator under maximum demagnetizing status. Compared with experiment data, it can be seen that the prediction results have a good precision, as shown in Table 5. It can be seen that the calculation errors of temperature rise of AC winding and DC winding are 4.97% and 3.19%, respectively.

Table 5. Temperature rise comparison under demagnetizing status (/K).

<table>
<thead>
<tr>
<th>Temperature Rise</th>
<th>FEM</th>
<th>Test</th>
<th>Calculation error</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC winding</td>
<td>61.3</td>
<td>58.4</td>
<td>4.97%</td>
</tr>
<tr>
<td>DC excitation winding</td>
<td>64.7</td>
<td>62.7</td>
<td>3.19%</td>
</tr>
</tbody>
</table>

**Conclusion**

A technique combining 3D temperature field analysis and thermal experiment for hybrid excitation generator has been presented that makes it possible to predict the temperatures of key points inside the machine including the stator AC windings, DC windings and the rotor magnets. The calculation results under maximum demagnetizing status have been proved by experiment which is conducted on a 12kW hybrid excitation generator.

**References**


