Calculation and Analysis of Excitation Current for Brushless AC Exciter Based on Maxwell

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Abstract. In view of the complexity of the core structure of the brushless AC exciter and the influence of saturation characteristics of the ferromagnetic material, the finite element software Maxwell was used to create a two-dimensional model of the brushless AC exciter for no-load characteristics and Rated excitation current for research and analysis. Taking a 28KW brushless AC exciter as an example, the simulation analysis of the air gap magnetic field of the motor and the calculation of the no-load characteristics, the calculated fundamental wave potential is consistent with the measured results, and provides a theoretical basis for the design of the electromagnetic field of this type of motor. Based on this, through field-circuit coupling method, the external circuit is used to simulate the rated load condition, and the excitation current under rated condition is calculated. This method has practicality and can provide reference for the calculation of the general AC exciter excitation current.

Introduction

The brushless AC exciter acts as a synchronous generator that supplies excitation current to the main generator and plays an important role in the entire power generation system. In the design of synchronous generators, magnetic circuit design is the key, which largely determines the performance and quality of the motor. Magnetic circuit design relies on electromagnetic calculations [1]. By calculating the no-load characteristics of the motor, we can help us determine whether the motor's magnetic circuit design is accurate. The excitation current of one of the main operating data of the brushless AC exciter is also an important part of the motor design. The accuracy of the rated excitation current calculation also directly affects the operation of the brushless AC exciter. At present, most of the literatures use the finite element method to analyze the related research of permanent magnet motor, synchronous motor and brushless DC motor [2,3,4,5], but there is little research on the armature rotating brushless AC exciter. The brushless AC exciter was studied by Magnet software, and a two-dimensional transient motion field model was established. The spatial distribution, electromagnetic parameters and circuit parameters of the magnetic field under no-load conditions were simulated [6]. The finite element software is used to calculate the no-load characteristics of the generator, and the relevant characteristic curve is obtained and the excitation current under the rated load is calculated [7]. ANSYS software was used to establish a two-dimensional static magnetic field simulation model. The rated power factor and rated voltage iteration method were used to determine the excitation current under rated conditions and compared with the design values introduced by Westinghouse [8]. The literature [9] uses Excel VBA design program, one-button modeling and solution to calculate and compare the excitation current of 600MW turbo generator. In this paper, the brushless AC exciter is used to simulate the electromagnetic field of the motor based on Maxwell software. The air gap magnetic field distribution is analyzed to calculate the no-load potential of the motor under different excitation currents, and the no-load characteristic curve is obtained. The calculated fundamental potential and the plant are calculated. In the comparison of the test values, the error is small. The double iterative method of terminal voltage and power factor to calculate the excitation current will result in poor computational convergence. Therefore, the equivalent impedance method is used to simulate the
rated load condition in the external circuit, which effectively avoids the iteration of power factor and improves the efficiency. Calculate convergence [10].

Theory and Calculation Methods

No-load Characteristic Calculation

Each time an excitation current $I_f$ is given, the corresponding no-load potential $E_0$ is obtained, whereby the no-load characteristic curve $E_0 = f(I_f)$ of the AC exciter can be obtained.

The calculation steps are as follows:

1) Select the Transient field, establish a two-dimensional model, define the material properties of the stator, rotor core and magnetic pole, set the boundary conditions, set the split parameters, and load the solution time;
2) Given the initial current value of the field winding $I_{fn}$;
3) Start the split and calculate the magnetic field distribution;
4) Find the radial air gap magnetic density $B_r$ at the given value, and perform harmonic analysis to extract the fundamental wave $B_1$:

$$B_r(t) = \sum_{n=1}^{\infty} (a_n \sin(n\omega t) + b_n \cos(n\omega t))$$  \hspace{1cm} (1)

$$B_1(t) = \sqrt{a_1^2 + b_1^2} \cos(\omega t - \varphi) = B_m \cos(\omega t - \varphi)$$  \hspace{1cm} (2)

$a_1, b_1$—the Fourier coefficients of the sine and cosine of the fundamental wave, and $\varphi = \tan^{-1} \frac{a_1}{b_1}$

5) Calculate the fundamental flux of the fundamental air gap:

$$\varphi_0 = \frac{1}{2} B_m \tau l_{eff}$$  \hspace{1cm} (3)

$l_{eff}$—the effective length of the motor core;
$\tau$—pole pitch;
$\varphi_0$—the magnetic flux per pole of the motor.

6) If the air gap magnetic density is distributed sinusoidally along the circumference, the effective value of the rotor winding induced potential of the brushless AC exciter is:

$$E_0 = 4.44f_1 kN \varphi_0$$  \hspace{1cm} (4)

In the analysis of the no-load characteristics of the AC exciter, the voltage waveform distortion rate is an important parameter:

$$K_{N1} = \sqrt{\sum_{n=1}^{\infty} \frac{E_{mn}^2}{E_{M1}}} \times 100\%$$  \hspace{1cm} (5)

$E_{mn}$ is the amplitude of each harmonic

Rated Excitation Current Calculation

In order to avoid the influence of the double iterative convergence of the terminal voltage and the power factor angle, the field-circuit coupling method is used to simulate the rated load condition of the brushless AC exciter without iterating the power factor. Can improve computational convergence. The external circuit is constructed and coupled with the finite element model of the electromagnetic field to form a simulation system. The external circuit is shown in Figure 1. LWindingA, LWindingB, and LWindingC are three-phase windings coupled with the finite element model, and the equivalent resistance $R$ and $L$ The value of the inductance $L$ is negligible because the leakage inductance at the end is much smaller than the equivalent load impedance.
Using Maxwell to set the parameterized variable [11], the excitation current is set as a variable, and by adding a series of excitation current values, the fundamental voltage component of the terminal voltage is matched with the rated voltage, so that the terminal voltage meets the rated voltage and also satisfies the rated power factor. The current at this time is the rated excitation current.

### Establishment of Finite Element Model of Brushless AC Exciter

#### Calculation Model

<table>
<thead>
<tr>
<th>parameters</th>
<th>Numerical value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_N$/kW</td>
<td>28</td>
</tr>
<tr>
<td>$U_N$/V</td>
<td>100</td>
</tr>
<tr>
<td>$I_N$/A</td>
<td>180</td>
</tr>
<tr>
<td>$\cos \phi$</td>
<td>0.9</td>
</tr>
<tr>
<td>$f$/HZ</td>
<td>180</td>
</tr>
<tr>
<td>$m$</td>
<td>3</td>
</tr>
<tr>
<td>$n_N$(r/min)</td>
<td>3600</td>
</tr>
</tbody>
</table>

A two-dimensional simulation model of the transient field of the brushless AC exciter is established in the finite element calculation software Maxwell2D. Taking the whole model as the solution area, the stator outer diameter and the rotor inner diameter are taken as vector boundaries, and the physical model is shown in Figure 2.

### Material Properties of Brushless AC Exciter

There are 6 pole punching pieces on the stator, and each magnetic pole is wound with a field
winding. The magnetic pole and the yoke are made of the same material, and 1 steel plate #8 is used. The rotor has 54 slots, embedded with double-layer armature wave windings, and the pole distance is τ=9. The upper and lower sides of the winding are divided into three sets of series windings A, B, and C, and the number of parallel branches is 2. The armature punching material is made of 50W310 silicon steel sheet. The air gap δ=3mm, considering the saturation and nonlinearity of the ferromagnetic material, the magnetization curve of the core material is shown in Figure 3.

![Figure 3. Core material magnetization curve.](image)

**Brushless AC Exciter Meshing**

In practical engineering applications and simulation analysis, finite element meshing is an important part, which directly determines the final calculation accuracy and accuracy [12]. If you set too many grids, the calculation time is long and the amount of memory required is large, the calculation convergence will be reduced, and even some areas will not converge and the correct value will not be obtained; the number of grids is too small, and some large split areas For example, the stator core, the number of split triangles will be very sparse, so that the change sensitivity of the variables is not large, resulting in poor accuracy of the calculation results, so it is critical to select the appropriate splitting unit.

Maxwell 2D has an adaptive splitting technique that eliminates the need to manually set the split parameters. The software automatically determines the grid cells based on spacing, air gap and area size. Figure 4 shows the results of software adaptive segmentation.

It can be seen from Figure 4 that the adaptive meshing is not suitable for the splitting unit in the pole piece, the magnetic pole, the stator field winding, the rotor slot and the armature winding. It is necessary to set the splitting parameters of each part and adopt the sub-area. Local refinement is shown in Figure 5.

![Figure 4. Finite element adaptive meshing diagram.](image)

![Figure 5. Refined mesh map.](image)

**Analysis of Finite Element Simulation Results**

**No-load Characteristic Calculation Result**

The air gap magnetic density of the brushless AC exciter at no load is important to the electromagnetic design of the motor. It has a certain influence on the induced potential on the armature winding as well as the power and torque. The air gap magnetically dense radial fundamental wave under no-load conditions is shown in Figure 6.

![Figure 6. Air gap magnetic density](image)
Figure 6. Air gap magnetic dense fundamental wave. Figure 7. No-load voltage waveform.

Figure 6 is an air gap magnetic-dense fundamental wave diagram when the exciting current is 5 A. It can be seen from the figure that the fundamental wave amplitude is about 0.75T.

Since there is no influence of the armature reaction at no load, the magnetic potential is only provided by the excitation magnetic potential, so the transient waveform of the terminal voltage is close to the sinusoid. Figure 7 is a no-load voltage waveform of the A-phase winding of the brushless AC exciter, and Fourier decomposition is performed on the no-load voltage to obtain a no-load voltage amplitude of 102.7 V with an error of about 2.7%. B and C phase lag A phase 120°, 240°, and will not be described here.

The excitation current is iteratively calculated by Maxwell to obtain the data in Table 2, and the no-load characteristic curve is obtained. Comparing the calculated value of the fundamental potential with the experimental value, the average error is about 4%, which is within the actual engineering error range.

Table 2. No-load characteristics calculation results.

<table>
<thead>
<tr>
<th>Calculated $I_f$/A</th>
<th>Calculated $E_0$/V</th>
<th>Tested $I_f$/A</th>
<th>Tested $E_0$/V</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>51.9</td>
<td>2.5</td>
<td>50</td>
</tr>
<tr>
<td>5.0</td>
<td>102.6</td>
<td>5.0</td>
<td>100</td>
</tr>
<tr>
<td>7.5</td>
<td>142.4</td>
<td>5.5</td>
<td>110</td>
</tr>
<tr>
<td>10.0</td>
<td>163.8</td>
<td>7.4</td>
<td>140</td>
</tr>
<tr>
<td>12.5</td>
<td>175.8</td>
<td>9.7</td>
<td>160</td>
</tr>
<tr>
<td>15.0</td>
<td>183.9</td>
<td>13</td>
<td>180</td>
</tr>
<tr>
<td>17.5</td>
<td>189.2</td>
<td>23</td>
<td>220</td>
</tr>
<tr>
<td>20.0</td>
<td>193.2</td>
<td>23</td>
<td>220</td>
</tr>
<tr>
<td>22.5</td>
<td>196.6</td>
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<td></td>
</tr>
<tr>
<td>25.0</td>
<td>199.6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 8. No-load characteristic curve.
It can be seen from the calculation results that the no-load characteristic curve basically reflects the magnetic saturation characteristics of the AC exciter core. The comparison between the calculated value and the experimental value in Figure 8 proves that the finite element method is effective for the analysis of the no-load characteristics of the brushless AC exciter and has good simulation performance. At the same time, based on the study of the no-load characteristics, further analysis and calculation of other properties of the exciter can be performed.

**Rated Excitation Current Calculation Result**

Using the Maxwell parameterization setting, the excitation current is arrayed so that the fundamental voltage component of the terminal voltage is consistent with the rated voltage and also satisfies the power factor. At this time, the corresponding excitation current is the rated excitation current. Figure 9 is the distribution of magnetic lines of force under nominal motor conditions at $t = 0.01$ s. The voltage and current waveforms of phase B are extracted separately, as shown in Figure 10. It can be seen from the figure that the first zero-crossing point of the voltage is 2.4ms, the first zero-crossing point of the current is 2.8ms, and the current hysteresis voltage is 25.92°, that is, the power factor is $\cos(25.92°) = 0.899$, and the rated power factor is 0.9. (hysteresis) is consistent.

![Figure 9. Rated load magnetic line distribution.](image1)

![Figure 10. Rated load voltage and current diagram.](image2)

When analyzing the air gap magnetic density under the rated working condition, due to the load current applied to the rotor, the influence of the armature reaction causes the calculated air gap magnetic density waveform to be distorted, as shown in Figure 11. The excitation current is added from 5A to 30A (step length is 5), and the corresponding load voltage is obtained on the armature winding. Through analysis and calculation, we obtain the results of Table 3, and the error with the factory test value is 6.03%.

![Figure 11. Air gap flux density at rated load.](image3)

<table>
<thead>
<tr>
<th>Calculated $I_f$ (A)</th>
<th>Tested $I_f$ (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.45</td>
<td>5.8</td>
</tr>
</tbody>
</table>

**Conclusion**

In this paper, the finite element software Maxwell is used to model, simulate and calculate the
28kW brushless AC exciter. The air gap magnetic density, no-load potential and magnetic flux density distribution of the motor under no-load are studied. Finally, the no-load characteristic is calculated and the no-load characteristic curve is drawn. The field-circuit coupling method is used to simulate the rated load condition, and the rated excitation current is calculated. The result is consistent with the actual rated condition and the error is within the effective range, which proves the feasibility of modeling and meets the actual engineering design requirements. This method has high practicability and can be applied to the calculation of the rated excitation current of general synchronous motors. It can also be extended to the research and analysis of rotary motors and other types of motors. It can also study the transient circuit characteristics of steady-state short circuits and faults.

References


