Research on Life Loss of Generator Retainer Caused by Negative Sequence Current

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Abstract. With a large number of wind and solar power sources connected to the power grid, higher requirements are put forward for the power generation equipment to respond to the power grid imbalance. The safety research of generator rotor retaining ring under the impact of negative sequence current is of great significance. For 300MW turbogenerator, the two-dimensional and three-dimensional eddy current, temperature rise, stress and life of generator rotor under the impact of negative sequence current are analyzed and studied. The two-dimensional calculation models of stator and rotor are established, and the distribution of negative sequence eddy current field in rotor section is analyzed; considering the contact resistance between rotor and retaining ring and the end effect of magnetic field, a three-dimensional analysis model is established, and the calculation results of three-dimensional eddy current field, temperature field and stress field are obtained. The analysis shows that after considering the contact resistance between rotor and retaining ring and end effect, the current density at the contact between retaining ring and rotor big tooth edge is 17.6 times of the two-dimensional calculation result of rotor section, and the maximum temperature of rotor retaining ring reaches 170.36°C.

1. Introduction

In the current new power system with the theme of new energy, the ability of power generation equipment to resist all kinds of grid load fluctuations is increasing. When the two-phase imbalance or three-phase imbalance fault occurs in the power grid, it is easy to cause the asymmetric operation of the generator. The asymmetric stator current can lead to local overtemperature of the generator rotor and its parts. In serious cases, it may lead to local overheating or rotor burnout. The transient negative sequence current induces negative sequence eddy current on the surface of the generator rotor. The negative sequence eddy current will generate a lot of heat through the parts in contact with the rotor, significantly improve the local temperature and local thermal stress of the generator rotor, generate compressive stress on the rotor surface and tensile stress inside. After the impact of transient negative sequence current, the generator rotor and related components experienced a low cycle fatigue life loss.

Many scholars have studied the electric vortex flow field and temperature field on the surface of generator rotor caused by negative sequence current. Negative sequence eddy current has been studied over the world for a long time \cite{1,2}, such as analysing the influence of damping structure on the additional loss of negative sequence eddy current. Salof \cite{3} used the difference method to solve the two-dimensional section temperature field of rotor under negative sequence current. Batch \cite{4}
analysed the negative sequence eddy current and temperature field of the three-dimensional model of the test rotor.

Li Junqing, proposed the method of using hybrid element (hybrid coordinate system) to calculate the motor temperature field[5]; Kou Pangao studied the electromagnetic analysis, temperature and thermal stress of large hydro generator[6]; Ma Minghan et al. Established the three-dimensional heat transfer model of steam turbine generator by using the finite element method, calculated and analysed the temperature field of typical fault of generator rotor[7]; Hu Xiancheng and Bai Yamin[8,9] used the finite element method to complete the negative sequence eddy current field, additional loss and temperature field of the two-dimensional rotor model; Xu Song[10] carried out nonlinear temperature field analysis of two-dimensional model of generator rotor; Lu Diqiang et al[11]. analysed the temperature field at the end of Turbogenerator by using quasi three-dimensional traveling wave method; Zhou Guanghou[12] calculated the negative sequence capacity of the generator based on the negative sequence test data; Dong Jianyang et al[13,14]. analysed the negative sequence eddy current field and temperature field of the rotor section of the imported generator, and mainly studied the middle section of the generator rotor without considering the end effect; Huang Hao, Shi Nan and Wang Honghu[15-17] completed the analysis of magnetic field, eddy current field and temperature field at the end of generator rotor during steady-state and leading phase operation without contact resistance and additional parts. Li Weili[18] analysed the eddy current loss and temperature rise of turbine generator rotor under steady-state and negative sequence conditions. Dong Chuanyou[19] made a theoretical analysis on the transient negative sequence current of generator in nuclear power plant. Guo Wu [20] carried out the analysis of loss and temperature field under different negative sequence currents.

Taking 300MW steam turbine generator as the research object, this paper establishes the two-dimensional and three-dimensional mathematical models for the calculation of negative sequence eddy current field of generator rotor and studies the eddy current distribution law of steam turbine generator rotor end considering component contact resistance under the condition of negative sequence current. The calculation and analysis of negative sequence electromagnetic field, eddy current field, temperature field and stress field of three-dimensional solid model at the end of generator are realized. The local overheating caused by the contact resistance between the rotor and the retaining ring and its influence on the life of the retaining ring are studied.

2. Physical structure of the end of the generator rotor
In order to analyse the distribution law of sequence eddy current on the rotor and its parts, two-dimensional and three-dimensional geometric models are established according to the design drawing and assembly drawing of 300MW steam turbine generator, as shown in figure 1, which are used for two-dimensional and three-dimensional numerical calculation of rotor negative sequence eddy current. The basic design parameters of the geometric model are as follows: the diameter of the rotor is 1100mm, the air gap thickness is 75mm, the diameter of the stator slot bottom is 1582mm, and the outer diameter of the stator core is 2500mm.
As shown in figure 1(a), the two-dimensional calculation model includes the stator coil, stator core, rotor bar and rotor core of the generator, in which the stator winding is given different colours according to the phase sequence; the three-dimensional calculation model in figure 1(b) includes the stator core, stator bar, rotor core, rotor retaining ring and rotor winding of the generator. In the process of electromagnetic calculation, the air area covering all parts is established.

3. Theoretical basis of negative sequence eddy current calculation

The symmetrical component method is used to decompose the three-phase asymmetric current into three parts: zero sequence component, positive sequence component and negative sequence component. The composite value of zero sequence component in space is zero; the positive sequence component generates a rotating magnetic field in the same direction and frequency as the operating magnetic field; the negative sequence component generates a spatial rotating magnetic field opposite to the running direction in the stator winding. The three-phase negative sequence current is equal and the phase difference is -120°. Negative sequence magnetic field induces negative sequence eddy current on the surface of various components (big teeth, small teeth, slot wedge, retaining ring, damping winding, excitation winding, etc.) on the rotor surface.

3.1. Mathematical model of eddy current field and temperature field

For the convenience of program solution, Maxwell equations are transformed into general homogeneous wave equations according to the law of charge conservation and the relationship between potential shift vector, magnetic induction intensity and current density, as shown below:

\[
\begin{pmatrix}
    \nabla^2 - \mu \gamma \frac{\partial}{\partial t} - \mu \varepsilon \frac{\partial^2}{\partial t^2} \\
    \frac{H}{B} \\
    \frac{E}{D}
\end{pmatrix} = 0
\]

(1)

Where \( \mu \) is permeability; \( \gamma \) is conductivity; \( H \) is the magnetic field strength; \( B \) is magnetic induction intensity; \( E \) is the electric field strength; \( D \) is the potential shift vector.

The above formula is normalized to reduce the number of degrees of freedom to be solved. Since the eddy current field studied in this paper belongs to sinusoidal steady-state time harmonic field, the mathematical model in phasor form is obtained, as follows:

\[
(\nabla^2 - j \omega \mu \gamma) \cdot \begin{pmatrix}
    \dot{H} \\
    \dot{B} \\
    \dot{E} \\
    \dot{J}
\end{pmatrix} = 0
\]

(2)

Where \( \omega \) is the angular frequency of power supply; \( J \) is the current density.

For two-dimensional calculation, the eddy current region of the model is mainly concentrated on the surface of the rotor and the surface of the rotor winding; however, in the three-dimensional calculation, the eddy current area of the model includes the surface of the rotor, the surface of the retaining ring, the linear section and end section of the rotor winding [21,22]. Therefore, the eddy current solution area includes:

\[
\begin{cases}
    \nabla \times \left( \frac{1}{\mu} \nabla \times A \right) - \nabla \left( \frac{1}{\mu} \nabla \cdot A \right) + \sigma \frac{\partial A}{\partial t} + \sigma \nabla \phi = 0 \\
    \nabla \cdot \left( -\sigma \frac{\partial A}{\partial t} - \sigma \nabla \phi \right) = 0
\end{cases}
\]

(3)

In the non-eddy current solution area:

\[
\nabla \times \left( \frac{1}{\mu} \nabla \times A \right) - \nabla \left( \frac{1}{\mu} \nabla \cdot A \right) = J_s
\]

(4)
Where $A$ is the complex vector magnetic potential; $J_s$ is the source current density; $\mu$ is permeability; $\sigma$ is conductivity; $\omega$ is the angular frequency of the power supply.

In the rectangular coordinate system, the differential equation of heat conduction has [23]:

$$
\begin{align*}
\lambda \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) &= -q, \\
\kappa \left( \frac{\partial T}{\partial n} \right)_{x} &= 0, \\
\kappa \left( \frac{\partial T}{\partial n} \right)_{y} &= -\alpha(T - T_r).
\end{align*}
$$

Where $T$ is the temperature value of the object; $T_r$ is the temperature value of the surrounding medium; $\lambda$ is the thermal conductivity of the heat conducting medium; $\alpha$ is the heat dissipation coefficient of the heat dissipation surface; $q$ is the heat source density; $n$ represents the direction of the normal vector of the boundary surface.

### 3.2. Grid iteration principle

In the finite element calculation, the mesh of the weak part of the low cycle fatigue life of the rotor retaining ring is densely divided, and the division of the rest of the mesh is automatically completed by the software. The refinement of the mesh belongs to the discretization of the finite element. With the iterative solution of the calculation process, the size of the grid decreases continuously. According to the derivation in reference [8], let the solution of problem $V$ be $A_0$ and the finite element solution be $A^{(n)}$. Under the mesh division meeting certain conditions, there are:

$$
A_0 = A^{(n)}_0 + \epsilon^{(n)}_0.
$$

Where $A^{(n)}_0$ is the grid function and $\epsilon^{(n)}_0$ is the cutting value error.

When $n \to \infty$, $\|\epsilon^{(n)}_0\| \to 0$. That is, the finite element solution will converge to the solution of the original problem after iteration.

### 3.3. Boundary condition

Basic assumptions for temperature field calculation:

1. In the solving process, the rotor is always in adiabatic state;
2. The fluid density and pressure distribution in the motor are uniform, that is, the influence of fluid on negative sequence temperature distribution is ignored;
3. There is no energy transfer between the rotor and the rotating shaft, that is, the inner circular surface of the rotor is adiabatic to the rotating shaft.

Boundary conditions of calculation model:

1. The radial and axial sections of the outermost model are adiabatic boundary conditions;
2. Convective heat transfer surfaces are all surfaces in contact with the fluid.

According to the basic principle of finite element, the three-dimensional negative sequence temperature field distribution can be obtained, and the node temperature in the solution area of generator rotor retaining ring can be obtained.

### 4. Calculation of two-dimensional negative sequence eddy current field

#### 4.1. Mesh generation of two-dimensional eddy current field considering skin effect

In order to better simulate the negative sequence eddy current field and capture the skin effect of eddy current in the solution process, a very thin surface eddy current layer is specially divided on the rotor surface when dividing the grid, and the initial size of the grid is set to 2mm, which can minimize the amount of calculation and shorten the calculation time on the premise of ensuring the solution accuracy. With the iterative solution of the calculation process, the size of the grid decreases continuously. The local grid is shown in figure 2.
The current phase sequence in the stator coil is set according to the phase sequence distribution, the negative sequence eddy current field on the rotor surface in two-dimensional is calculated by using the two-dimensional eddy current field calculation solver, and the distribution law of negative sequence eddy current on the rotor surface is analysed.

4.2. Analysis of calculation results of two-dimensional electromagnetic field

The distribution of negative sequence eddy current along the radial direction of rotor large teeth at 0° phase angle is shown in figure 3. It can be observed that the magnitude of negative sequence eddy current is close to 0 from the rotor centre to the position 7mm close to the rotor surface, and the current density is greater than 10000 A/m² within the range 7mm close to the rotor surface. The maximum value of $7.84 \times 10^5$A/m² is reached at the position 2.3mm away from the rotor surface and the skin effect depth of negative sequence current are consistent with the calculation results of the formula.

In order to reduce the energy residual and improve the calculation accuracy, the number of grids used in the calculation is increased from less than 50000 to 345000, and the energy residual is 0.156%, which meets the calculation accuracy of the solution. Figure 4 shows the grid independence verification results of two-dimensional finite element calculation, and the number of grids meets the independence requirements.
Figure 4. Grid Independence Verification of Two-dimensional Model

The negative sequence current has a sinusoidal distribution of 100Hz, and the current density of the negative sequence eddy current induced on the rotor surface is also sinusoidal distribution. According to the calculation results, the variation of induced current density on the surface of big teeth and small teeth with phase angle is extracted. Figure 5 shows the variation of induced current density distribution on the big tooth surface with phase angle, and the depth of sampling curve is 0.1mm from the big tooth surface. It can be seen that the maximum induced current distribution is between 60° and 90°, and the maximum value is greater than 2500000A/m².

Figure 5. Variation of Negative Sequence Eddy Current Distribution with Phase Angle on Large Tooth Surface

The maximum induced current density occurs near 0° and has a phase difference of more than 60° with the big tooth. This result can be more clearly observed from the negative sequence eddy current...
density vector on the rotor surface in figure 6. The dark red and above areas in the figure represent eddy currents with absolute current greater than $10^6$A/m². In the circumferential direction, the negative sequence eddy current is nearly sinusoidal along the axial direction. Since the direction of the magnetic field generated by the negative sequence current is in the plane of the rotor section, the current density of the induced negative sequence eddy current is perpendicular to the rotor section.

Due to the large sampling density used in post-processing, the current density of negative sequence eddy current in figure 6 is basically continuously distributed. At the same time, it can be inferred that the negative sequence eddy current density approximately presents a spatial sinusoidal distribution in the circumferential direction of the rotor at each phase angle; the current density on the tooth surface is slightly higher than that on the small tooth surface; some negative sequence vortices are basically distributed on the surface of the rotor and the inner surface of the slot wedge; at the inner surface of the slot wedge, the negative sequence current decreases with the decrease of the radius, and the current density at the bottom of the rotor slot is basically close to 0.

![Figure 6. Vector Diagram of Negative Sequence Eddy Current Density on Rotor Surface (2D Model)](image)

5. Calculation of three-dimensional negative sequence eddy current field

5.1. Geometric model of three-dimensional negative sequence eddy current calculation
Because the damage of negative sequence eddy current to the rotor generally occurs at the end retaining ring of the rotor, the two-dimensional negative sequence eddy current calculation cannot consider the contact of rotor end parts, the end effect of electromagnetic field and the flow of negative sequence eddy current on the rotor retaining ring. In order to consider the end effect of generator stator and rotor and the contact resistance between generator rotor big teeth, small teeth and retaining ring, it is necessary to establish a three-dimensional generator model and analyse the negative sequence eddy current field distribution and heating at the end.

The difficulty in establishing the three-dimensional model lies in the spatial curve of the end stator winding. In order to reduce the force on the end coil and increase the reliability of the end coil, the involute equation on the conical surface is adopted in the design of the generator. According to the
derivation, the involute equation is obtained and the three-dimensional space curve is established. The three-dimensional model of the end stator winding coil in the form of conical involute is obtained by scanning, as shown in figure 7.

Figure 7. Spatial Modelling of Stator Winding

(a) 2 stator windings in space
(b) Assembly of stator winding and stator

5.2. Contact resistance and symmetrical boundary setting of three-dimensional rotors retaining ring

By using the equivalent resistance method to simulate the contact resistance between the rotor and the retaining ring, a thin sheet with small thickness is added between the rotor and the retaining ring, and the contact resistance between the retaining ring and the rotor is simulated by adjusting the resistance of the sheet. As shown in figure 8, a sheet with a thickness of 1mm is used to simulate the contact resistance between the generator retaining ring and the large and small teeth of the rotor.

Figure 8. Equivalent Resistance Sheet of Contact Part Between Large and Small Teeth of Generator Rotor and Retaining Ring

Because the model considering contact resistance calculation is very complex, there are 1mm sheets in the stator and rotor assembly model with a diameter of 2.5m, which makes the final mesh generation and solution workload very huge. Due to the distribution requirements of three-phase current phase sequence, the whole three-dimensional model adopts cyclic symmetry constraint, and half of the model is removed. The final calculation model uses 9.335 million grids, the single solution takes much more time than the two-dimensional negative sequence eddy current field calculation, and the energy residual is 0.64%. It shows that the three-dimensional calculation model in this paper also has high calculation accuracy. Figure 9 shows the grid independence verification of the three-dimensional negative sequence eddy current field calculation model.
5.3. Analysis of calculation results of three-dimensional negative sequence eddy current field
The variation of three-dimensional negative sequence eddy current field distribution of generator rotor with phase angle is obtained by using half model calculation. The cloud diagram of negative sequence eddy current density including retaining ring is shown in figure 10. The dark red and above areas in the figure represent eddy currents with absolute current greater than $10^6$A/m².

By comparing the negative sequence eddy current density nephogram of the six phase angles, it can be seen that the induced negative sequence current rotates in the circumferential direction with the change of phase angle, and its maximum value appears at the part where the edge of the rotor big tooth contacts the retaining ring, and the maximum current density is $1.38 \times 10^7$A/m², which is 17.6 times of the two-dimensional calculation result. It can be seen that after considering the contact resistance between the rotor and the retaining ring and the end effect of the magnetic field, the current density of the negative sequence eddy current field is greater, which is consistent with the actual situation that the temperature rise caused by the negative sequence current is easy to burn out the generator retaining ring.

6. Calculation and analysis of temperature field, stress field and life

6.1. Analysis of calculation results of temperature field generated by three-dimensional negative sequence eddy current
According to the three-dimensional negative sequence eddy current field distribution, the heat generated by negative sequence eddy current is applied to the rotor surface in the form of heat source, and the temperature field distribution of generator rotor can be obtained. In view of the fact that rotor
damage usually occurs at the retaining ring, the retaining ring of generator rotor is selected as the research object to analyse the change of its temperature field with time. According to national standards, the generator is allowed to bear \( \left( \frac{I_2}{I_N} \right)^2 \cdot t = 10 \) negative sequence current under transient conditions. The temperature field distribution of rotor retaining ring \( \left( \frac{I_2}{I_N} \right)^2 \cdot t = 10 \) under 10% negative sequence current of generator is shown in figure 11.

![Figure 11. Temperature Field Distribution of Rotor Retaining Ring under 10% Negative Sequence Current of Generator](image)

Figure 11. Temperature Field Distribution of Rotor Retaining Ring under 10% Negative Sequence Current of Generator

Figure 12 shows the variation curve of temperature on generator rotor retaining ring with time. It can be seen that under the condition of \( \left( \frac{I_2}{I_N} \right)^2 \cdot t = 10 \) allowed by the national standard, the temperature of generator rotor retaining ring will rise by 40°C and the maximum temperature will be 170.36°C.

![Figure 12. Variation of maximum and minimum temperature of retaining ring with time](image)
6.2. Analysis of calculation results of stress field generated by three-dimensional negative sequence eddy current

Taking the negative sequence eddy current as the internal heat source, the temperature field of the rotor retaining ring of the sub motor is calculated as the boundary condition, which is substituted into the generator retaining ring structure to calculate and analyse the change of the stress field caused by the negative sequence eddy current. The stress field distribution of generator rotor retaining ring as shown in figure 13 is obtained.

Figure 13. Stress Field Distribution of Generator Rotor Retaining Ring Caused by Negative Sequence Current

It can be seen from the figure that the position with the maximum surface thermal stress caused by the negative sequence eddy current of the generator retaining ring is where the generator rotor retaining ring contacts the edge of the rotor big teeth. The distribution calculation results of the stress field will be combined with the rated load calculation results to calculate the power generation and rotor retaining ring.

6.3. Analysis of calculation results of life loss caused by three-dimensional negative sequence eddy current

The assembly model of rotor contacts with retaining ring and centre ring is used in the calculation of steady-state temperature field and stress field of generator rotor retaining ring. After analysis, 18 typical weak strength sites of rotor retaining ring are selected, as shown in figure 14.

Figure 14. Weak Parts of Generator Rotor Retaining Ring Life

The calculation results of steady-state temperature field and stress field of rotor retaining ring are tensor summated with the equivalent stress of generator rotor retaining ring due to negative sequence eddy current field. According to the calculation method of equivalent stress amplitude of asymmetric cycle, the calculation results of life loss of 18 strength weak points of generator rotor retaining ring are obtained, which are listed in table 1.
Table 1. Life loss of generator rotor retainer

| Position | Equivalent stress /MPa | Life times |
|----------|------------------------|------------|
| A        | 416.51                 | >10⁵       |
| B        | 429.17                 | >10⁵       |
| C        | 496.30                 | 42777      |
| D        | 598.71                 | 9918       |
| E        | 393.31                 | >10⁵       |
| F        | 398.43                 | >10⁵       |
| G        | 373.55                 | >10⁵       |
| H        | 380.84                 | >10⁵       |
| I        | 404.23                 | >10⁵       |
| J        | 425.59                 | >10⁵       |
| K        | 370.18                 | >10⁵       |
| L        | 363.77                 | >10⁵       |
| M        | 291.12                 | >10⁵       |
| N        | 292.99                 | >10⁵       |
| O        | 342.78                 | >10⁵       |
| P        | 365.24                 | >10⁵       |
| Q        | 388.31                 | >10⁵       |
| R        | 419.45                 | >10⁵       |

It can be seen from the above table that under the condition of negative sequence current allowed by the national standard, the service life of point D is less than 10⁴ times, which is more prone to failure. It is the key maintenance position for the generator rotor retaining ring to withstand the eddy current impact of negative sequence current.

7. Conclusion

Taking 300MW turbogenerator as an example, this paper establishes two-dimensional and three-dimensional eddy current field calculation models of rotor, studies the distribution law of negative sequence eddy current density on rotor surface under two-dimensional and three-dimensional conditions, further calculates and analyses the temperature field change and stress field distribution of rotor retaining ring, calculates and compares the life of typical weak points of rotor retaining ring, and obtains the following conclusions:

1) At each phase angle, the negative sequence eddy current density approximately presents a spatial sinusoidal distribution in the circumferential direction of the rotor; the current density on the surface of big teeth is slightly higher than that on the surface of small teeth; all negative sequence vortices are basically distributed on the surface of the rotor and the inner surface of the slot wedge; at the inner surface of the slot wedge, the negative sequence current decreases with the decrease of the radius, and the current density at the bottom of the rotor slot is basically close to 0.

2) The induced negative sequence current rotates in the circumferential direction with the change of phase angle. The position with the largest induced negative sequence current is located at the position where the edge of the rotor big tooth contacts the retaining ring, and the maximum current density is \(1.38 \times 10^7 A/m^2\) is 17.6 times higher than the two-dimensional calculation result. It can be seen that after considering the contact resistance between the rotor and the retaining ring and the end effect of the magnetic field, the current density of the negative sequence eddy current field is greater, which is consistent with the actual situation that the temperature rise caused by the negative sequence current is easy to burn out the generator retaining ring.

3) Under the condition of \((I_2/I_0)^2\cdot t=10\) allowed by the national standard, the temperature of generator rotor retaining ring will rise by 40°C and the maximum temperature is 170.36°C.

4) Under the impact of negative sequence eddy current, the rotor retaining ring has a large loss of service life, which should be the key part of maintenance.
In addition, in the life calculation of generator rotor retaining ring, considering the influence of creep, mechanical fatigue and other factors on the life, the life damage caused by negative sequence eddy current impact shall be less than 10% of the total life damage, leaving a margin for the life damage caused by other factors.

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