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Analysis of Stator Circulating Current Characteristics under Eccentricity Faults of Hydro Generator

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Abstract: *To study the harmonic characteristics of circulating current between the stator windings in parallel branches of the hydro generator under eccentric faults, the mechanism of circulating current is theoretically analyzed. On this basis, an eccentric fault model of the hydro generator is established by ANSYS, and the eccentric fault model is simulated and calculated to obtain the harmonic characteristics of the circulating current. The results indicate that the magnitude of circulating current increases with the degree of eccentricity. Under static eccentric faults, odd-order harmonic circulating currents are generated, while under dynamic eccentric faults, both odd-order and fractional-order harmonic circulating currents are produced.*

Keywords: *hydro generator; eccentric faults; circulating current inside parallel branches; finite element analysis*

1. Introduction

The majority of generators have air gap eccentricity flaws as a result of production process limitations and assembly errors. This problem may result in distortion of the magnetic field, which would change the air gap magnetic flux density, increase the imbalanced magnetic forces acting on the stator and rotor windings, and decrease the generator's operational dependability[1,2]. Consequently, it is crucial to investigate the circulation properties of eccentricity faults in generator air gaps, identify faults as soon as feasible, and lessen the damage from mishaps like generator shutdown brought on by the growth of eccentricity faults.

References [3,4] studied the spectral characteristics of the circulating current generated during eccentric faults in turbo-generators. References [5-7] analyzed the stator and rotor's radial vibration characteristics during the air gap eccentricity faults in the generator. Reference [8] investigated the variations in synchronous generator rotor core losses and temperatures before and after eccentric faults. Those papers mentioned above focus mostly on rotor losses, change in temperature, vibration characteristics of the stator and rotor winding, and the circulating current characteristics of parallel branches in steam turbine generators. The research findings offer a theoretical foundation for this paper's study of air gap eccentricity faults in hydro generators.

Taking the hydro generator as the research object in this paper, theoretically analyzes the mechanism of circulating current generation after a fault occurs in the hydro generator. Additionally, the finite element simulation model for the hydro generator eccentric fault is established. The paper studies the variation characteristics of circulating currents between the stator winding branches when the hydro generator experiences an eccentric fault under no-load operating conditions, providing a reference for the diagnosis of eccentric faults in hydro generators.

2. Air gap magnetic flux density before and after eccentricity in hydro generator

The air gap magnetomotive force of the hydro generator during normal operation is:

$$f(\alpha_m, t) = F_{vm} cos[v(\omega t - p\alpha_m)] \tag{1}$$

Where F_{vm} is the amplitude of the v-th harmonic magnetomotive force, ω is the electrical angular velocity, p is the number of pole pairs of the generator, α_m is the stator's circumferential mechanical

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angle, and $\nu = 1,3,5 \cdots$

When a hydro generator experiences eccentricity fault, there is no change in the air gap magnetomotive force, only the air gap magnetic conductivity changes. The magnitude of air gap magnetic conductivity per unit area is related to the radial air gap length between the stator and rotor inside the hydro generator.

Schematic diagrams of static and dynamic eccentricity in a hydro generator are shown in Fig 1 and Fig 2, respectively.

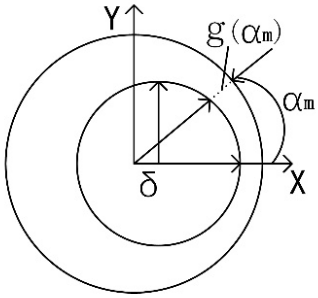

Figure 1: Schematic diagram of static eccentricity fault in a hydro generator

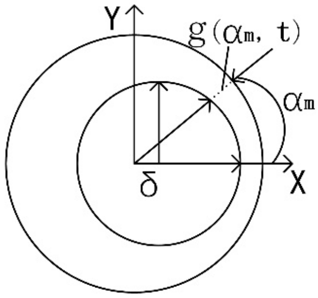

Figure 2: Schematic diagram of dynamic eccentricity fault in a hydro generator

The degree of offset in hydro generator is expressed using rotor eccentricity as follows:

$$\varepsilon = \frac{\delta}{g_0} \times 100\% \tag{2}$$

Where ε is rotor eccentricity, δ is the distance of rotor offset from the stator's geometric center, and g_0 is the radial average air gap length of hydro generator.

According to reference, the internal average radial air gap length of the hydro generator is:

$$\begin{cases} g_0 & Normal \\ g_0(1 - \varepsilon_s cos\,\alpha_m) & SE \\ g_0[1 - \varepsilon_d cos(\alpha_m - \omega t/p)] & DE \end{cases} \tag{3}$$

Where ε_s is static eccentricity, ε_d is dynamic eccentricity, SE is an abbreviation for static eccentricity faults, and DE is an abbreviation for dynamic eccentricity faults.

Because the ratio of magnetic permeability of air to air gap length is equal to the unit area air gap magnetic conductance, the reciprocal of the radial air gap length is expanded in a power series, and the higher-order harmonic component is ignored, magnetic permeability per unit area of the air gap is:

$$\begin{cases} \Lambda_0 = \mu_0/g_0 & Normal \\ \Lambda_0 + \Lambda_s cos\,\alpha_m & SE \\ \Lambda_0 + \Lambda_d cos(\alpha_m - \omega t/p) & DE \end{cases} \tag{4}$$

Where μ_0 is magnetic permeability of air, Λ_0 is invariant component of air gap magnetic permeability, Λ_s is the variation component of air gap magnetic permeability under static eccentricity fault, and Λ_d is the variation component of air gap magnetic permeability under dynamic eccentricity fault.

The product of air gap permeability per unit area and the air gap magnetomotive force is the air gap magnetic flux density. In the case of static and dynamic eccentricity faults in hydro generator, the air gap

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magnetic flux density generated by the ν-th harmonic magnetomotive force is given by equations (5) and (6) respectively.

$$\begin{aligned}B_{s\nu}(\alpha_m,t) &= F_{\nu m}cos[\nu(\omega t-p\alpha_m)](\Lambda_0+\Lambda_s cos\,\alpha_m)\\ &= F_{\nu m}\Lambda_0 cos(\nu\omega t-p\alpha_m)+\frac{1}{2}F_{\nu m}\Lambda_s\{cos[\nu\omega t-(\nu p-1)\alpha_m]+cos[\nu\omega t-(\nu p+1)\alpha_m]\}\end{aligned} \tag{5}$$

$$\begin{aligned}B_{d\nu}(\alpha_m,t) &= F_{\nu m}cos[\nu(\omega t-p\alpha_m)][\Lambda_0+\Lambda_d cos(\alpha_m-\omega t/p)] = F_{\nu m}\Lambda_0 cos(\nu\omega t-p\alpha_m)\\ &+\frac{1}{2}F_{\nu m}\Lambda_d\{cos[(\nu-1/p)\omega t-(\nu p-1)\alpha_m]+cos[(\nu+1/p)\omega t-(\nu p+1)\alpha_m]\}\end{aligned} \tag{6}$$

Based on equations (5) and (6), we observe that in the presence of a static eccentricity fault in a hydro generator, the air gap magnetic flux density includes odd harmonic components. Conversely, with a dynamic eccentricity fault, the air gap magnetic flux density comprises not only odd harmonic components but also fractional harmonic components. These harmonic components in the air gap magnetic flux density result in the generation of corresponding harmonic currents within the stator windings.

3. Simulation verification

3.1 Simulation modeling

Assuming that the magnetic permeability of the iron core material is isotropic, the magnetic field inside the motor is quasi-steady. Neglecting displacement currents and stator core eddy current losses, the boundary value problem of the two-dimensional transient field inside the hydro generator is:

$$\begin{cases}\Omega: \frac{\partial}{\partial x}\left(\frac{1}{\mu}\frac{\partial A}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{1}{\mu}\frac{\partial A}{\partial y}\right)=-J+\sigma\frac{dA}{dt}\\ \Gamma: A=0\end{cases} \tag{7}$$

Where A is the magnetic vector potential, μ is the magnetic permeability, σ is the electrical conductivity, J is the source current density, Ω is the magnetic field integration surface, Γ is the stator outer boundary and rotor inner boundary.

To verify the correctness of the theoretical analysis results, the finite element simulation model of the hydro generator is established based on the boundary conditions given in equation (7) and the parameters of the hydro generator in Table 1, as shown in Fig 3. The mesh division of the model is shown in Fig 4.

Table 1: Main parameters of the hydro generator

Parameters	Value
Rated capacity	227.8 MVA
Rated voltage	15.75kV
No-Load excitation current	1204A
Power factor	0.9
Number of poles P	10
Stator parallel branches	4
Rated speed	300r/min

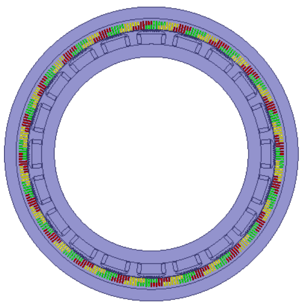

Figure 3: Schematic diagram of model for the hydro generator

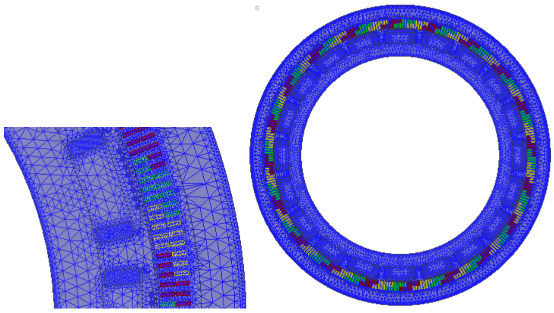

Figure 4: Schematic diagram of grid division for the hydro generator

3.2 Simulation results analysis

Based on the established finite element simulation model, simulations are conducted for the hydro generator under no-load conditions in both the normal state and in the presence of static and dynamic eccentricity faults. The static and dynamic eccentricities are set at 10%, 20%, and 30% respectively.

3.2.1 Simulation results for static eccentricity fault

The simulation results for the hydro generator with the static eccentricity faults are shown in Fig 5 and Fig 6.

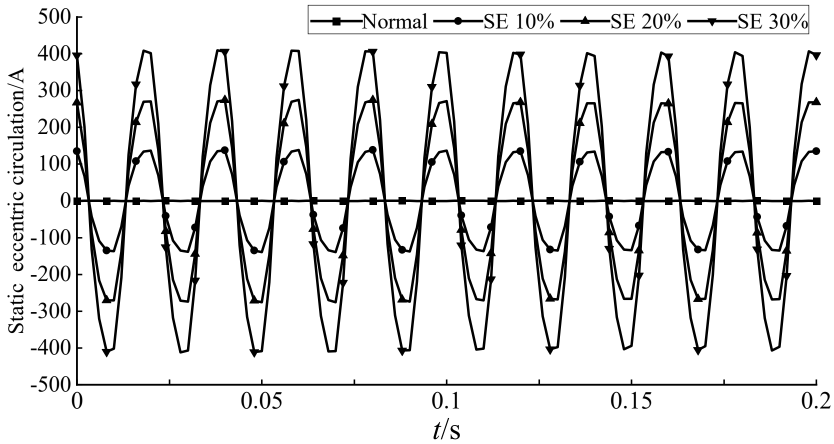

Figure 5: Schematic diagram of circulating currents in stator branch windings under static eccentricity fault

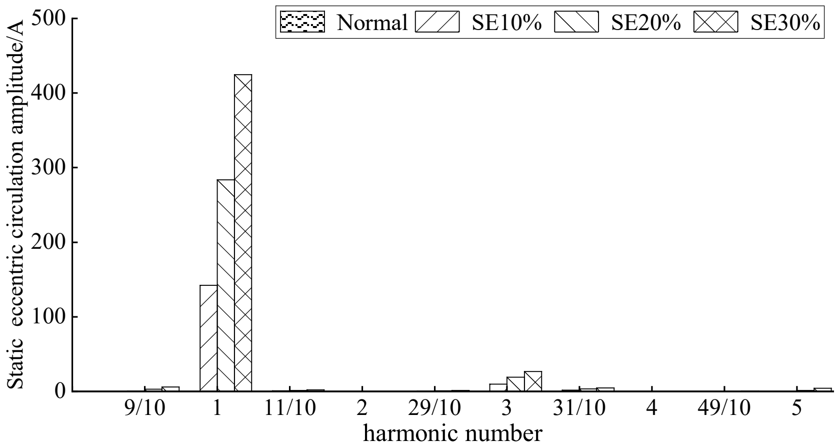

Figure 6: Spectral diagram of circulating currents in stator branch windings under static eccentricity fault

As shown in Fig 5, there is no circulating current between parallel branches of stator windings during normal operation of the hydro generator. However, in the case of a static eccentricity fault, the circulating current increases with the degree of eccentricity, and the magnitude of the circulating current remains constant. According to Fig 6, the circulating current contains odd harmonic components and the fundamental component increases significantly during the static eccentricity faults.

3.2.2 Simulation results for dynamic eccentricity fault

The simulation results for the hydro generator with the dynamic eccentricity faults are shown in Fig 7 and Fig 8.

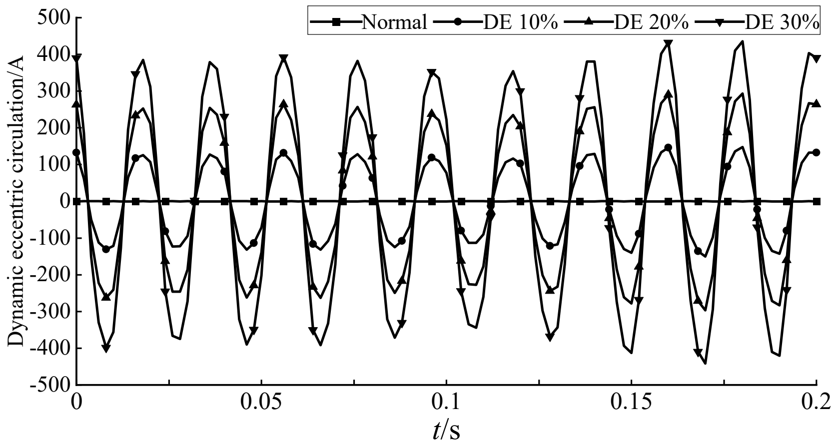

Figure 7: Schematic diagram of circulating currents in stator branch windings under dynamic eccentricity fault

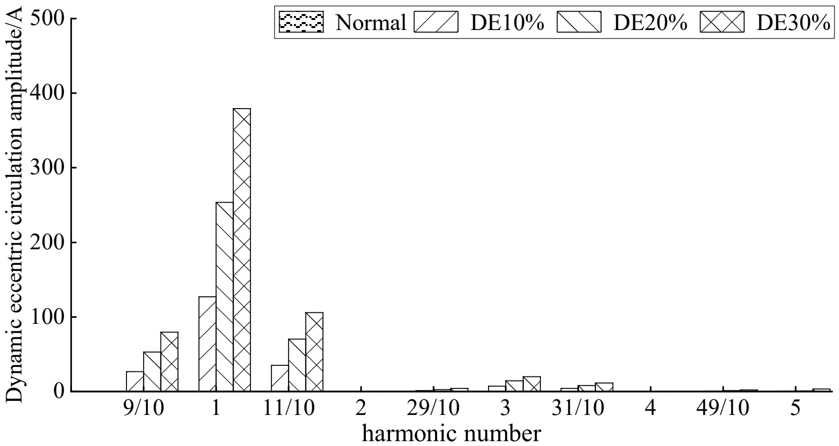

Figure 8: Spectral diagram of circulating currents in stator branch windings under dynamic eccentricity fault

As shown in Fig 7, there is no circulating current between parallel branches of stator windings when the hydro generator is operating normally. However, when the hydro generator experiences dynamic eccentricity fault, the circulating current increases with the degree of eccentricity, and the amplitude of the circulating current changes differently. According to Fig 8, when the dynamic eccentricity fault occurs, the circulating current contains odd harmonic components and fractional harmonic components.

4. Summary

Through the study of eccentricity faults for hydro generators in this paper during no-load operation, the following conclusions have been reached:

(1) When a hydro generator is operating normally, there is no circulating current between the parallel branches of the stator windings. However, in the case of static or dynamic eccentricity faults, a circulating current occurs between the parallel branches of the stator windings. The magnitude of circulating current increases with the degree of eccentricity, and the amplitude variation of static and dynamic eccentric current waveforms is different.

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(2) When a hydro generator experiences a static eccentricity fault, the circulating current between the parallel branches of the stator windings contains odd-harmonic components, and the fundamental frequency component increases significantly.

(3) When a hydro generator experiences a dynamic eccentricity fault, the circulating current between the parallel branches of the stator windings contains not only odd-harmonic components but also fractional harmonic components.

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