Research Article

Electromagnetic Forces and Mechanical Responses of Stator Windings before and after Rotor Interturn Short Circuit in Synchronous Generators

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This paper studies the stator winding electromagnetic force behaviors before and after rotor inter-turn short circuit (RISC) in synchronous generator. Different from other studies, this paper not only studies the electromagnetic force characteristics, but also investigates the mechanical responses, the damage regularity, and the countermeasure of the stator winding. Firstly, formulas of electromagnetic force online and end part are obtained. Then, a 3D finite element model of a 3-pair-pole simulation generator is applied to get the electromagnetic force, and the dangerous stator slot is found. Finally, the mechanical response of each end winding is acquired, and especially the directional deformations of nose part are calculated. It shows that the occurrence of RISC will bring in times of rotor rotating frequency components to electromagnetic force, but the DC component and 2p times of rotor rotating frequency components are still the main that will be decreased. Additionally, the winding insulation wear in the same layer is more serious than that in a different layer, nose fatigue fracture begins with the center, and nose insulation wear starts from the top.

1. Introduction

With the increase of the generator capacity, the winding electromagnetic force that generates alternating stresses and stimulates vibrations becomes larger as well. Consequently, the winding will endure worse fatigue fracture and insulation wearing.

By far, scholars have made a lot of efforts in studying the winding electromagnetic force properties. For instance, Merkhouf et al. proposed a quasi-3D electromagnetic model to compute the forces on the conductor bars in hydro-generators [1], while Sanosian et al. demonstrated how saturation of the stator teeth, actual magnetic field distribution inside the slot, eddy current in the damper bars, and the shape of the salient poles impacted the electromagnetic forces in the slot [2]. According to Biot-Savart Law, the mirror image method was employed to analyze the end magnetic field, and the electromagnetic force of the end winding was acquired by using the ampere force formula [3]. Meanwhile, Ghaempanah and Faiz reviewed the calculation methods for the magnetic force exerted on the stator end winding comprehensively [4]. Comparing the finite element method (FEM) with Biot-Savart method, it has been found that FEM was more effective for electromagnetic analysis [5]. Andrey Tatevosyan and Fokina made the study on the electromagnetic field of a synchronous generator based on the three-phase induction machine [6]. The 2D field–circuit–motion coupling analysis was employed to calculate the stator current in inverter-fed induction machine, as well as hydrogenators. And the distribution of electromagnetic force on stator windings was calculated [7, 8]. Comparatively, Stancheva and Iatcheva employed the 3D FEM to analyze the electromagnetic force distribution characteristics of the stator winding in turbo-generators [9, 10]. Chong et al. explored the electromagnetic force of involute part of the end windings by 3D FEM on nuclear
generator, and the vulnerable parts of double windings on

different layers are obtained [11]. In Ref. [12], the elec-

tromagnetic forces of transformer windings in the occurrence

of magnetic flux shunts were studied based on the finite

element method, which was validated by a double Fourier

series method. An advanced FEM has been used in [13] by

defining the superconductivity characteristic, and the results

show the efficiency of the applied method to mitigate the

leakage flux and electromagnetic forces of the windings. It

has been found that, under the steady-state condition in an

induction motor, there were radial, circumferential, and

axial forces consisting of a constant component and a si-
nusoidal component at the double frequency [14]. Besides,

the armature winding properties, such as the number of

winding layers and the slot fill factor, will affect the mag-

netomotive force harmonic components, leading to the

magnetic field changes. Consequently, the electromagnetic

force on stator windings will be influenced [15]. It shows that

choosing a right coil pitch may reduce the harmonic con-

ents and improve the conductor utilization ratios effec-

tively [16].

At the meantime, Stermecki et al. calculated the me-

chanical deformations of end winding in three-phase in-

duction machines under operating load condition, using a

3D FEM [17]. Fang et al. analyzed the electromagnetic forces

and stresses on the stator end windings of an electrical

submersible motor during the starting transient operation

[18]. Normally, the nose top, the middle point of the in-

volute, and the joint between the line part and the end part

are the most dangerous three positions since they get the

max stresses and deformations in a 600 MW turbo-generator

[19]. Meanwhile, the forces on the knuckle part of the upper

part of a coil end are larger than those on the other parts. In

addition, the constant components and the amplitudes of the

sinusoidal components of the forces on the same positions of

different coil ends in a phase belt are nearly different on

induction machine.

In summary, most of the studies focus on the winding

electromagnetic force properties in normal conditions, and

few of them have considered the electromagnetic force

behavior in faulty cases. Albanese et al. and Zhao et al.

studied on the end winding electromagnetic force spectrum

characteristics, modal, stress, deformation, and main vi-

bration shape in inter-phase short circuit conditions [20, 21].

However, the rotor inter-turn short circuit (RISC) is gen-

erally neglected because the generator can still run for a long

term until the planned maintenance point when the fault

degree is weak. Actually, it occurs from time to time due to

many causes such as the frictions by the residual metal

particles in the slots and in-proper assembling, and in this

case, the exciting electromagnetic force, as well as other

typical faulty properties, is different from that in the normal

conditions. For example, Nadarajan et al. proposed a hybrid

modeling approach to model synchronous generator by

combining the dq0 modeling with the winding function

approach for turn-to-turn short circuit [22]. Yucai and

Yonggang analyzed the difference between the virtual power

and the actual electromagnetic power when RISC occurs

[23], while Valavi et al. and Yun et al. studied the effect of the

fault on air gap flux density and the monitoring method

based on the distorted flux density [24, 25]. Furthermore, the

electromagnetic characteristics and mechanical character-

istics, as well as the correlative variety of the electrical pa-

rameters induced after rotor inter-turn short circuit on

turbine generator, are analyzed by Wan et al. [26–28]. Then,

the BP neural network method and the sensorless online

detection method were proposed to diagnosis rotor winding

inter-turn short circuit fault [29, 30].

Actually, the authors have also proposed a prestudy on

the electromagnetic force, as well as the mechanical re-

sponses of the stator end windings in a RISC case; more

details can be found in [31]. However, the theoretical model

in this prestudy is somewhat complex and hard to under-

stand, while the FE model, as well as the calculation result, is

not accurate enough (only part of the stator/rotor/winding is

established in the FE model). Moreover, there was no ex-

periment study for the validation in this aforementioned

work. As an improvement, in this paper, we improve both

the theoretical model and the 3D FE model and present an

experiment study, to obtain a more accurate result. The

remainder of this paper is arranged as follows. Section 2 puts

forward the theoretical analysis of the winding electro-

magnetic force for multi-pair-pole generator. Section 3

calculates the electromagnetic force distribution on the line

and end part, respectively, with FEM, and it is more rea-

sonable for comparing with the experimental results as the

vibration of end part winding is mainly caused by elec-

romagnetic force of the end. At the same time, it carries out

the experiment study and validates the correction of theo-

retic and simulated analysis. Then, the mechanical response

analysis is illustrated in Section 4, and a detailed analysis on

the directional deformations and the insulation wearing

regularity is specifically carried out for the nose part con-

sidering the complex structure and weakness. Finally, main

conclusions are drawn in Section 5.

2. Theoretical Analysis

2.1. Electromagnetic Force. The MMF in generator has been

obtained in Ref. [32], but the situation is just for one pair of

poles. Since there are some differences between the one-pair

and multipair poles, hereafter, we particularly carried out the

derivation for the multi-pair-pole generators.

For the sake of convenience, in this paper, we ignore the

higher harmonics whose values are relatively much smaller,

and the normal MMF can be written as

\[
\begin{align*}
\dot{F}_c (\alpha_m, t) & = F_c \cos (\omega t - p \alpha_m - \psi - 0.5 \pi) + F_r \cos (\omega t - p \alpha_m) \\
& = F_c \cos (\omega t - p \alpha_m - \beta) = F_c \cos (\omega t - p \alpha_m - \beta), \\
F_r & = \sqrt{F_r^2 \cos^2 \psi + (F_r - F_c \sin \psi)^2}, \\
\beta & = \arctan \frac{F_r}{F_r - F_c \sin \psi}
\end{align*}
\]

(1)
where $\alpha_m$ is the mechanical angle to indicate the circumferential position; see Figure 1(d). $p$ is the number of the pole pairs, \( \omega \) is the electrical angular frequency (\( \omega = p \omega_r \), $\omega_r$ is the mechanical angular frequency of the rotor), $\Psi$ is the internal power-angle of generator, $F_s$ and $F_r$ are the 1st harmonic MMF of the stator and the rotor, respectively, and $F_{cs}$ is the vector summation of $F_s$ and $F_r$ as indicated in Figures 1(a) and 1(b).

For the sake of clarification, we assume that the interturn short circuit takes place on the position of $\beta'$, as illustrated in Figure 1(d). $I_p$ is the exciting current, and $n_m$ is the number of the short circuit turns. The impact of RISC on MMF is equal to adding an inverse MMF to the normal one [33, 34]. For better comprehension, the involved MMF produced by the short circuit turns is also shown in Figure 1(c). Based on the magnetic flux conservation principle, the reversed MMF can be expressed as

\[
F_{r, m}(\alpha_m) = \begin{cases} \frac{I_p n_m (\pi - \beta')}{\pi}, & -\beta' \leq \alpha_m \leq \beta', \\ \frac{I_p n_m \beta'}{\pi}, & \text{other}, \end{cases}
\]

(2)

where $F_{rd}$ can be expanded by Fourier series as

\[
F_{rd}(\alpha_m) = a_0 + \sum_{n=1}^{\infty} a_n \cos(n \alpha_m) + b_n \sin(n \alpha_m),
\]

(3)

with

\[
\begin{align*}
a_0 &= \frac{1}{2\pi} \int_{-\pi}^{\pi} F_{rd}(\alpha_m) d\alpha_m = 0, \\
a_n &= \frac{1}{\pi} \int_{-\pi}^{\pi} F_{rd}(\alpha_m) \cos(n \alpha_m) d\alpha_m = -\frac{2I_p n_m \sin(n \beta')}{n \pi}, \\
b_n &= \frac{1}{\pi} \int_{-\pi}^{\pi} F_{rd}(\alpha_m) \sin(n \alpha_m) d\alpha_m = 0.
\end{align*}
\]

(4)

Then, $F_{rd}$ can be reduced to

\[
F_{rd}(\alpha_m) = -\sum_{n=1}^{\infty} F_{dn} \cos(n \alpha_m), F_{dn} = \frac{2I_p n_m \sin(n \beta')}{n \pi}.
\]

(5)

Considering that the rotor is rotating at $\omega_r$, the reversed MMF at position $\alpha_m$ can be finally described as

\[
F_{rd}(\alpha_m) = -\sum_{n=1}^{\infty} F_{dn} \cos(n \omega_r t - n \alpha_m).
\]

(6)

As indicated in Figure 1(b), the MMF after RISC can be written as

\[
\begin{align*}
f(\alpha_m, t) &= F_s \cos(p \omega_r t - p \alpha_m - \psi - 0.5\pi) + (F_r - F_{dp}) \cos(p \omega_r t - p \alpha_m) - \sum_{n=1, n \neq p}^{\infty} F_{dn} \cos(n \omega_r t - n \alpha_m) \\
F_{cs} &= \sqrt{F_s^2 \cos^2 \psi + (F_r - F_{dp} - F_s \sin \psi)^2}, \\
\gamma &= \arctan \frac{F_s \sin \psi}{F_r - F_{dp} - F_s \sin \psi}.
\end{align*}
\]

(7)

where $F_{cs}$ is the vector summation of $F_s$, $F_r$ and $F_{dp}$, as indicated in Figure 1(b).

Comparing Figure 1(c) and equation (7) with the result in Ref. [32] (Figure 2 and equation (11) in this reference), it is shown that the multi-pair-pole generators will have a different MMF distribution from that of one-pair generators.

The magnetic flux density (MFD) is composed of the MMF and the permeance per unit area (PPUA), and it can be obtained by multiplying these two [33].

\[
B(\alpha_m, t) = f(\alpha_m, t) \Lambda_0,
\]

(8)

where $\Lambda_0$ is the PPUA ($\Lambda_0 = \mu_0 g_0$), $g_0$ is the average value of the radial air-gap length between the stator core and the rotor core (as shown in Figure 1(d)), and $\mu_0$ is the permeability of air/vacuum.

Neglecting the affection of windings connection, the current of winding on $\alpha_m$ can be written as

\[
I(\alpha_m, t) = B(\alpha_m, t) l v = \frac{f(\alpha_m, t) \Lambda_0 l v}{z},
\]

(9)

where $l$ and $v$ are the effective length and the line velocity of the magnetic flux cutting the stator bar, and $Z$ is the reactance of the stator winding.
Figure 1: MMFs before and after RISC: (a) normal condition, (b) RISC case, (c) inversed MMF (down) and Rotor MMF (up), and (d) schematic diagram of air gap.

Figure 2: End winding model: (a) end winding support; (b) simplified mechanics model in radial direction.
According to the electromagnetic induction law, the force on the winding whose upper line (see Figure 3(f)) is at the circumferential position $\alpha_m$ can be written as

$$F_{I}(\alpha_m, t) = B(\alpha_m, t)I(\alpha_m, t)I = \frac{f^{2}(\alpha_m, t)A_{v}^2v}{Z}$$

$$= \frac{F_{c}^2\lambda_{v}^2v}{2Z} \left[ \cos(2\omega_{r}t - 2p\alpha_m - 2\beta) + 1 \right],$$

$$= \frac{F_{c}^2\lambda_{v}^2v}{2Z} \left[ F_{c}^{2} \cos 2(\omega_{r}t - p\alpha_m - \gamma) + \sum_{n=1, n \neq p}^{\infty} F_{dn}^{2} \cos 2(n\omega_{r}t - n\alpha_m) + F_{c}^{2} + \sum_{n=1, n \neq p}^{\infty} F_{dn}^{2} - \sum_{n=1, n \neq p}^{\infty} 2F_{c}F_{dn} \cos [(p - n)(\omega_{r}t - \alpha_m) - \gamma] \right]$$

$$+ \sum_{n=1, n \neq p}^{\infty} \sum_{k=1, k \neq n}^{\infty} F_{dn}F_{dk} \cos [(n - k)(\omega_{r}t - \alpha_m) - \gamma]$$

$$= \frac{F_{c}^2\lambda_{v}^2v}{2Z} \left[ F_{c}^{2} \cos 2(\omega_{r}t - 2p\alpha_m - 2\beta - p\alpha_k) + \cos \alpha_k \right],$$

$$= \frac{F_{c}^2\lambda_{v}^2v}{2Z} \left[ F_{c}^{2} \cos 2(\omega_{r}t - 2p\alpha_m - 2\beta - p\alpha_k) + \sum_{n=1, n \neq p}^{\infty} F_{dn}^{2} \cos 2(n\omega_{r}t - 2\alpha_m - \alpha_k) + F_{c}^{2} \cos \alpha_k + \sum_{n=1, n \neq p}^{\infty} F_{dn}^{2} \cos n\alpha_k \right]$$

$$- \sum_{n=1, n \neq p}^{\infty} F_{c}F_{dn} \cos [(p + n)(\omega_{r}t - \alpha_m) - \gamma - p\alpha_k],$$

$$- \sum_{n=1, n \neq p}^{\infty} F_{c}F_{dn} \cos [(p - n)(\omega_{r}t - \alpha_m) - \gamma - p\alpha_k],$$

$$+ \sum_{n=1, n \neq p}^{\infty} \sum_{k=1, k \neq n}^{\infty} F_{dn}F_{dk} \cos [(n - k)(\omega_{r}t - \alpha_m) - \gamma - n\alpha_k]$$

$$+ \sum_{n=1, n \neq p}^{\infty} \sum_{k=1, k \neq n}^{\infty} F_{dn}F_{dk} \cos [(n + k)(\omega_{r}t - \alpha_m - \alpha_k) - n\alpha_k]$$

where $F_{r}$ and $F_{l}$ are the forces on the end part and the line part, respectively, and $F_{Ekh}$ is the electromagnetic force at an arbitrary point $K$ of the end winding, and a bar to indicate a space vector. $l_{end}$ is the curve of the end part, $(\alpha_m + \alpha_k)$ refers to the circumferential position of point $K$, $k_{m}$ is the MFD factor of end point $K$, and $\theta_k$ is the angle between the current vector and MFD.

As indicated in equations (10) and (11), in normal conditions, the electromagnetic force on both the line part and the end part includes mainly a DC component and a harmonic component at $2p\omega_{r}$ (that is, $2\omega$), which accords with the result presented in Ref. [9]. It is also suggested that the electromagnetic force in RISC case has much more components, and the frequencies of these new components are times of the rotor’s mechanical rotating frequency $\omega_{r}$. Because the amplitude of $F_{dn}$ is much smaller, especially when the harmonic order $n$ goes larger, these new components are mainly weak harmonics, so the DC and the $2\omega$ component are still the main ones. However, their amplitudes are both decreased due to the reduction of the MMF by the short circuit, as shown in Figures 1(a) and 1(b), and $F_{c}$ is smaller than $F_{c}$.

Although RISC decreases the primary components (DC and $2\omega$), it brings in new harmonics that could be closer to the natural frequencies of the winding. Consequently, the winding is potential to endure the sympathetic vibration,
Figure 3: Continued.
Figure 3: Continued.
which is of high probability to damage the winding in both the metal structure and the insulation properties. Therefore, it is of great significance to study these new force components. For the sake of comparison reference, the amplitudes of the former 6 force harmonics of a 3-pair poles synchronous generator, which is the study object in the next section, are listed in Table 1.

2.2. Mechanical Response. The structure of the stator end winding is illustrated in Figure 2(a). The electromagnetic force can cause the end of stator winding to vibrate and bring about insulation wear, while the line part of stator winding is fixed in the stator slot and fastened with slot wedge. Hence, the influence of line part’s electromagnetic force on the end part can be ignored. The mechanical model of stator-winding system is shown in Figure 2(b). The dynamic equation can be listed as follows:

$$ M \ddot{x}(t) = F_{E_k}(\alpha_m, t) - D \dot{x}(t) - Kx(t), $$

where $M$ is the mass of the stator winding end part, $D$ is the damping provided by the tie lines, $K$ is the stiffness provided by both the winding’s material elasticity and the tie line, and $x(t)$ is the displacement/movement matrix of the mass points.

Specifically, the electromagnetic force excitation on the end winding corresponds to the response of the first order vibration. The displacement represents the amplitude of vibration. As the electromagnetic force is periodic, the corresponding response will also be periodic, and this periodicity of the end winding displacement is represented by vibration. The vibration will aggravate the winding insulation wear and reduce the service life of generator.

Hereafter, we will carry out the finite element calculation through electromagnetics-mechanical coupling and the experiment study. The finite element analysis includes both the electromagnetic force and the mechanical response calculation, while the experiment study mainly tests the winding vibrations (response of the exciting forces). More details can be found in Section 3.

3. FEA and Experimental Study

3.1. FEA and Experiment Setup. We employ the MJF-30-6 type prototype generator as the study object as illustrated in Figure 3(a). It is in the State Key Laboratory of Alternate Electrical Power systems with Renewable Energy Sources, P.R. China. The primary parameters of the generator are listed in Table 2, and the stator winding connection of Phase A is indicated in Figures 3(c) and 3(d).

For the electromagnetic force FEA, the 3D transient solution type is selected, and the physical model is shown in Figure 3(e). The stator winding includes four parts, namely, the line part, the joint, the involute part, and the nose part, of which the latter three form the end winding, as shown in Figure 3(f). The line parts are laid in double layers in the slots and are defined as upper bar/line and lower bar/line, respectively. The end part extends outside the stator core and forms a basket-shape. Since each coil is composed of an upper bar and a lower bar, for clarification, each winding is marked by the slot number of the upper bar. For example, Winding 1 refers to the winding that is composed of the upper bar in Slot 1, the lower bar in Slot 9 (see Figure 4), and the end part, which connects these two line parts. Moreover, the excitation current is set to DC 1.8A in the coupling circuit of armature winding. As shown in Figures 3(g) and 3(h), there are three types of grids in meshing, and the total number of mesh elements is 146787. The “length based” grid is used for both cores and windings, and the “surface approximation based” grid is also chosen for windings.
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<table>
<thead>
<tr>
<th>Component</th>
<th>Normal condition</th>
<th>RISC</th>
<th>Amplitude varying tendency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Line: (x_0.5A^2P^2v/z_1))</td>
<td>(Line: (x_0.5A^2P^2v/z_1))</td>
<td>Decreased</td>
</tr>
<tr>
<td></td>
<td>(End: (x_0.5k_A^2v\sin\theta/k))</td>
<td>(End: (x_0.5k_A^2v\sin\theta/k))</td>
<td></td>
</tr>
<tr>
<td>DC component</td>
<td>(F_c^2)</td>
<td>(F_{c'}^2)</td>
<td></td>
</tr>
<tr>
<td>(\omega_1) (16.67 Hz)</td>
<td>0</td>
<td>Line and end: (F_{c'1x} + F_{c'1y})</td>
<td>Increased</td>
</tr>
<tr>
<td>2(\omega_1) (33.33 Hz)</td>
<td>0</td>
<td>Line and end: (F_{c'2x} + F_{c'2y})</td>
<td>Increased</td>
</tr>
<tr>
<td>3(\omega_1) (50 Hz)</td>
<td>0</td>
<td>Line and end: (F_{c'3x} + F_{c'3y})</td>
<td>Increased</td>
</tr>
<tr>
<td>4(\omega_1) (66.67 Hz)</td>
<td>0</td>
<td>Line and end: (F_{c'4x} + F_{c'4y})</td>
<td>Increased</td>
</tr>
<tr>
<td>5(\omega_1) (83.33 Hz)</td>
<td>0</td>
<td>Line and end: (F_{c'5x} + F_{c'5y})</td>
<td>Increased</td>
</tr>
<tr>
<td>6(\omega_1) (100 Hz)</td>
<td>(F_c^2)</td>
<td>Line and end: (F_{c'6x})</td>
<td>Decreased</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated capacity</td>
<td>30 kVA</td>
</tr>
<tr>
<td>Rated voltage</td>
<td>400 v</td>
</tr>
<tr>
<td>Rated rotating speed</td>
<td>1000 rpm</td>
</tr>
<tr>
<td>Number of pole pairs</td>
<td>3</td>
</tr>
<tr>
<td>Connection mode of stator winding</td>
<td>2Y</td>
</tr>
<tr>
<td>Coil pitch</td>
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</tr>
<tr>
<td>Power factor</td>
<td>0.8</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>75°C</td>
</tr>
<tr>
<td>Indexing slots of rotor</td>
<td>42</td>
</tr>
<tr>
<td>Real slots of rotor</td>
<td>30</td>
</tr>
<tr>
<td>Number of stator slots</td>
<td>54</td>
</tr>
<tr>
<td>Rated exciting current</td>
<td>1.8 A</td>
</tr>
<tr>
<td>Number of turns in per stator slot</td>
<td>72 turns</td>
</tr>
<tr>
<td>Number of turns in per rotor slot</td>
<td>88 turns</td>
</tr>
<tr>
<td>Length of rotor</td>
<td>220 mm</td>
</tr>
<tr>
<td>Stack length</td>
<td>220 mm</td>
</tr>
<tr>
<td>Inner diameter of stator</td>
<td>1230 mm</td>
</tr>
<tr>
<td>Outer diameter of stator</td>
<td>2400 mm</td>
</tr>
<tr>
<td>Inner diameter of rotor</td>
<td>500 mm</td>
</tr>
<tr>
<td>Outer diameter of rotor</td>
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</tr>
<tr>
<td>Air-gap length</td>
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</tr>
<tr>
<td>Stacking factor</td>
<td>0.95</td>
</tr>
</tbody>
</table>

Considering the complexity of the structure, for the air gap between the rotor and stator cores, the “cylindrical gap based” grid is adopted because of the smallness of the space. The solution time is solved for 400 ms, and the step length was set to 0.5 ms. All of the end windings are assigned parameters of force, and the field results of 240 ms to 400 ms are saved for postprocessing.

During the experiment, the generator was connected to the power grid. The exciting current was set to 1.8 A, the line voltage was 380 V, and the phase current was 30 A. RISC is set by connecting the short circuit taps C1 and C2 through a rheochord, as shown in Figure 3(a). The short circuit degree can be changed by adjusting the value of the rheochord, and it is calculated by

\[
F_d = \frac{I'_f}{I_f} \times 25\%,
\]

where \(I'_f\) is the short circuit current, and \(I_f\) is the exciting current. During the experiment, \(I'_f\) was 0.09 A, and the interturn short circuit degree was 1.25%.

### Table 2: Key parameters of MJF-30-6 prototype generator.

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</tr>
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</tr>
<tr>
<td>Operating temperature</td>
<td>75°C</td>
</tr>
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<td>Indexing slots of rotor</td>
<td>42</td>
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</tr>
<tr>
<td>Length of rotor</td>
<td>220 mm</td>
</tr>
<tr>
<td>Stack length</td>
<td>220 mm</td>
</tr>
<tr>
<td>Inner diameter of stator</td>
<td>1230 mm</td>
</tr>
<tr>
<td>Outer diameter of stator</td>
<td>2400 mm</td>
</tr>
<tr>
<td>Inner diameter of rotor</td>
<td>500 mm</td>
</tr>
<tr>
<td>Outer diameter of rotor</td>
<td>1228.3 mm</td>
</tr>
<tr>
<td>Air-gap length</td>
<td>0.85 mm</td>
</tr>
<tr>
<td>Stacking factor</td>
<td>0.95</td>
</tr>
</tbody>
</table>

### Figure 4: Most dangerous insulation damage windings, which are in black circles.

Three PCB accelerometers with very little volume and mass are fixed to the same stator end winding bar. One was set in radial direction to acquire the radial vibration signal, one was set in the tangential direction for the tangential vibration, and the other was set in the axial direction to acquire the axial vibration signal, as shown in Figure 3(b).

3.2 Results and Discussion. Since the three-phase windings are symmetrically distributed, the electromagnetic force on the three-phase windings should be similar as well. Limited by the calculating resource, only Phase-A windings are calculated as presentation.

The MFD on the stator winding is shown in Figures 5(a) and 5(b). It indicates that the MFD on the line part is larger than that on the end part since the magnetic field in the end region is generally a leakage field, which has smaller amplitudes. Moreover, it is shown that the occurrence of RISC will decrease the MFD. This result coincides with the previously theoretical analysis because \(F_c\) is smaller than \(F_{c'}\), as indicated in equations (1) and (7), and Figures 1(a) and 1(b). And it can be further verified by the current, which is a significant reflect of MFD, as illustrated in Figures 5(c) and 5(d).
The electromagnetic forces are displayed in Figure 6. It is suggested that the electromagnetic force on the joint is the largest, while the nose part is the second, as shown in Figures 6(a) and 6(b). This result is consistent with [19]. The electromagnetic force waves are similar before and after RISC; see Figures 6(c) and 6(d). However, it is distinct that the electromagnetic forces on each winding in the RISC cases are smaller than those in normal conditions, as illustrated in Figures 6(e)–6(g). This can be easily comprehended since $F_e > F_{cs}$ and the electromagnetic force $F$ is in proportion to the square of MMF $f$, as shown in equations (10) and (11).

Comparing Figures 6(e)–6(g) with each other, it is suggested that the electromagnetic forces on different windings will be varied. The upper bars have a larger value than the lower bars, since they are closer to the rotor, and the magnetic resistance is smaller (the magnetic resistance is in proportion to the radial air-gap length). The max electromagnetic force on the line part appears on winding 1 upper line, while the max electromagnetic force on the end part occurs on winding 2. Therefore, slot 1 and its wedge may endure larger stress, and special attention should be paid to it during design and manufacturing. However, the data in Table 3 shows that the max stress does not happen on the end winding 2 because of the complex end involute shape and force directions.

The electromagnetic force spectra of winding 1 are illustrated in Figures 7(a)–7(f). It is shown that, in both the normal and the RISC conditions, the electromagnetic force includes obvious DC and 100Hz components. However, as RISC takes place, some weak components, which are 1–5 times the rotor’s mechanical rotating frequency (16.7Hz, 1000rpm), will appear.

For a better comparison, the electromagnetic forces spectra of Phase A windings on the upper line parts (U1, U2, U3), the lower line parts (L1, L2, L3), and the end parts (E1, E2, E3) are illustrated in Figures 7(g)–7(i). Since there are no such harmonics whose angular frequencies are from $\omega_r$ to $5\omega_r$, in normal conditions, in Figure 7(h), the force distribution displays only the RISC case. It is suggested that the amplitudes of both the DC and the 100 Hz components will be decreased as RISC occurs, as illustrated in Figures 7(g) and 7(i). These conclusions are consistent with the previous theoretic analysis in Table 1. In the meantime, these weak
Figure 6: Continued.
components on the lower line parts are not as clear as those on the other parts; see Figure 7(h).

The tested vibration result is indicated in Figure 8. It is shown that the harmonic at 100 Hz has the prominent amplitude. As RISC happens, the amplitude of the key vibration component at 100 Hz will be decreased. It is consistent with the previously theoretical analysis and electromagnetic force FEA result, as shown in Table 1 and Figure 7(i). Moreover, the vibration is larger in radial than in axial or tangential direction, and this phenomenon is in accordance with the deformation property in the structure FEA simulation, as shown in Figure 9. Because the rotor is rotating at 16.7 Hz, there are some components that are times of the rotating frequency, for example, 50 Hz, 68.4 Hz, and so on.

4. Winding Damage Regularity

The insulation property will be degraded due to the intensified alternating stress for a long term, and then the fatigue fracture will happen. On the other hand, the winding deformation reflects the vibration amplitude since the vibration is the periodic movement (deformation). So the insulation material will be damaged by the wearing due to the excessive deformation. To study the impact of RISC on the winding stress and deformation, the physical model, as well as two cycles of electromagnetic force density data, was imported to the transient structural module for the mechanical response calculation. The winding material is defined as copper alloy whose yield strength and ultimate strength are 280 MPa and 430 MPa, respectively. The line parts are constrained by fixed supports. Automatic meshing is adopted, and 1082 nodes are generated for each end winding.

Considering that the stress and deformation distributions of the winding will be similarly repeated, only the results of winding 1 are presented as shown in Figures 10 and 11. The maximum values of the deformation and the stress, together with their occurring moments, are listed in Table 3.

As indicated in Figures 10 and 11, the joint and the nose of end winding are the two most dangerous positions because they have the serious stress and the max deformation. The occurrence of RISC will not change these dangerous positions. During practical monitoring, these two positions should be paid more attention since fatigue fracture and insulation wear will most probably start from these two locations. Practically, we also found some damage pictures in these two parts; see Figure 12. The significant countermeasure against insulation damage is that, during the manufacturing/assembling, the nose part is screened with a wear-resistant coating such as graphene, and the joint is protected with high-strength load reduction kits.

It is suggested from Table 3 that winding 3 endures the most serious stress and deformation, while winding 1 stands the second largest value. The value on winding 2 is much smaller than that on winding 3. The reason is that windings 1 and 3 are in the phase-shift boundaries, as the armature magnetic fields of the neighboring phases interact with each other. Additionally, it is shown that the RISC will decrease the max stress of winding 1 and deformation of winding 2, while increasing the others.

### Table 3: The maximum of deformation and stress of each winding.

<table>
<thead>
<tr>
<th>Winding</th>
<th>Deformation ($10^{-7}$m)/time (s)</th>
<th>Tendency</th>
<th>Stress ($10^4$Pa)/time (s)</th>
<th>Tendency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Normal 9.187/0.0385</td>
<td>Increase</td>
<td>5.974/0.0620</td>
<td>Decrease</td>
</tr>
<tr>
<td></td>
<td>RISC 9.188/0.0385</td>
<td></td>
<td>5.928/0.0385</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Normal 2.1138/0.0555</td>
<td>Decrease</td>
<td>2.508/0.002</td>
<td>Increase</td>
</tr>
<tr>
<td></td>
<td>RISC 2.1129/0.0555</td>
<td></td>
<td>2.818/0.002</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Normal 719.3/0.0380</td>
<td>Increase</td>
<td>540/0.0380</td>
<td>Increase</td>
</tr>
<tr>
<td></td>
<td>RISC 736.3/0.0380</td>
<td></td>
<td>554/0.038</td>
<td></td>
</tr>
</tbody>
</table>

![Figure 6: Electromagnetic forces on Phase A windings: (a) normal force distribution, (b) force distribution in RISC case, (c) and (d) electromagnetic force waves of winding 1 before and after RISC, and (e), (f), and (g) max value of force on upper line, lower line, and end part, respectively.](image)
Figure 7: Continued.
Figure 7: Electromagnetic force spectra: (a–c) winding 1 upper line, lower line, and end part in normal case, respectively, (d–f) winding 1 upper line, lower line, and end part after RISC, respectively, (g) DC component comparison, (h) force amplitude in RISC case for components from $\omega_r$ to $5\omega_r$, and (i) amplitude comparison at $6\omega_r$ (100 Hz).

Figure 8: Stator end winding vibration: (a), (b), and (c) vibration acceleration spectra in normal, respectively, (d), (e), and (f) vibration acceleration spectra after RISC, respectively.
In actual generators, for instance, hydrocool generators, the nose is not only the electrical connecting part, but also the connecting part for the cooling water. So this part is always the weak point. Figures 8 and 10 indicate that, for the nose part, the max stress and deformation occur on center and top, respectively, so the nose fatigue fracture will begin from the center, and nose insulation wear will start from the top.

To better study the deformation components in the radial, axial, and tangential directions of the nose part, we
illustrate these directional deformations before and after RISC for the three windings of Phase A, respectively, as shown Figure 9. It is found that the axial deformation on the nose of winding 1 will be enlarged by RISC, while the radial and the tangential deformations will generally keep stable. For winding 2, the deformation components in the three directions will all be slightly decreased. On the contrary, the radial deformation for winding 3 will be greatly increased, while the tangential and the axial deformations will generally keep the same. Additionally, the deformation is larger in radial than in tangential direction. Actually, In view of the double-layer lap structure of the end windings, the insulation wearing in the same layer is mainly caused by the radial and the axial deformations, while the insulation wearing in different layers depends on the tangential and the axial deformations. Consequently, the winding wearing...
would be more serious in the same layer than different layers.

According to Table 3 and Figure 9, in one phase, the nose part on the last winding, which touches the main flux lines later than others along the rotor’s rotating direction, will be the most dangerous position for insulation wearing. The most dangerous positions for Phases B and C have the same regularity, as the black circled windings illustrated in Figure 4.

5. Conclusions

This paper carries out a detailed investigation on the electromagnetic force behaviors of stator windings before and after RISC in multi-pair-pole synchronous generator. Primary conclusions obtained from theoretical analysis, the finite element calculation, and the experimental study are drawn as follows.

The mathematical expressions show that the electromagnetic force includes both DC and AC components. Normally, the $2p\omega_r$ harmonic is the prominent electromagnetic force component that will excite the winding to vibrate at 100 Hz. The occurrence of RISC will decrease the $2p\omega_r$ harmonic but will bring in new fractional harmonics, which are times of the rotor’s mechanical rotating frequency $\omega_r$. Consequently, the stator winding will have more vibration components, which may be close to its own natural frequencies and lead to a sympathetic vibration. By these analytical electromagnetic force formulas, the vibration developing tendency can be assessed fast, and therefore, they are potential to be applied for the stator winding monitoring.

Finite element analysis and experimental study are carried out on a MJF-30-6 prototype generator, which is of 6 poles and 1000 rpm. It is found that the upper bar will endure larger electromagnetic forces than the lower bar. There are two positions that are most probably to get the insulation damage. One is the nose part, which endures both the largest deformation and the second largest stress. The other is the joint part (the connection between the line winding and the end winding), which stands the most intensified stress. In the same phase, the inter-phase winding (neighboring winding between two phases), especially these end ones of the phases, will experience much larger deformations and stresses than the other windings. To better protect the windings against insulation damage, we recommend that the nose part and the joint be screened with wear-resistant coating and high-strength load reduction kits, respectively.

Although the research content is based on synchronous generators, other types of synchronous machine have the same structure and working principle as synchronous generators. After a long period of operation, synchronous machinery may come into being RISC caused by vibration, insulation aging, and other factors. Therefore, the study is applied to the most synchronous machinery that uses wound rotor. Since the findings in this paper include the insulation damage regularity and propose the possible countermeasure, they will be beneficial for the manufacturing technique improvement and the monitoring convenience. Meanwhile, the study achievements obtained in this paper are highly potential to be employed as a basis for the further investigations in other related problems for the similar electric machines.

Moreover, further study will be based on the shape of stator winding [see Figure 3, and (8)] in the electromagnetic property, and it will be beneficial for the condition monitoring and fault diagnosis, as well as the calculation improvement during design session.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

All the authors declare that there are no conflicts of interest regarding the publication of this paper.

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