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Analysis of Stator Core Magnetic Tension under Inter-turn Short Circuit of Excitation Winding

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Abstract: *The characteristics of unbalanced magnetic tension of stator core before and after the inter-turn short circuit fault of excitation winding of synchronous generator are analyzed in this paper. Firstly, the expression of air gap magnetic density and stator core magnetic tension under normal condition and inter-turn short circuit fault of excitation winding are analyzed theoretically. Then, a two-dimensional model was established based on CS-5 synchronous motor, and nine force analysis points were set up in the stator core, what's more, the magnetic tension simulation analysis was carried out for the nine analysis points. Finally, the mechanical response characteristics of the stator core under normal working conditions and inter-turn short circuit of excitation winding are verified by experiments. The experimental results are consistent with the theoretical analysis and simulation analysis results. The results show that even frequency doubling occurs in the air gap flux density after the inter-turn short circuit fault occurs in the field winding. The magnetic tension per unit area of the stator core has an odd frequency doubling, and the force increases with the increase of short circuit degree. The maximum stress point of the stator core is located at an Angle of about 45 degrees with the central axis of the big rotor tooth, which provides a basis for setting the stress monitoring point of the stator core and fault diagnosis.*

Keywords: *Excitation Winding; Inter-Turn Short Circuit; Magnetic Tension of Stator Core*

1. Introduction

The inter-turn short circuit of the excitation winding is one of the common electrical failures of the steam turbine generator, which may be caused by the poor manufacturing process or operation failure, which may result in the rotor winding current increases, the winding temperature rises, and limit the reactive power of the motor and even have grounding failure.

For the short-circuit fault of the motors, most of the experts and scholars have studied the magnetic tension, vibration characteristics and torque characteristic of the motor before and after the failure. Document [1] takes the 600MW turbine generator as the research object, analyzes the electromagnetic force of the excitation winding under the combined faults of air gap eccentricity and inter-turn short circuit with the finite element simulation software. The literature [2] presents a fast calculation model for the multi-loop method and performs some studies on the unbalanced magnetic tension and the resulting mechanical vibration of the generator. The literature [3] analyzes the mechanism of inter-turn short circuit fault and establishes the calculation model of generator unbalanced magnetic tension according to the magnetic potential distribution and Maxwell formula. The literature [4] studies the unbalanced magnetic force caused by inter-turn short circuit of the excitation winding, and analyzes the relationship between the unbalanced magnetic force and the running state of the generator. and analyzes the relationship between it and generator operation. Document [5] established the finite element analysis model of the generator and obtained the trend of the magnetic field line inside the motor under the inter-turn short circuit fault state of the rotor excitation winding and the change of the generator's air gap flux density, and obtained the influence of the short circuit position, the number of turns of the short circuit and the excitation current on the unbalanced magnetic tension of the rotor. Document [6] analyzes the unbalanced electromagnetic force expression acting on the rotor during the short circuit fault. Document [7] evaluates the influence of the inter-turn short circuit of excitation winding on the steady state variable and analyzes the electromagnetic torque changes after the short circuit fault of steam turbine generator by finite element method. Literature [8] analyzed and calculated the electromagnetic torque of the field winding after inter-turn short circuit fault based on the multi-loop mathematical model. Literature [9] The theoretical analysis on the electromagnetic torque characteristics of turn short circuit in generator excitation winding is conducted. Literature [10] theoretically deduces and analyzes the electromagnetic torque of the generator before and after the inter-turn short circuit fault of the excitation winding, and analyzes the influence of the fault degree of rotor inter-turn short circuit fault and the position of inter-turn short circuit on the radial electromagnetic force. Literature [11] studied the electromagnetic characteristics of the inter-turn short circuit fault of excitation windings, calculated the unbalanced magnetic pull of the motor rotor when the inter-turn short circuit fault of different excitation windings was issued by Maxwell stress tensor method, and studied the mechanical characteristics of the inter-turn short circuit fault of excitation windings. Literature [12] analyzes the radial vibration characteristics of the stator and the parallel branch circulation characteristics of the stator under the normal operation condition of the generator and the inter-turn short circuit fault of the excitation winding.

The above literatures have laid a good foundation for the detection of the inter-turn short circuit fault of the excitation winding. Most literatures take the whole rotor or stator as the object to analyze the fault characteristics, but the actual stator core magnetic tension monitoring needs to select the monitoring point reasonably. So in this paper, we take steam turbine generator as the research object, using the analytical analysis, simulation analysis and mechanical response analysis as research method to reveal the normal working conditions and different circumstances inter-turn short circuit of the stator core force of the number of points, the lead to exciting winding inter-turn short circuit fault before and after the magnetic force characteristic of the stator core and stator core largest stress point, provide the basis for fault diagnosis.

2. Theoretical Analysis

2.1 Effect of Inter-turn Short Circuit on Magnetic Density of Air Gap

2.1.1 Air Gap Magnetic Density under Normal Working Conditions

The air gap of the generator is located between the generator rotor and the stator. Under normal operating condition, the winding of the generator is symmetric, and the three-phase load is also symmetrical, and the base wave of the armature magnetic motive force will be a synchronous rotating magnetic motive force. The air gap magnetic field is constituted by the base wave of the excitation magnetic dynamic potential and the base wave of the armature magnetic dynamic potential, so that in the normal state it can be represented by Fig. 1[12].

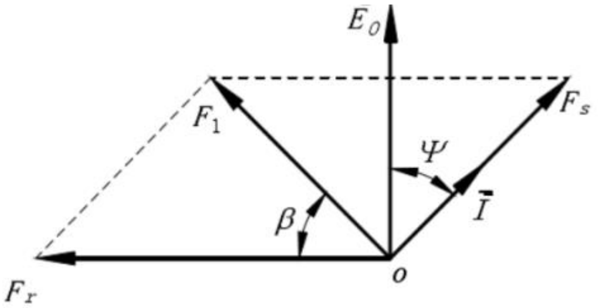


Fig. 1 Magnetic flux density of turbo generator under normal operation.

F_s in the Figure is the armature reaction base wave magnetic potential generated by the stator winding, F_r is the base wave main magnetic potential generated by the rotor excitation winding, F_1 is the synthetic magnetic potential of the base wave, φ is the internal function angle, determined by the added load, I is the armature current, E_0 is armature magnetic dynamic potential. According to the stator rotor magnetic potential relationship shown in the figure, the generator gas gap magnetic energy expression can be written as:

$$f(\alpha_m, t) = F_s \cos(\omega t - \alpha_m - \psi - \frac{\pi}{2}) + F_r \cos(\omega t - \alpha_m)$$

$$= F_1 \cos(\omega t - \alpha_m - \beta)$$

Among which:

$$F_1 = \sqrt{F_s{}^2 \cos^2 \psi + (F_r - F_s \sin\psi)^2}$$

$$\beta = arctg\,\frac{F_s \cos\psi}{F_r - F_s \sin\psi}$$

In the normal operation state of the generator, there is no air gap eccentric and other faults, the generator magnetic field can be regarded as a symmetrical distribution, the air gap magnetic guide is shown as the formula.

$$\Lambda = \frac{\mu_0}{g} = \Lambda_0$$

Where g is the radial air gap length, μ_0 is the vacuum permeability.

Further, we can obtain the air gap magnetic density formula of the generator in the normal state.

$$B(\alpha_m, t) = f(\alpha_m, t)\Lambda = F_1 \cos(\omega t - \alpha_m - \beta)\Lambda_0$$

2.1.2 Air Gap Magnetic Density under Short Circuit

The inter-turn short circuit of the excitation winding mainly affects the air gap magnetic density of the generator. After the short circuit, the air gap magnetic density base affects the double frequency magnetic potential as shown in Figure 2 [12].

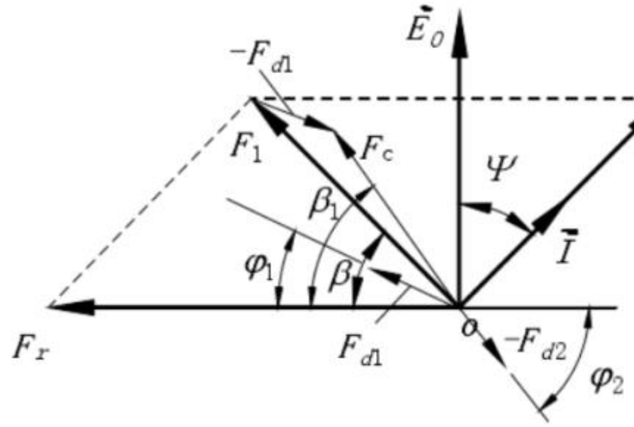


Fig.2 Air gap magnetic potential of turbo generator under inter turn short circuit of excitation winding.

In the figure, F_{d1} and F_{d2} are the fundamental wave amplitude and the double harmonic amplitude of the reverse magnetic potential generated by the short circuit, and φ_1 and φ_2 are the angles between the fundamental wave component and the double harmonic component of the reverse magnetic potential and the horizontal axis. The air gap magnetic potential after the inter-turn short circuit of the excitation winding can be expressed as:

$$f_{(short)}(\alpha_m, t) = F_s \cos(\omega t - \alpha_m - \psi - \frac{\pi}{2}) + F_r \cos(\omega t - \alpha_m)$$

$$-F_{d1} \cos(\omega t - \alpha_m - \varphi_1) - F_{d2} \cos 2(\omega t - \alpha_m - \varphi_2)$$

$$= F_C \cos(\omega t - \alpha_m - \beta_1) - F_{d2} \cos 2(\omega t - \alpha_m - \varphi_2)$$

$$F_C = \sqrt{(F_r - F_s \sin\psi - F_{d1} \cos\varphi_1)^2 + (F_s \cos\psi - F_{d1} \sin\varphi_1)^2}$$

$$\beta_1 = arctg\,\frac{F_s \cos\psi - F_{d1} \sin\varphi_1}{F_r - F_s \sin\psi - F_{d1} \cos\varphi_1}$$

Further obtain the air gap magnetic density under the short circuit between turns.

$$B(\alpha_m, t) = f(\alpha_m, t)\Lambda_0 \quad = [F_C \cos(\omega t - \alpha_m - \beta_1) - F_{d2} \cos 2(\omega t - \alpha_m - \varphi_2)]\Lambda_0$$

2.2 Effect of Inter-turn Short Circuit on Magnetic Tension of Stator Core

2.2.1 Magnetic Tension of Stator Core under Normal Working Conditions

The force range of the stator core is the inner round surface, so the stator core vibration force is the magnetic pull force per unit area of the inner circle surface. What’s more, under normal working state, the magnetic pull force per unit area is zero. The magnetic tension on unit area during normal operation is shown in the formula[12]:

$$q(\alpha_m,t)=\frac{B(t)^2}{2\mu_0}=\frac{[F_1\cos(\omega t-\alpha_m-\beta)\Lambda_0]^2}{2\mu_0}$$

$$\approx\frac{F_1{}^2\Lambda_0{}^2}{4\mu_0}[1+\cos(2\omega t-2\alpha_m)]$$

It can be seen that in the normal operation state, the magnetic pull force per unit area of the staor core is composed by a constant force and double frequency alternating force. Where, the amplitude of the constant force is $\frac{F_1^2\Lambda_0^2}{4\mu_0}$, This constant force acts uniformly on the inner surface of stator core and the resultant force is zero, without vibration of stator core of generator; while the amplitude of alternating force is $\frac{F_1^2\Lambda_0^2}{4\mu_0}$, The magnitude of this force changing over time will cause the vibration at the same frequency of the alternating frequency. Therefore, there is only double frequency vibration in the stator core of the steam turbine generator.

2.2.2 Magnetic Tension of Stator Core under Inter-turn Short Circuit

Magnetic tension per unit area of generator stator core under inter-turn short circuit is as follows:

$$q(\alpha_m,t)=\frac{B^2(\alpha_m,t)}{2\mu_0}=\frac{\Lambda_0^2}{2\mu_0}[F_C\cos(\omega t-\alpha_m-\beta_1)-F_{d2}\cos 2(\omega t-\alpha_m-\varphi_2)]^2$$

$$=\frac{\Lambda_0^2}{4\mu_0}[F_C^2+F_{d2}^2-2F_cF_{d2}\cos(\omega t-\alpha_m+\beta_1-2\varphi_2)+F_C^2\cos 2(\omega t-\alpha_m-\beta)$$

$$-2F_CF_{d2}\cos(3\omega t-3\alpha_m-\beta_1-2\varphi_2)+F_{d2}^2\cos 4(\omega t-\alpha_m-\varphi_2)]$$

It can be seen that one to four times the vibration of the generator stator core under the inter-turn short circuit fault of the excitation winding, due to the presence of DC force component, the stator core may produce a certain degree of deformation under long-term action.

3. Finite Element Simulation Analysis

3.1 Effect of Inter-turn Short Circuit on Magnetic Density of Air Gap

3.1.1 Air Gap Magnetic Density under Normal Working Condition

In this paper, CS-5 hidden pole fault simulation generator is taken as the research object, and its models under normal working conditions are shown in Fig. 3 to Fig. 5.

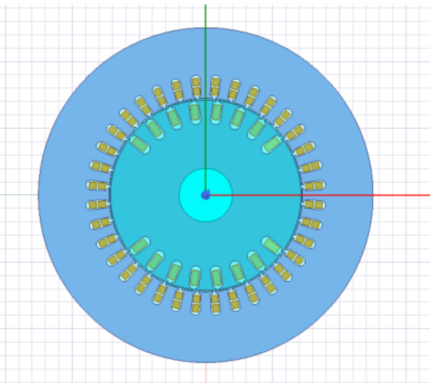


Fig.3 Two dimensional analysis model of turbo generator under normal condition.

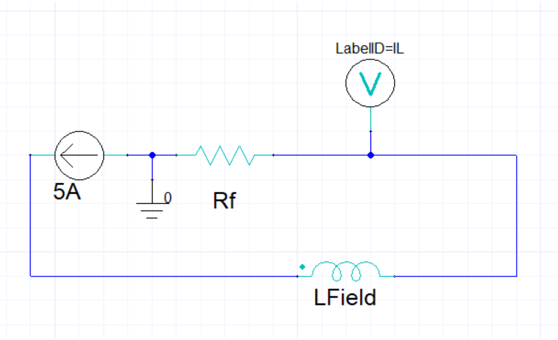


Fig.4 External coupling circuit of turbo generator rotor winding under normal conditions.

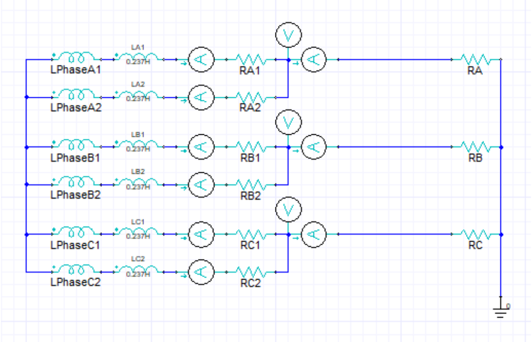


Fig.5 External coupling circuit of stator winding of Turbo generator under normal condition.

Through software simulation calculation, the whole magnetic density spectrum of the generator under normal condition is obtained as shown in the fig.6.

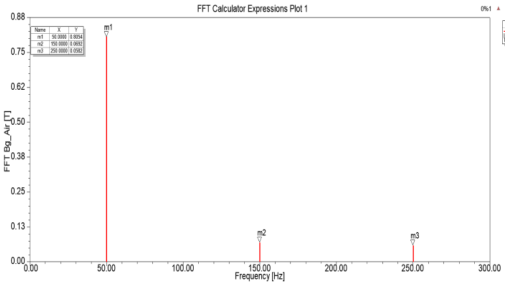


Fig.6 Magnetic density spectrum under normal working condition

Through the figure above, it is found that the generator gas gap magnetic density has only an odd number of times the frequency component, which is basically consistent with the theoretical analysis results.

3.1.2 Air Gap Magnetic Density under Inter-turn Short Circuit

The position of the inter-turn short circuit is near big tooth end, with 5%, 10% and 15%, as shown in fig7 to fig.10.

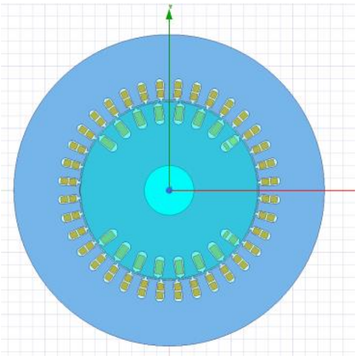


Fig.7 Two dimensional model of turbo generator with 5% inter-turn short circuit.

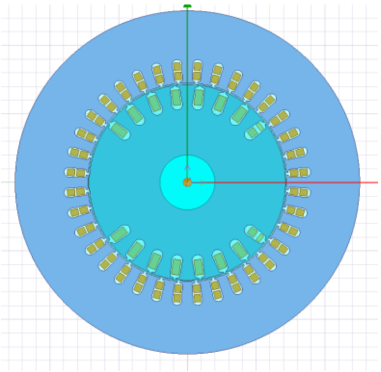


Fig.8 Two dimensional model of turbo generator with 10% inter-turn short circuit.

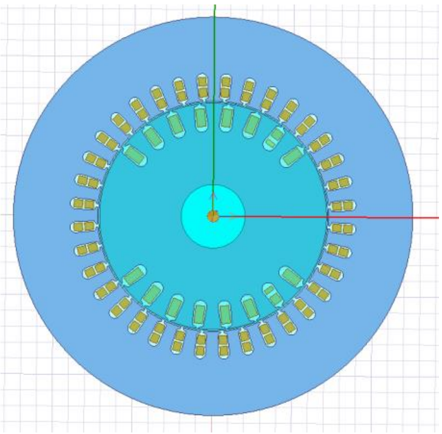


Fig.9 Two dimensional model of turbo generator with 15% inter-turn short circuit.

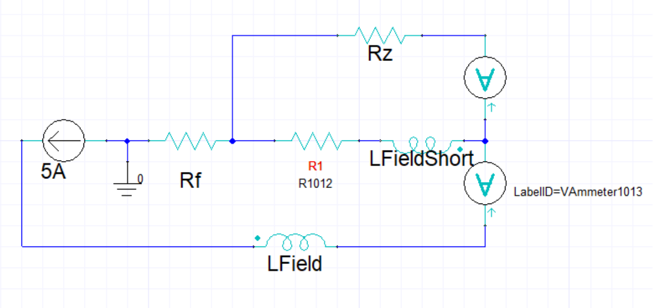
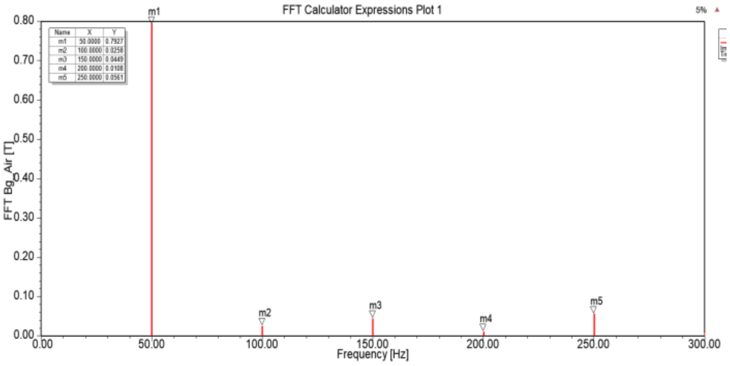


Fig.10 External coupling circuit of turbo generator rotor winding under inter-turn short circuit.

Through software analysis, the whole weekly magnetic density spectrum of the generator under different inter-turn short circuit can be obtained as shown in fig.11 to fig 14.



Name	X	Y
m1	50.0000	0.7927
m2	100.0000	0.0258
m3	150.0000	0.0449
m4	200.0000	0.0108
m5	250.0000	0.0561

Fig.11 Magnetic density spectrum under 5% inter-turn short circuit

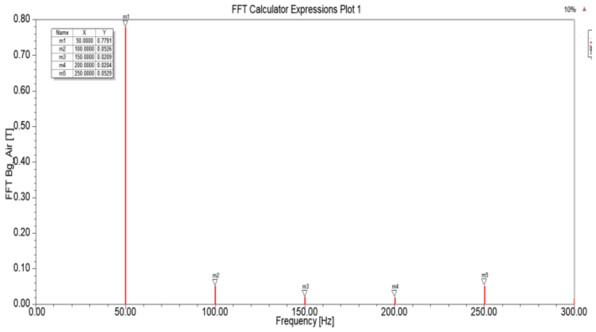


Fig.12 Magnetic density spectrum under 10% inter-turn short circuit

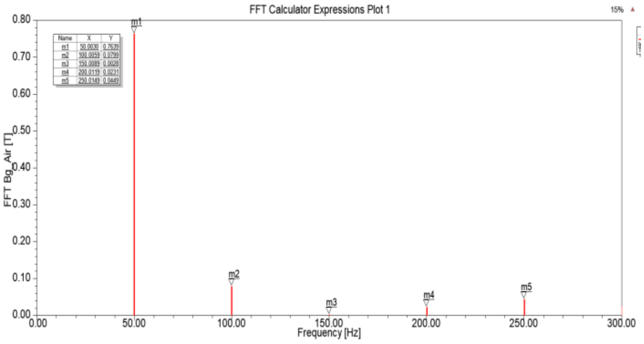


Fig.13 Magnetic density spectrum under 15% inter-turn short circuit

Seen from the figures, even frequency components begin to appear in the air gap magnetic density due to the occurrence of inter-turn short circuit. According to fig.3-12, with the deepening of the inter-turn short circuit, the even frequency component become larger, the magnetic density spectrum is consistent with the theoretical results.

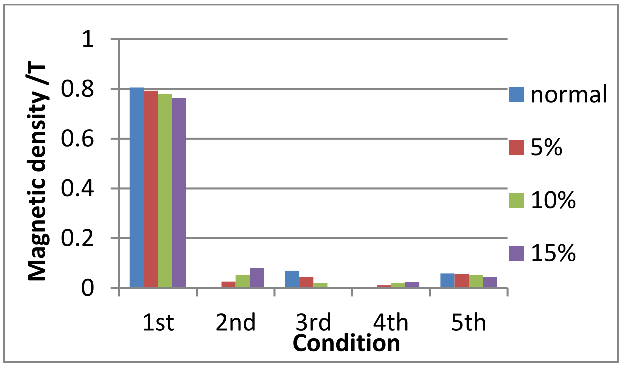


Fig.14 Frequency characteristics column chart of air gap flux density under different working conditions

3.2 Effect of Inter-Turn Short Circuit on Magnetic Tension of the Stator Core

Nine points are taken uniformly from the stator core model, left to right, with 1 and 9 close to the large tooth end and on the same diameter, as shown in fig.15.

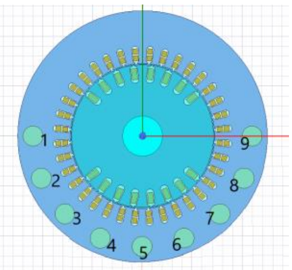


Fig.15 Distribution of generator analysis points.

3.2.1 Stator core magnetic tension under normal condition

The above 9 points are stress analyzed. Taking 1 point as an example, the stress spectrum diagram under normal working conditions can be obtained through software analysis.

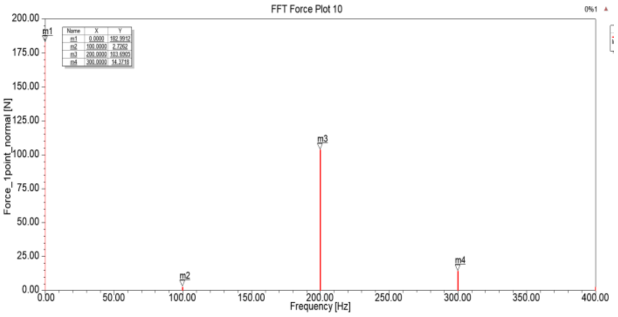


Fig.16 Stress spectrum diagram of point 1 under normal condition.

It can be found from the fig.16 that in the normal state, the main component is only even double frequency except for the large DC component, which agrees with previous theoretical formulas.

3.2.2 Stator core magnetic tension under inter-turn short circuit

Taking 1 point as an example again, the stress spectrum diagram under different inter-turn short circuit cases can be obtained, as shown in fig.17 to3-20.

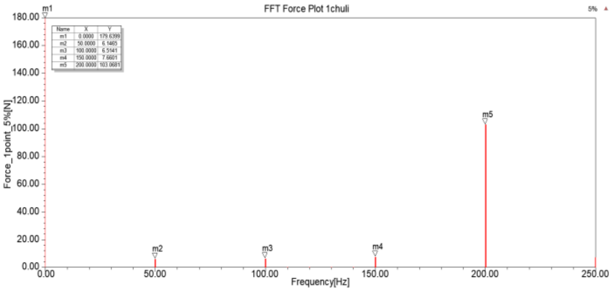


Fig.17 Stress spectrum diagram of point 1 under 5% inter-turn short circuit.

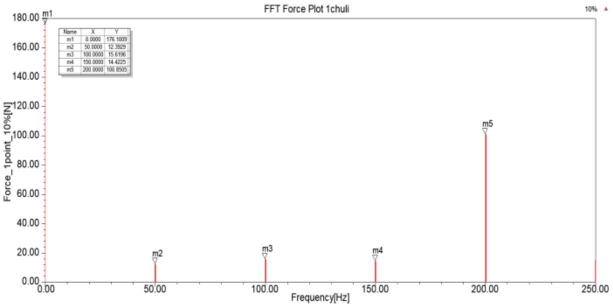


Fig.18 Stress spectrum diagram of point 1 under 10% inter-turn short circuit.

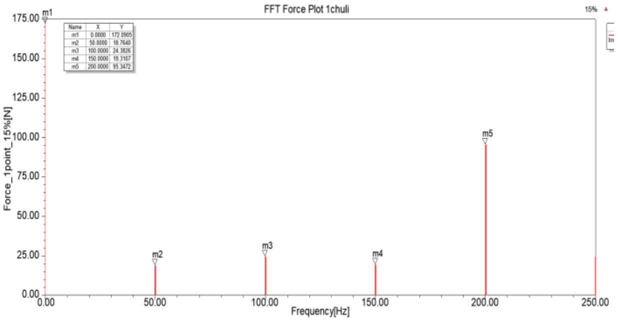


Fig.19 Stress spectrum diagram of point 1 under 15% inter-turn short circuit.

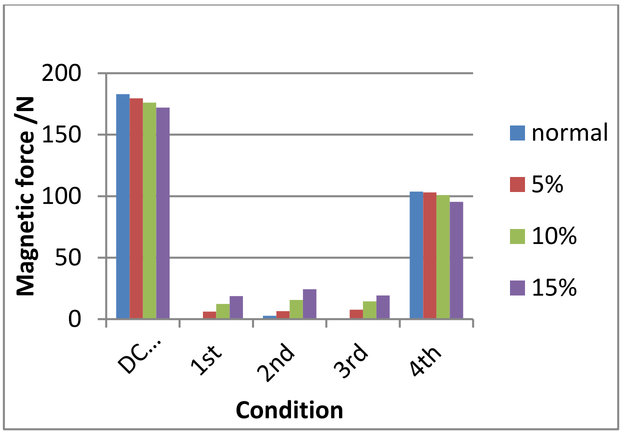


Fig.20 Column chart of force spectrum characteristics at one point.

It can be found from fig.20 that with the deepening of the inter-turn short circuit degree, the DC component decreases, and the odd frequency component began to appear and gradually increases, showing the overall vibration of one to four times the frequency, which is also consistent with the theoretical formula results.

Next, the stress situation of 9 points is compared, taking the stress situation under normal working conditions as an example.

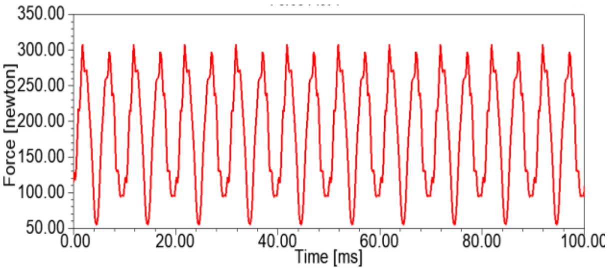


Fig.21 Time domain diagram of point 1 force under normal working condition.

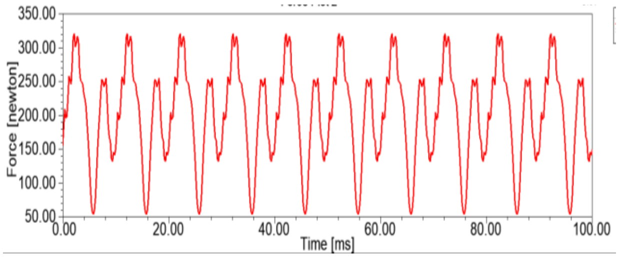


Fig.22 Time domain diagram of point 2 force under normal working condition.

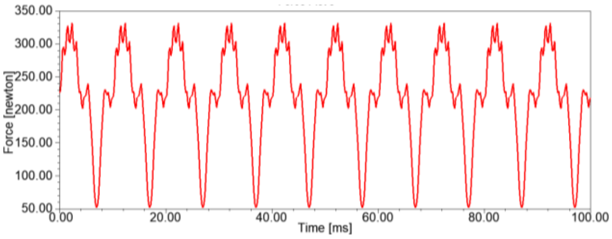


Fig.23 Time domain diagram of point 3 force under normal working condition.

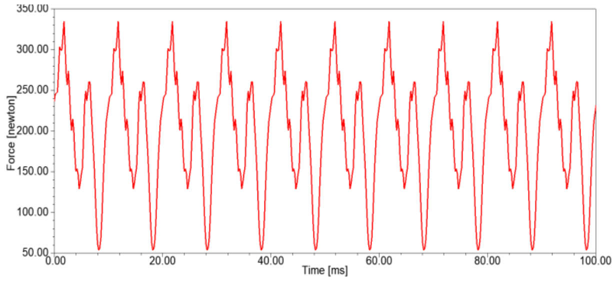


Fig.24 Time domain diagram of point 4 force under normal working condition.

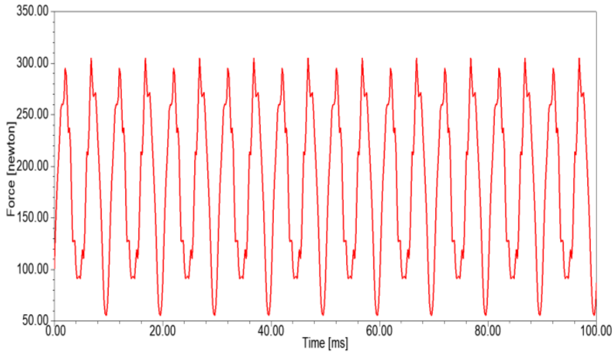


Fig.25 Time domain diagram of point 5 force under normal working condition.

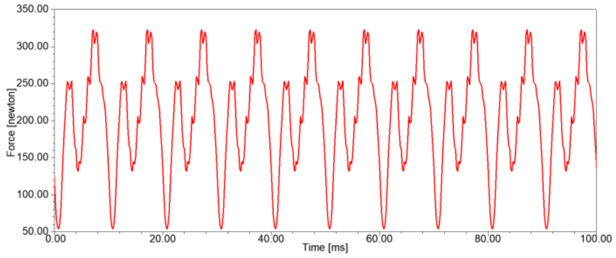


Fig.26Time domain diagram of point 6 force under normal working condition.

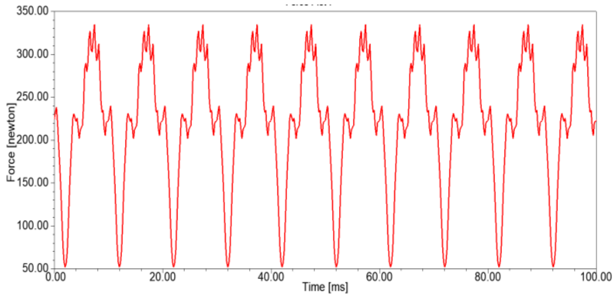


Fig.27 Time domain diagram of point 7 force under normal working condition.

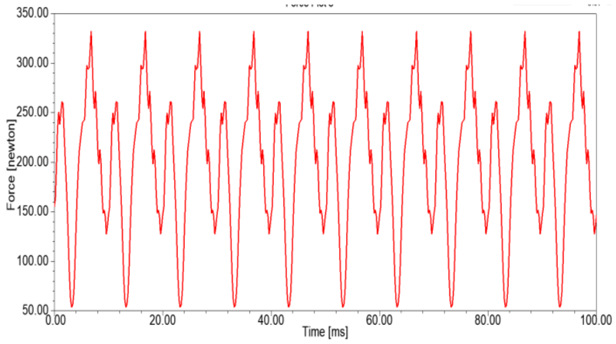


Fig.28 Time domain diagram of point 8 force under normal working condition.

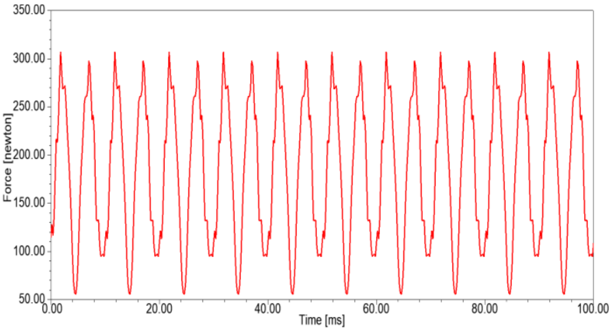


Fig.29: Time domain diagram of point 9 force under normal working condition.

According to Fig.21~29, the stress results diagram of 9 points, The stress cycle is the same, and the time of the maximum stress point gradually moves backward.

According to Fig.30, the maximum stress point on the stator core is located at an Angle of about 45 degrees with the central axis of the rotor's large tooth, and the minimum stress point is located at the near and far tooth ends.

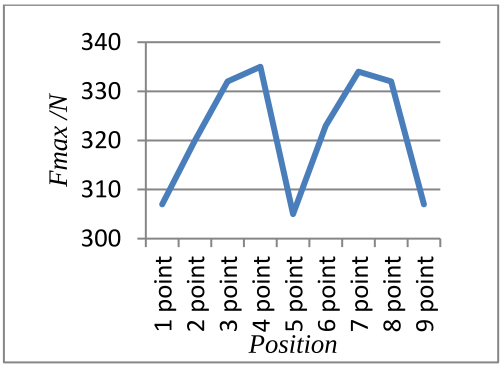


Fig.30: 9-point stress line diagram

4. Mechanical response analysis

The experimental bench used for mechanical response analysis is as shown in fig.31. The rotor short circuit tap is shown in fig.32.

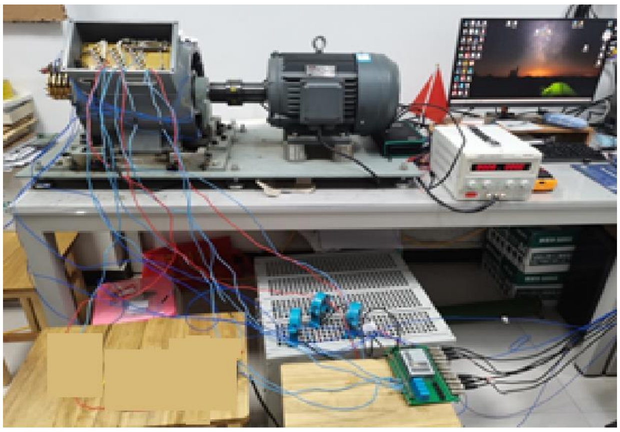


Fig.31: Schematic diagram of experimental platform.

Fig.32 Rotor short circuit taps.

The experimental data are processed, and the stress amplitude at different harmonics is shown in the figure below.

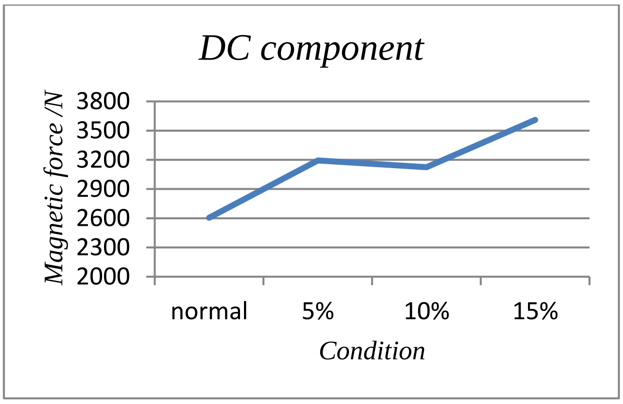


Fig.33 Variation of DC component amplitude in different states.

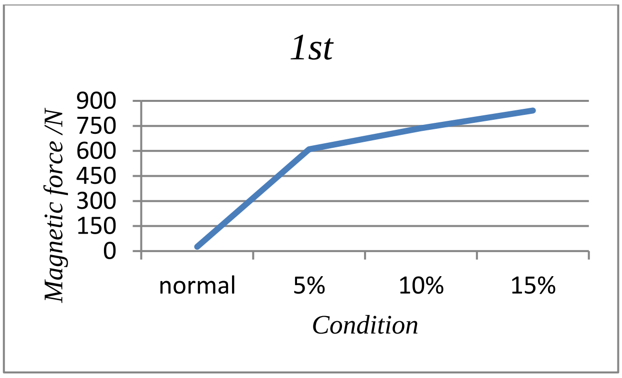


Fig.34 Amplitude variation of first harmonic generation in different states.

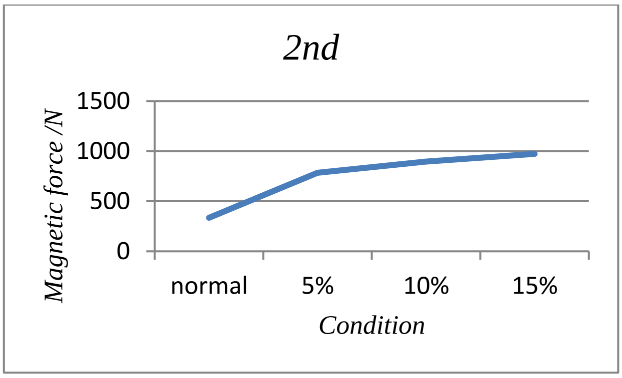


Fig.35 Amplitude variation of second harmonic generation in different states.

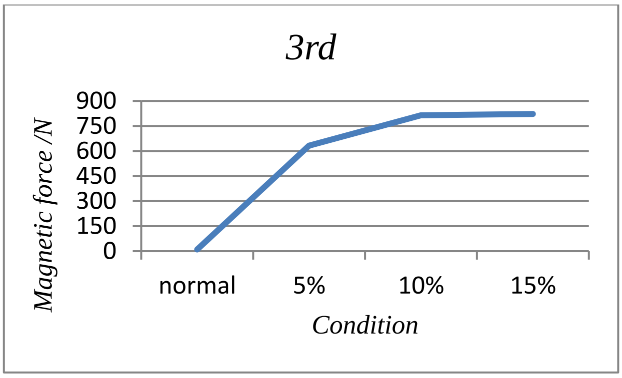


Fig.36 Amplitude variation of third harmonic generation in different states.

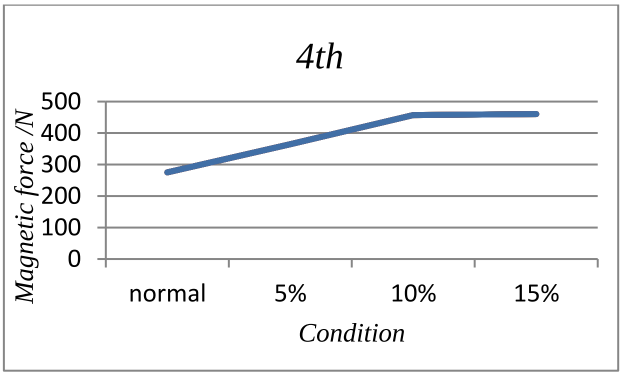


Fig.37 Amplitude variation of fourth harmonic generation in different states.

According to the figures (fig.33 to 37), the DC component and the first four frequency doubling components of the stator force will change in a single trend after the occurrence of inter-turn short circuit, which is consistent with the results of theoretical derivation and policy analysis.

5. Conclusion

This paper presents theoretical analysis, finite element simulation and experimental verification of the stator core force before and after inter-turn short circuit of synchronous generator excitation winding as follows:

(1) Under normal operating conditions, the air gap magnetic density mainly includes odd times the frequency components, while the stator magnetic tension unit area only includes the DC component and double the frequency component;

(2) After the occurrence of inter-turn short circuit fault, the air gap magnetic density has an even frequency doubling component, and the stator unit area magnetic tension has an odd frequency doubling. The stress increases with the increase of short circuit degree;

(3) Nine stress reference points are set in the stator core. According to the stress results of the nine points, the maximum stress point on the stator core is located at an Angle of about 45 degrees with the central axis of the big rotor tooth, which provides a basis for the setting of stator core stress monitoring points and fault diagnosis.

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