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RESEARCH ARTICLE

Study on Analysis of Causes for Loosening in the Ring Leads Fixed Structure at the Generator End and Improvement Measures

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ABSTRACT In response to the repeated occurrence of loosening in the fixed structure of the ring leads at the end of generator, as well as issues such as bolt loosening and lead wear, during the recent major overhauls of a large steam turbine generator, this paper conducts an analysis of the causes of loosening and proposes corresponding improvement measures. Taking the generator end ring leads fixed structure as the research object, this paper employs comparative analysis and finite element simulation methods to analyze the causes of loosening. It identifies factors such as bolt fixing methods and cleat support methods contributing to loosening, and proposes improvement solutions including increasing the wrapping angle of the cleat and enhancing pretightening force of the bolts. According to the actual component size of the unit, a sample test platform is designed and built, and the correctness of the loosening cause and the effectiveness of the improvement plan are verified by the sample test. The experimental results confirm that the cleat support form and bolt fixing method significantly contribute to fixing structural loosening, while the proposed improvements effectively delay bolt loosening. Increasing the cleat wrapping angle and pre-tightening force of the bolts are both feasible on-site and offer practical engineering value, laying the foundation for solving the technical challenges associated with securing the generator's end ring lead structure and ensuring safe and stable generator operation.

INDEX TERMS Large generators, electromagnetic exciting force, vibration control, analysis of loosening causes, structural improvement scheme.

I. INTRODUCTION

With the development of generators towards high capacity and reliability, the safe and stable operation of generators has been widely concerned [1], [2]. Due to the presence of a strong electromagnetic field in the end region of large turbogenerator during operation, the end of the generator is subjected to alternating loads generated by electromagnetic forces [3], [4]. This phenomenon has been identified as a significant contributing factor to the occurrence of severe accidents in large generators, as it can lead to the loosening of the fixed structure of the ring leads [5], [6].

For the loosening of ring leads fixed structure at the end of generator, the manufacturer can only rely on the on-site structure and drawings for qualitative analysis of the cause, and cannot give an effective solution.

The ring leads fixed structure is shown in Fig. 1, where the bottom of the bolt is fixed in the conical groove of the insulating cone. The cleat, under the pretightening force of the bolt, fixes the ring leads in the U-shaped groove of the insulating cone. A felt is placed between the cleat and the insulating cone to provide vibration damping and reduce wear.

Currently, over the course of ten years, more than 200 instances of loosening in the fixed structure of the ring leads have been identified during unit overhaul of the 10 operational units of a certain type of generator. This loosening

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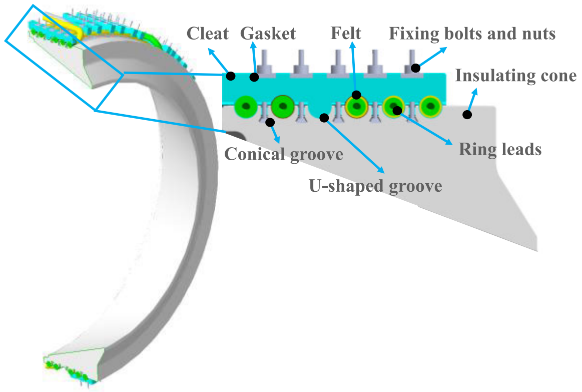


FIGURE 1. Fixed structure of ring leads.

can lead to wear of the lead insulation, collision of foreign objects between the stator and rotor, and other faults. Notably, worn insulation might cause serious malfunctions such as short circuits or grounding in the generator [7], [8]. Loose structural components falling into the machine could block part of the cooling air path and damage the stator and rotor through impact, posing significant risks to the safe and stable operation of the generator and potentially leading to unplanned shutdowns, causing economic losses [9], [10]. The failure of complex systems is often caused by a variety of reasons [11], [12], so it is necessary to comprehensively consider the influence of various factors and make a comprehensive evaluation by combining theoretical analysis and test verification [13], [14]. Currently, the manufacturer has not definitively determined the cause of the loosening in the structural fixtures, thus urgently requiring analysis of the reasons for the loosening and validation of improvement measures to ensure stable operation of the generator.

II. CAUSE ANALYSIS AND IMPROVEMENT MEASURES OF RING LEAD FIXED STRUCTURE LOOSENING

In this section, fixed structure of the ring leads is taken as the research object. Comparative analysis was conducted between the current faulty unit structure and other non-faulty unit structures, with a focus on analyzing the causes of failure. The reasons for bolt loosening are listed as follows.

A. CLEAT SUPPORT FORM

According to the support form of cleat, the non-faulty unit is characterized by an upper-cleat and a lower-cleat, with the U-shaped groove for placing the ring leads is arranged in the lower-cleat to avoid the U-shaped groove and the conical groove being arranged on the insulating cone at the same time, as shown in Fig. 2. This "Thick-wall support" design ensures the support stiffness of the insulating cone, can give sufficient support to the ring leads, and reduce the vibration response under the same excitation.

For the faulty unit, the U-shaped groove and conical groove are arranged on the insulating cone at the same time, and the leads are fixed directly by the upper-cleat without the lower-cleat, as shown in Fig. 3. This innovative design can significantly reduce the unit size, but also forms a "Thin-wall structure" on the insulating cone, sacrificing some support stiffness.

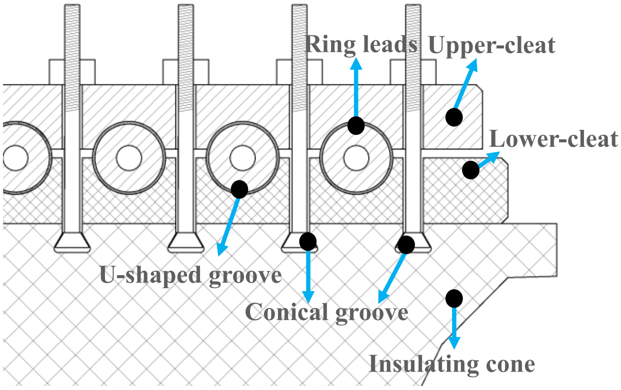


FIGURE 2. "Thick-wall support" fixed structure.

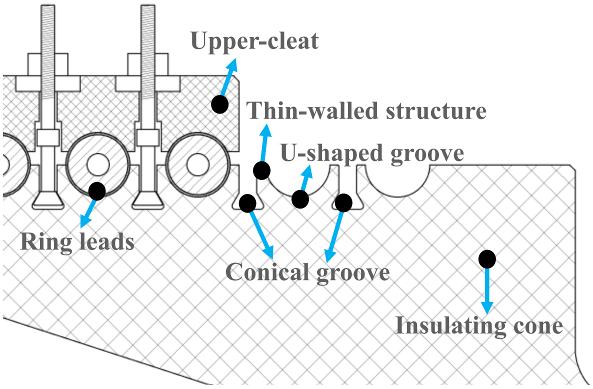
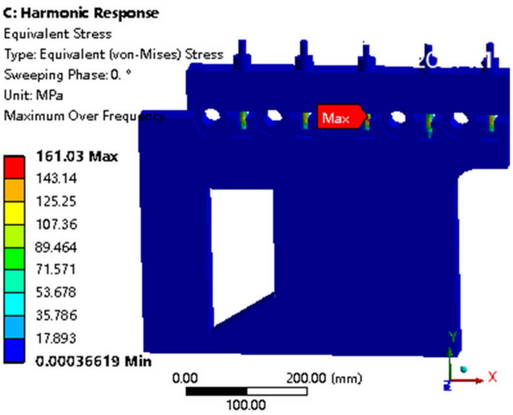
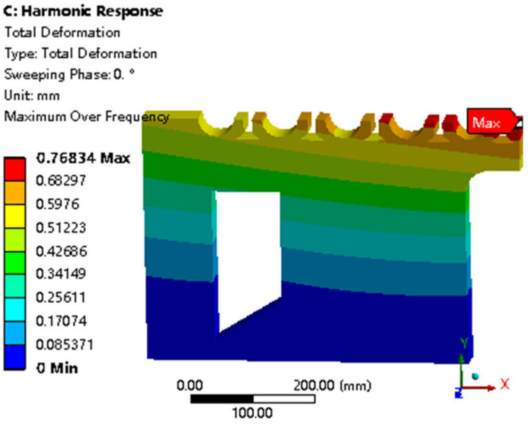


FIGURE 3. "Thin-wall support" fixed structure.

In order to explore the effect of different cleat support form on structural vibration response, the "Thin-wall structure" and "Thick-wall structure" models were established to study the dynamic characteristics of the structure under "Thin-wall and Thick-wall" cleat support form, and the vibration response of the structure under alternating loads was analyzed. The simulation imposes fixed constraints on the base of the structure, applies pretightening force to the bolts, and subjects the leads to excitation forces in the positive X, Y, and Z directions. A harmonic response analysis is conducted within the frequency range of 99 Hz to 102 Hz to evaluate the structure's vibration response under alternating dynamic loads. The following Fig. 4 and Fig. 5 show the harmonic response analysis results for thin-wall and thick-wall supports, respectively. The analysis results in the figures show that the maximum stress in the Thin-wall support is 7.6 times that of the Thick-wall support, and the maximum displacement in the Thin-wall support is 1.5 times that of the Thick-wall support. It can be seen that the cleat support form has a significant impact on the dynamic response of the fixed structure.



（a） Structural stress nephogram of “Thin-wall support”



（b） Structural displacement nephogram of “Thin-wall support”

FIGURE 4. Structural vibration response under “Thin-wall support”.

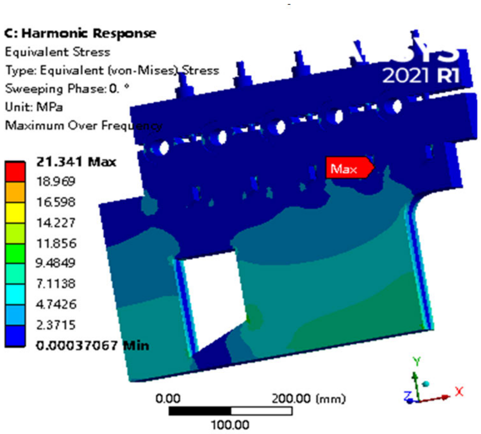
B. BOLT INSTALLATION METHOD

For the installation method of bolts, the non-faulty unit uses a threaded fixing method. Although the threaded fixing method makes the bolt fixing position less flexible, it avoids the 360-degree circumferential conical groove, does not compromise strength, and provides greater support stiffness and strong vibration resistance, as shown in Fig. 6.

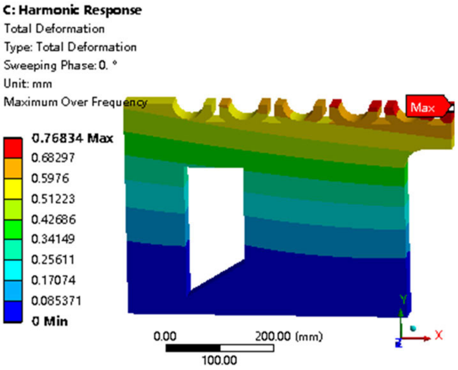
In contrast, the faulty unit uses conical groove fixing method. This design allows the bolts to be fixed at any position circumferentially, enhancing the flexibility of bolt fixing, but it also sacrifices the strength of the insulating cone, as shown in Fig. 7. Practical operations have proven that the threaded fixing method experiences fewer incidents of bolt loosening.

C. CLEAT WRAPPING ANGLE

The wrapping angle of the fixing structure refers to the angle at which the cleat wraps around the ring lead. A larger coverage area can better secure the ring lead within the U-shaped groove, limiting the vibration of the ring lead, reducing the loss of pretightening force caused by fretting wear and minimizing the occurrence of component loosening [15], [16].



（a） Structural stress nephogram of “Thick-wall support”



（b） Structural displacement nephogram of “Thick-wall support”

FIGURE 5. Structural vibration response under “Thick-wall support”.

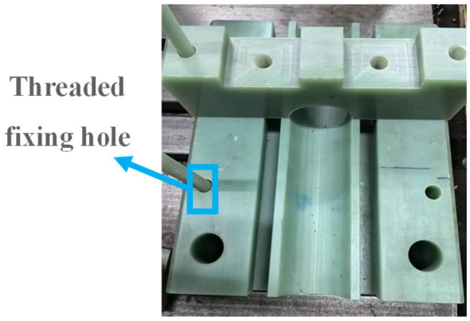


FIGURE 6. Threaded fixing method.

The faulty unit has a cleat wrapping angle of 126° to the ring lead, as shown in Fig. 8.

In non-faulty unit, cleat wrapping angle is close to 180°. By comparison, the wrapping angle of faulty unit is smaller and lacks sufficient stiffness. A larger wrapping angle should be set to increase structural stiffness, mitigate fretting wear due to vibration.

D. INITIAL PRETIGHTENING FORCE OF BOLT

Bolted connections mainly achieve fastening by applying a preload that stretches the bolt, as shown in Fig. 9, but threaded fasteners may become loose under vibration

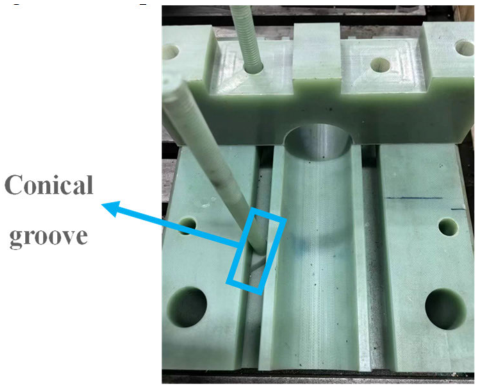


FIGURE 7. Conical groove fixing method.

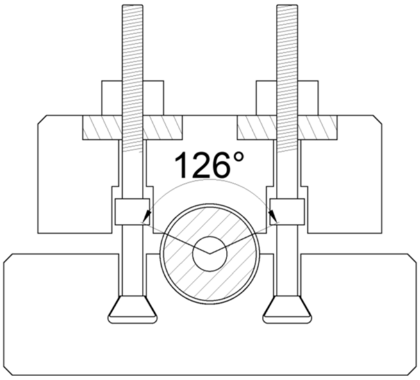


FIGURE 8. Cleat wrapping angle of faulty unit.

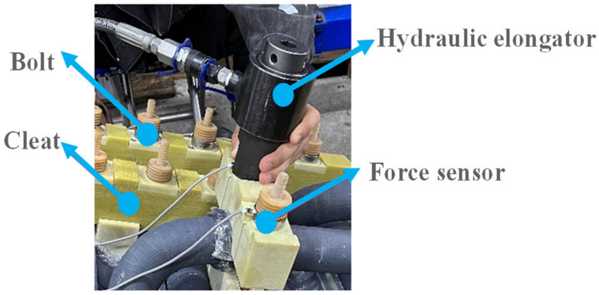


FIGURE 9. Bolt pretension.

conditions, leading to a reduction in pretightening force and bolt connection failure [17]. Therefore, the magnitude of the pretightening force is crucial to the reliability of bolted connections [18], [19].

The decrease of pretightening force is the most direct factor leading to bolt loosening. Therefore, increasing the initial pretightening force of bolt can delay bolt loosening and improve the stability of bolt connection.

III. EXPERIMENTAL VERIFICATION OF LOOSENING CAUSES AND IMPROVEMENT MEASURES

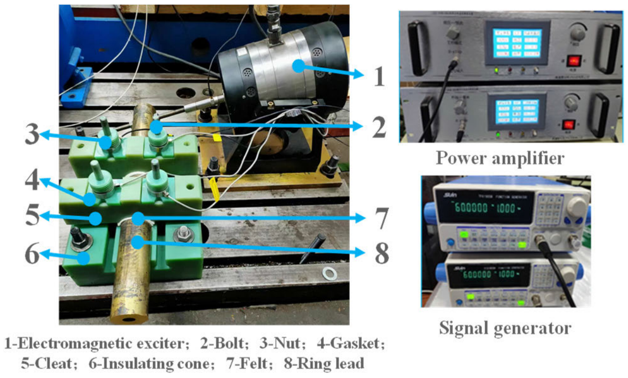
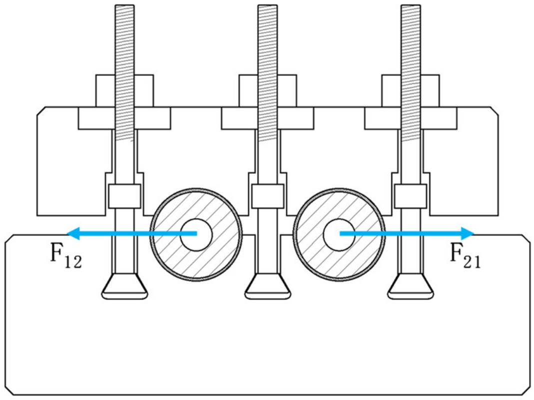


FIGURE 10. Thin-wall support sample test platform.

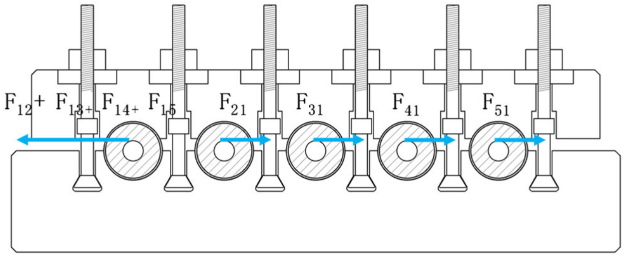
According to the loosening causes analyzed above and the corresponding improvement plan, the Thin-wall support sample test platform is set up to carry out the experimental verification of loosening causes and improvement measures. In order to be close to the actual situation, the component material and size of the sample test platform are consistent with the actual unit. The sample test platform mainly includes electromagnetic exciter, bolt, nut, gasket, cleat, insulating cone, felt and ring lead, as shown in Fig. 10. The excitation signal generated by the signal generator passes through the power amplifier and is transmitted to the electromagnetic exciter to generate exciting force.

A. ELECTROMAGNETIC EXCITATION FORCE CALCULATION

The main source of excitation force for fixed structures is the alternating electromagnetic force between leads [20], [21], as shown in Fig. 11. In order to be close to the actual situation,



（a） Double leads cleat.



（b） Five leads platen.

FIGURE 11. Schematic diagram of electromagnetic force on leads of different cleat types.

the setting of exciting force in the test process refers to the electromagnetic exciting force of a single cleat when the unit is running.

Firstly, the electromagnetic force between adjacent ring leads is calculated, and the ring leads are simplified into two coaxial parallel ring currents C_1 and C_2 with radii a and b, currents I_1 and I_2, and center distance h, as shown in Fig. 12. The electromagnetic force between the ring leads is calculated by referring to the formula of electromagnetic force between the currents of two coaxial parallel rings [22].

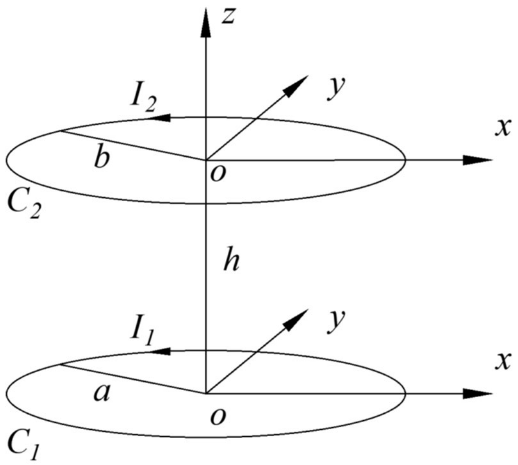


FIGURE 12. Two coaxial ring currents.

The mutual inductance coefficient between the currents of two coaxial parallel rings is:

$$M = \mu_0 (ab)^{1/2} \left[\left(\frac{2}{k} - k \right) K(k) - \frac{2}{k} E(k) \right] \tag{1}$$

Of which:

$$K(k) = \int_0^{\pi/2} \frac{dx}{(1 - k^2 \sin^2 x)^{1/2}} \tag{2}$$

$$E(k) = \int_0^{\pi/2} (1 - k^2 \sin^2 x)^{1/2} dx \tag{3}$$

$$k^2 = \frac{4ab}{h^2 + (a+b)^2} \tag{4}$$

Since the electromagnetic force between two coaxial parallel toroidal currents is only a component in the z-axis direction, it follows:

$$F = F_Z = I_1 I_2 \frac{\partial M \partial k}{\partial k \partial h} \tag{5}$$

Substituting For (1), (2), (3), and (4) into (5) gives:

$$F = \frac{\mu_0 I_1 I_2 h}{\left[(a+b)^2 + h^2\right]^{1/2}} \left[K(k) - \frac{1 + k'^2}{2k'^2} E(k) \right] \tag{6}$$

The electromagnetic force of a single cleat from a single lead is:

$$f = \frac{F}{n} \tag{7}$$

In the above formula:

F—Electromagnetic force between the currents of two coaxial parallel rings;

μ_0— vacuum permeability is $4\pi \times 10^{-7}$ N/A^2;

n—Number of cleats;

Since there are many different cleat type and leads arrangement modes in the actual unit, the worst stress conditions are considered, as shown in Fig.11 (b). The actual data of the unit is substituted into the above formula, and the maximum electromagnetic excited force of the cleat is 350 N. So, in this experiment, the frequency of the exciting force was maintained at 100 Hz and the magnitude of the exciting force was 350 N [23]. The reduction in bolt pretightening force after one hour of excitation was used as the basis for judging the loosening condition. The force sensor is placed between the nut and the gasket to make the bolt pretightening force act on the sensor, and the sensor signal is output to the software through the acquisition card to display the change curve of the pretightening force and the current value of pretightening force, as shown in Fig. 13.

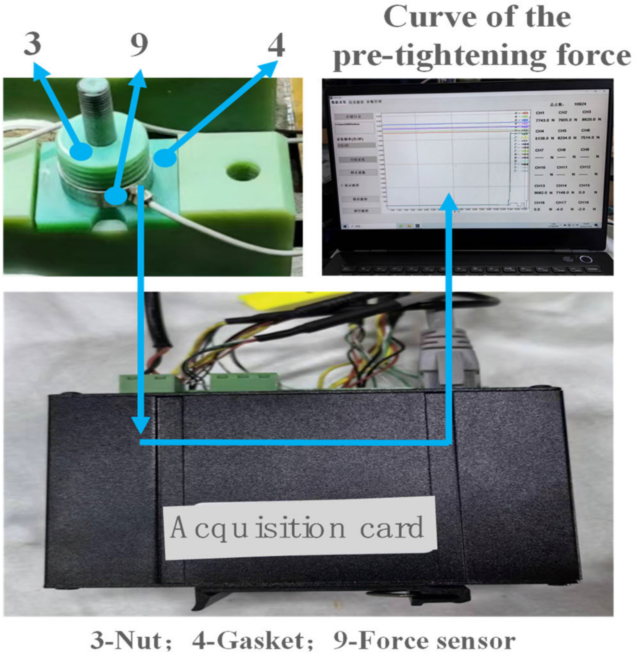
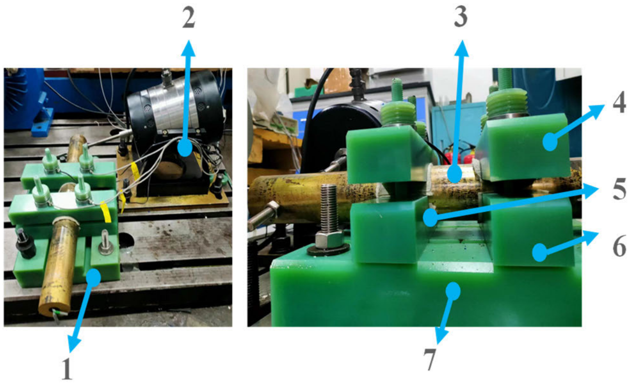


FIGURE 13. Arrangement of force sensors.

B. COMPARISON OF DIFFERENT CLEAT SUPPORT FORMS

For the support form of cleat, the Thin-wall support and Thick-wall support test platform was built to compare and verify the vibration response of the structure with different cleat support form, as shown in Fig. 10 and Fig. 14. Both test bench maintained identical conditions except for the support style of the cleats to ensure the singularity of the experimental variable.

In the experiments, a signal generator produced a 100 Hz sinusoidal signal, which was amplified by a power



1-Conical groove；2-Electromagnetic exciter；3-Ring leads；
4-Upper-cleat；5-U-shaped groove；6-Lower-cleat；7-Insulating cone

FIGURE 14. Thick-wall support test platform.

amplifier and transmitted to an exciter. This setup applied a vibratory force of 350 N through a connecting rod to the leads, simulating the electromagnetic vibratory forces experienced during actual generator operation. Force sensors were placed between each nut and gasket to collect the data of the initial bolt pretightening force before excitation and the bolt pretightening force after 1h excitation at the four bolt measurement points. The average reduction in bolt pretightening force within one hour at each measurement point was calculated and recorded as the average reduction of bolt pretightening force. This metric is used to evaluate bolt loosening and describe the influence of various loosening causes and improvement measures on bolt loosening and pretightening force losses.

The variation of bolt pretightening force under Thin-wall support and Thick-wall support can be seen in Table 1. It shows that the average reduction of pretightening force under Thick-wall support is significantly lower than that under Thin-wall support, from 118 N under Thin-wall support to 25 N under Thin-wall support, with a reduction of 78.8%. It shows that the Thick-wall support can better support the ring leads fixed structure, slow down the loosening speed of bolts, and enhance the anti-loosening effect of the structure.

TABLE 1. Influence of cleat support form on bolt pretightening force.

Support form	Measuring point	Bolt pretightening force(N)		Average reduction of bolt pretightening force（N）
		Before excitation	After 1 hour of excitation	
Thin-wall support	1	8060	7914	118
	2	8084	7938	
	3	8003	7896	
	4	7963	7890	
Thick-wall support	1	8093	8066	25
	2	8077	8051	
	3	8002	7979	
	4	7970	7946	

C. BOLT FIXING METHOD

The test platform is used to test and explore two different bolt fixing methods for conical groove fixing and threaded fixing method. Fig. 10 shows the fixing method of conical groove and Fig. 15 shows the fixing method of threaded.

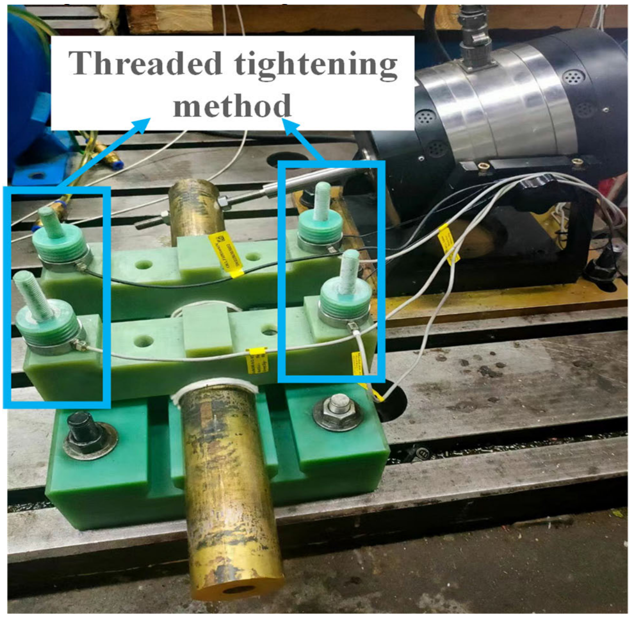


FIGURE 15. Thick-wall support test platform.

From the experimental results in Table 2, it can be seen that the average reduction of bolt pretightening force under the threaded fixing method is lower than that under the conical groove fixing method, decreasing from 118 N in the conical groove fixing to 104 N in the threaded fixing, with a reduction of 11.9%. It shows that the threaded fixing method can slow down the loosening speed of bolts and has better anti-loosening effect

TABLE 2. Influence of different bolt fixing methods on bolt pretightening force.

Bolt fixing method	Measuring point	Bolt pretightening force(N)		Average reduction of bolt pretightening force（N）
		Before excitation	After 1 hour of excitation	
Conical groove fixing method	1	8060	7914	118
	2	8084	7938	
	3	8003	7896	
	4	7963	7890	
Threaded fixing method	1	8093	7952	104
	2	8077	7887	
	3	8002	7917	
	4	7970	7972	

D. DIFFERENT WRAPPING ANGLE OF CLEAT

Comparison tests were carried out for different cleat wrapping angles, and in addition to the original 126° cleat wrapping angle, cleats with three different wrapping angles of 148°, 160°, and 172° were fabricated, as shown in Fig. 16.

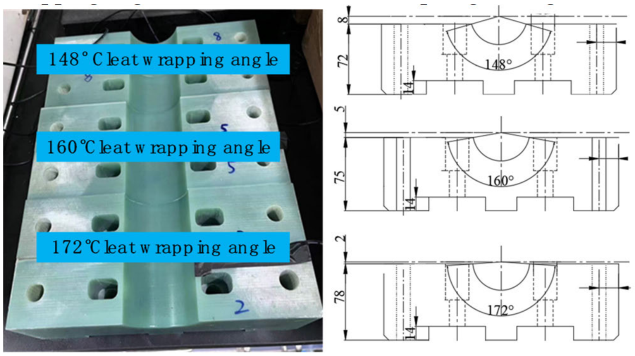


FIGURE 16. Cleat with different wrapping angle.

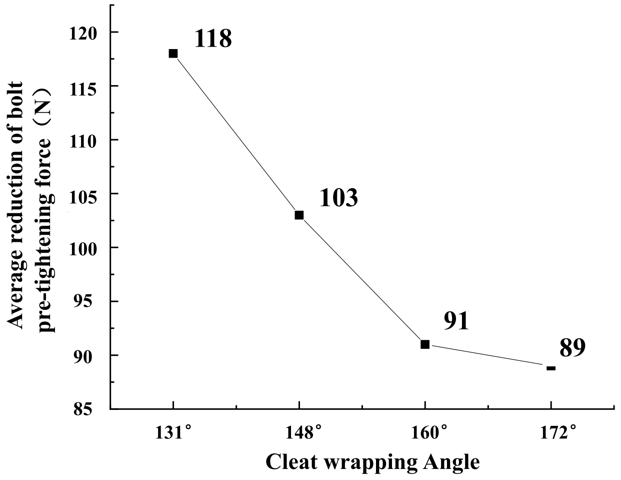


FIGURE 17. Average reduction of bolt pretightening force with different wrapping angle of cleat.

TABLE 3. Influence of different wrapping angle of cleat on bolt pretightening force.

Cleat wrapping Angle	Measuring point	Bolt pretightening force(N)		Average reduction of bolt pretightening force（N）
		Before excitation	After 1 hour of excitation	
131°	1	8060	7914	118
	2	8084	7938	
	3	8003	7896	
	4	7963	7890	
148°	1	8039	7967	103
	2	8037	7939	
	3	7949	7811	
	4	8000	7894	
160°	1	8005	7982	91
	2	7991	7887	
	3	8038	7952	
	4	8070	7972	
172°	1	8094	8017	89
	2	8094	8020	
	3	7936	7811	
	4	7928	7846	

Cleat with different wrapping angles were installed on the test platform shown in Fig. 10 to investigate the effect of cleat with different wrapping angles on the variation of bolt pretightening force.

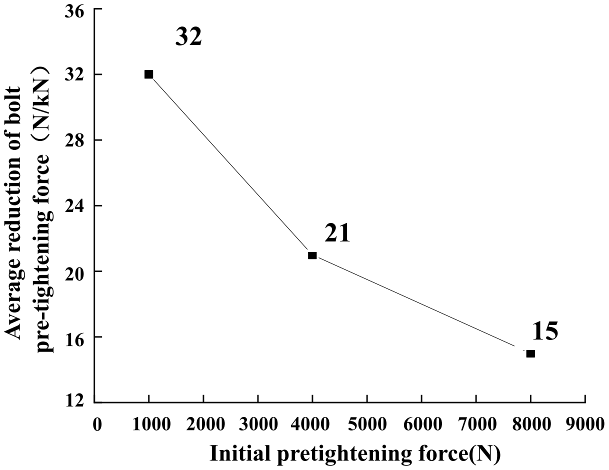


FIGURE 18. Average reduction of bolt pretightening force with different initial pretightening force.

TABLE 4. Influence of initial pretightening force on bolt pretightening force.

Initial pretightening force (N)	Measuring point	Bolt pretightening force(N)		Average reduction of bolt pretightening force （N/kN）
		Before excitation	After 1 hour of excitation	
1000	1	1001	976	32
	2	963	932	
	3	984	947	
	4	980	944	
4000	1	3976	3892	21
	2	4049	3977	
	3	3877	3779	
	4	3936	3848	
8000	1	8060	7914	15
	2	8084	7938	
	3	8003	7896	
	4	7963	7890	

Similarly, the test collected the bolt pretightening force data of four bolt measurement points before excitation and after 1h of excitation, and recorded the variation of bolt pretightening force at different cleat wrapping angles, as shown in Table 3 and Fig. 17. From the table, it can be seen that with the increase of the cleat wrapping angle, the reduction of bolt pretightening force decreases gradually, from 118 N at 131° cleat wrapping angle to 89 N at 172° cleat wrapping angle, which is a decrease of 24.6%. It shows that a larger angle of the cleat wrapping slows down the bolt loosening and prevents it from loosening better. Therefore, the unit should be set with a larger wrapping angle cleat, which improves structural rigidity, slows down the fretting wear due to vibration, and improves component life.

E. INITIAL PRETIGHTENING FORCE OF BOLT

Test platform was used to investigate the influence of different initial pretightening force of bolt on the variation of

TABLE 5. Summary of experimental results of the improvement measures.

Improvement measures	Value	Average reduction of bolt pretightening force	Reduction
Increasing the cleat wrapping angle	131°	118 N	\
	148°	103 N	12.7%
	160°	91 N	22.9%
	172°	89 N	24.6%
Increasing initial pretightening force of bolt	1000 N	32 /kN	\
	4000 N	21 N/kN	34.4%
	8000 N	15 N/kN	53.1%

bolt pretightening force. During the test, the frequency of the excitation force was 100 Hz, excitation force was 350 N, the excitation time was one hour. The table 4 and Fig. 18 shows the variation of bolt pretightening force under different initial pretightening force levels.

From the test results, it can be seen that with the increase of the initial pretightening force, the average reduction of bolt pretightening force tends to decrease, from 32 N/kN at 1000 N initial pretightening force to 15 N/kN at 8000 N initial pretightening force, a drop of 53.1%. The experimental results show that the bolt loosening can be delayed and the stability of the bolted connection can be improved by increasing the initial pretightening force.

IV. CONCLUSION

This study focuses on the lead fixing structure at the generator end, employing comparative analysis of different unit structures and simulation methods to investigate the loosening mechanisms. It identifies the cleat support form and bolt fixing method as key factors contributing to loosening. The paper proposes increasing the cleat wrapping angle and the pre-tightening force of the bolts as improvement measures. Additionally, a test bench is constructed to validate the correctness of the loosening cause analysis and the effectiveness of the improvement measures. The experimental results confirm these findings.

(1) Experimental results validating the causes of loosening indicate that the support method of cleat significantly affects the bolt loosening. The average reduction of bolt pretightening force dropped from 118 N with Thin-wall support to 25 N with Thick-wall support, a reduction of 78.8%. Different bolt fixing methods also have a certain impact on bolt loosening, with the average reduction of bolt pretightening force dropping from 118 N under the conical groove fixing method to 104 N under the threaded fixing method, a reduction of 11.9%, as shown in Table 5.

(2) Experimental results validations of the improvement measures indicate that increasing the wrapping angle of cleat reduces the average reduction of bolt pretightening force drop from 118 N at a 131° wrapping angle to 89 N at a 172° wrapping angle, a decrease of 24.6%. This suggests that a larger wrapping angle can mitigate fretting wear among components and consequently minimize the loss of preload. Furthermore, increasing the initial pretightening force of bolts demonstrated a reduction in the average reduction of bolt pretightening force drop from 32 N/kN at 1000N initial preload to 15 N/kN at 8000N, marking a decrease of 53.1%, indicating that higher initial bolt preload effectively delays bolt loosening, as shown in Table 5.

(3) Both improvement measures are feasible for on-site implementation and can effectively delay the reduction of bolt pre-tightening force. For example, increasing the wrap angle of cleat simply involves manufacturing a cleat with larger wrap angle and replacing the existing one during overhaul. To increasing the pre-tightening force of the bolts, it is only necessary to optimize the bolt preload process and increase the final preload target value during equipment maintenance. These approaches do not necessitate any modifications to other structures and hold practical engineering value. They lay the foundation for solving the technical challenges associated with securing the generator's end ring lead structure and ensuring safe and stable generator operation.

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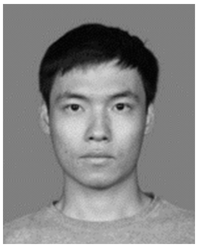

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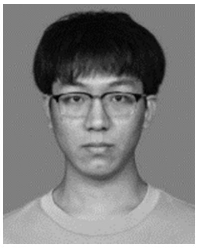

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