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A1 - ROTATING ELECTRICAL MACHINES
PS 2 / ASSET MANAGEMENT OF ELECTRICAL MACHINES

Preventive Maintenance Technology for Enhancement of Turbine Generator Reliability

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SUMMARY

In recent years, power generation systems using renewable energy have been steadily increasing. The role of thermal power plants is expected to change from conventional base-load operation to peak-load operation depending on the power demand. Since generators for peak-load use are operated only for the necessary hours in one day (daily start and stop (DSS)), the number of starts and stops tends to increase. As it increases, there is growing concern about damage of generator rotor parts due to low cycle fatigue. In contrast, inspection opportunity tends to decrease because periodic inspection of thermal power plant is postponed or cancelled to enhance the plant availability. Once rotor parts damage occurs, it may result in unscheduled stoppage of a thermal power plant in the worst case.

Firstly, accurate evaluation of the lifetime is essential, and we have developed large scale 3D structural analysis in order to evaluate the stress of rotor parts accurately where higher stress concentration and low cycle fatigue are concerned. The developed analysis model contains almost all major parts around the rotor coil end portion, and it is possible to simulate the asymmetric deformation of the parts in axial and circumferential directions. The optimized 3D model was introduced through repeated trial and error by comparing the result of 3D analysis with the operational data and appearance of actual damaged parts, and it was found that maximum stress amplitude of the parts in the 3D model is higher than that of calculation result of the conventional 2D model. Consequently, we concluded that the developed technology can provide high reliability, over 99.9%, to prevent fatal accidents under the assumption that a generator rotor runs under DSS operation for 30 years with appropriate inspection and maintenance.

Secondly, we established a new non-destructive testing (NDT) technology for detecting a flaw of rotor teeth under the retaining ring without disassembling the retaining ring. The inspection period of rotor teeth can be shortened significantly by the new NDT method.

By combining the accurate lifetime evaluation by 3D structural analysis and the new NDT method, it enables the owner to accurately evaluate remaining life of turbine generator rotor and maximize plant availability by planning of reasonable inspection frequency.

KEYWORDS

Turbine Generator – Rotor – Fatigue Failure – Preventive Maintenance - NDT

1. Introduction

The use of renewable energy has been expanding in the world for the purpose of reducing greenhouse gas emissions, and power generation cost of renewable energy has been close to reasonable one. Under this circumstance, the role of thermal power plant is expected to shift to peak-load operation, taking advantage of its flexibility for corresponding to the fluctuating demand, instead of conventional base-load operation. As a result, turbine generator will be operated only in a certain time of a day for adjustment of power supply, daily start and stop cycles of turbine generator will increase significantly. This also increases the number of repeated stress due to centrifugal force acting on rotor parts of the generators, inevitably increasing the risk of low cycle fatigue failure. If fatigue crack length of the parts propagates to a threshold, fatal accidents by scattering of the parts and unscheduled stoppage of a thermal power plant may occur as the worst case.

On the other hand, inspection opportunity tends to decrease because periodic inspection of thermal power plant is postponed or cancelled for improvement of the availability, new method of reliability assessment is strongly requested to accelerate transition to RBM (Risk Base Maintenance) taking limited machine monitoring data. Therefore, we developed the two technologies that enables the owner to accurately evaluate remaining life of turbine generator rotor and maximize plant availability by planning of reasonable inspection frequency.

2. DSS Operation of Generators and Low Cycle Fatigue Failure of Rotor Parts

In daily start and stop (DSS) operation, for example, a turbine generator is operated only in a certain time of a day for adjustment of power supply, and a start and stop cycle is repeated approximately once a day. By continuing this operation, the number of starts and stops will reach 1,000 in several years. While generators are operating, stresses due to centrifugal forces and thermal expansion occur at each section of the rotors. Even if the stress amplitude of rotor parts is lower than the yield point (the beginning point of plastic behaviour) of the materials, there is a possibility that the parts are damaged because of repeated stress. Generally, low cycle fatigue failure occurs at around 10^4 cycles. The threshold of failure is determined by the number of repetitions and the value of stress amplitude, and if the stress amplitude is large, failure may occur after only several thousand cycles.

We have observed some few breakage incidents of rotor parts during periodical inspections. Figure 1 shows an example of a broken part, a joint lead between the poles in rotor coils. Repeated stress occurs at the parts during stoppage and operation because joint lead between the poles has a circular structure, circumferential tensile force occurs due to its own centrifugal force during operation. To absorb the deformation against tensile force and suppress the excessive stress occurrence, flexible parts are

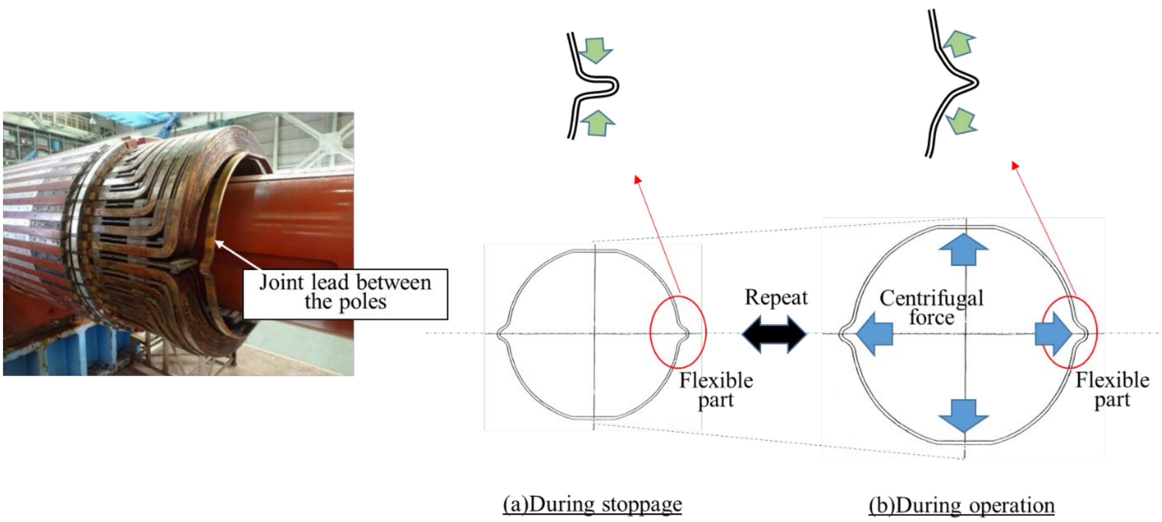
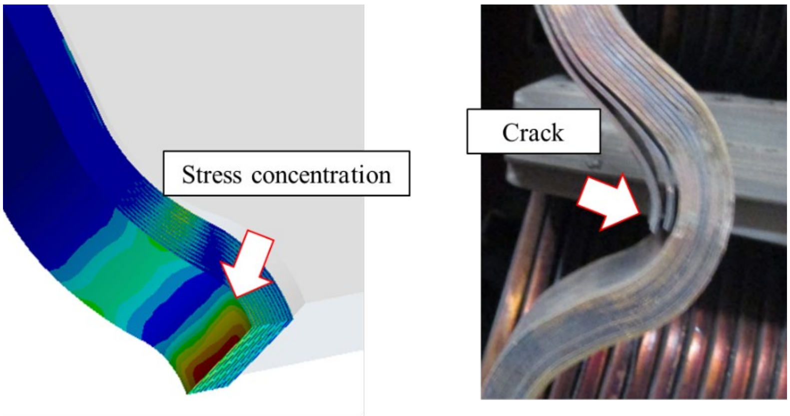


Figure 1 Repeated stress occurring at joint lead between the poles due to stoppage and operation

originally provided in the joint lead between the poles. Thus, circumferential stress is locally concentrated at the center of the flexible parts as shown in Figure 2(a). Although the value of stress on the parts is lower than the tensile strength of the material when the generator is operated at the rated rotational speed, if the number of starts and stops increases under high stress amplitude, a fatigue crack initiates and propagates in susceptible sections. As shown in Figure 2(b), the section where stress concentrates in the simulation often matches the section that broke.



(a)Stress destribution (b)The broken part

Figure 2 An example of broken rotor part

Another well-known example of broken part due to low cycle fatigue is the rotor tooth. Figure 3 illustrates the cross-section of a turbine generator rotor. A rotor mainly consists of rotor coils, rotor shaft (teeth), and wedges. The coils and wedges are stored in the slots along the axial direction of the shaft as its structure. During operation, the coils' centrifugal force is retained by the teeth via the wedges, causing tensile force on the teeth and wedges, and this tensile force is unloaded when the generator stops. In addition, the end portion of a rotor body which is assumed to be potential weak point is shown in Figure 4. In order to retain the centrifugal force acting on the rotor end winding and not to separate it from the rotor surface during operation, the retaining ring is strongly shrink-fitted with the shaft and end plates. Thus, compressive force acts on the teeth under the retaining ring due to the shrinkage fitting during stoppage. Because the tensile force and compressive force act in opposite directions, the cyclic stress amplitude of the teeth under the retaining ring is often the largest in the rotor parts.

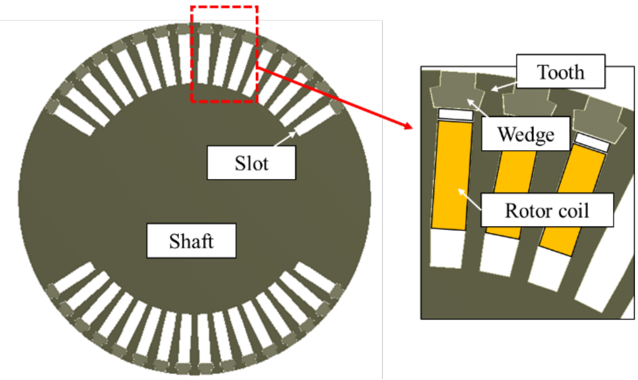
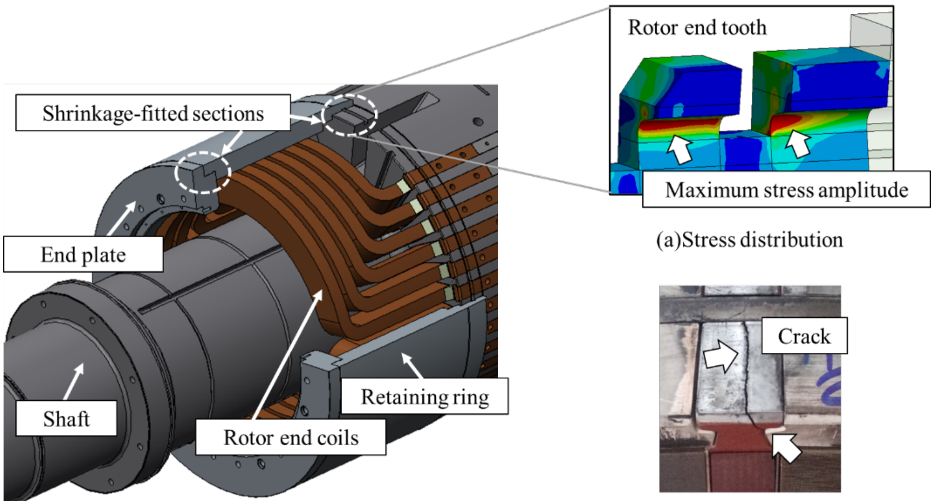


Figure 3 Cross-section of a rotor



(a)Stress distribution

(b)The broken part

Figure 4 Rotor parts under retaining ring

Other components whose low cycle fatigue failure needs to be evaluated are, for example, the retaining rings and end plates shown in Chapter 3. Accordingly, with increase in the number of starts and stops of a generator in the future, it becomes important to accurately calculate the stress amplitude at the sections where stress is concentrated to evaluate the low cycle fatigue strength. The start and stop cycles of both damaged rotor parts which were previously explained were actually confirmed to be smaller than the initial expectation at the design stage. After careful consideration, the cause was determined that physical deformation of the retaining ring and the other parts in rotor end portion are different from those calculated by conventional 2D structural analysis because the asymmetric structure of the parts could not be considered.

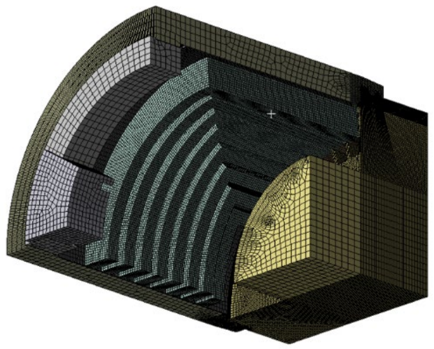
3. Accurate lifetime evaluation with large scale three-dimension (3D) structural analysis

In recent years, thanks to the improved performance of computers, the calculation time for models with complicated structures involving many elements has been remarkably reduced. Practical-level structural analysis of a 3D model of a whole rotor end structure including retaining rings, rotor winding, and other components is now possible. Figure 5(a) shows the structural analysis model of a rotor end. Thanks to this improvement, by re-evaluating element tests performed in the past and evaluation by comparison with actual generator rotor appearance, it is possible to evaluate with higher accuracy the aforementioned local stress at each section of a complexly shaped rotor, which affects the low cycle fatigue lifetime, thus enabling higher-accuracy lifetime evaluation of each part.

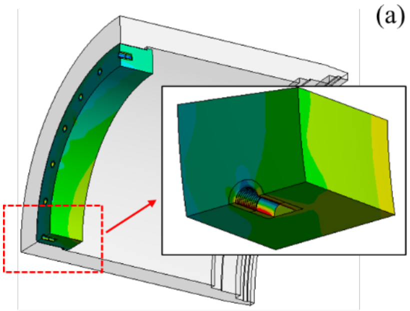
The calculation results of stress amplitude values (difference in stress between the generator under operation and standstill) of broken parts are shown in Figure 2(a) and Figure 4(a). The maximum values are distributed around the stress concentration parts marked by arrows and they match the sections with actual crack initiation due to low cycle fatigue. Figure 5(b) and 5(c) illustrate that the stress values differ according to location along the circumferential and the axial direction. The stress distribution is different from the results of conventional 2D analysis, and in some places the values calculated in 3D analysis exceed those assumed initially in 2D analysis. This new knowledge obtained by the 3D analysis shows that the allowable number of starts and stops regarding low cycle fatigue fracture for actual equipment is less than the assumed number. In conventional analysis, the rotor end was assumed to be symmetric in the circumferential direction. However, these results have revealed that slight structural asymmetries in actual equipment cannot be ignored when evaluating low cycle fatigue lifetime because asymmetric deformation of the retaining ring also affects the deformation of the rotor teeth, joint lead between the poles, and end plates.

Evaluation by comparison with existing data has confirmed that the estimation of the 3D analysis is accurate enough for designing. In order to prove the effectiveness when proposing preventive maintenance work, an actual rotor was used to measure the stress at each section to re-check the accuracy of the stress calculation. Figure 6 shows the measured circumferential stress on the rotor wedge and retaining ring as examples. The values in Figure 6 have been normalized by regarding the largest measured value for each part. In both cases, the measured values closely match the calculated ones including differences in the circumferential and axial directions, confirming the validity of the current analysis technique including boundary conditions. Regarding fatigue characteristics of the materials, test samples imitating actual equipment were used to collect data separately.

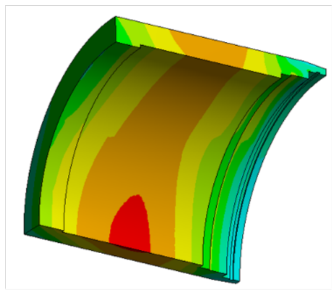
Consequently, our developed technology can provide high reliability, over 99.9%, to prevent fatal accidents in power generation plants under the assumption that a generator rotor runs under DSS operation for 30 years with appropriate inspection and maintenance.



(a) Mesh model



(b) Stress distribution of end plate



(c) Stress distribution of retaining ring

Figure 5 Structual analysis model for a rotor end (1/4 of the circumference)

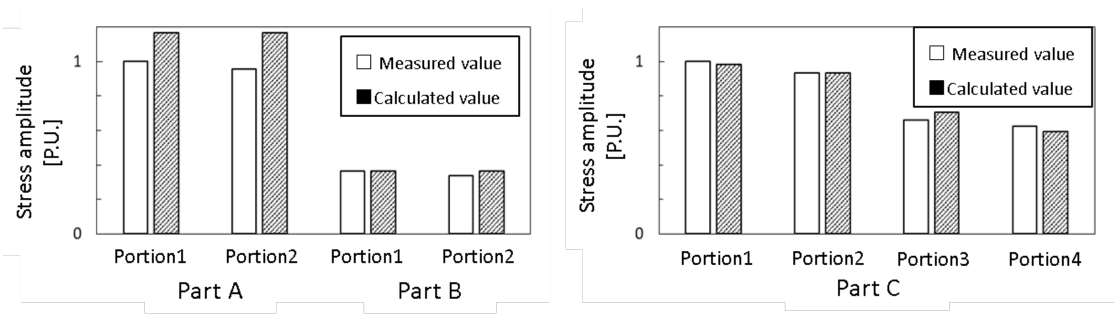


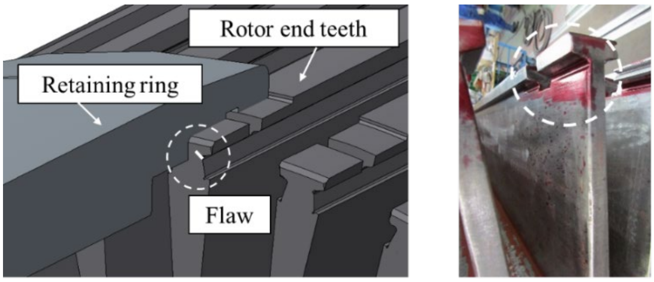
Figure 6 Comparison results between measured and calculated value

4. New NDT method for shortening the inspection period

The risk of breakage can be predicted by using the 3D analysis described in the previous chapter and then comparing the results with actual generator operation conditions. However, performing lifetime evaluation for all generators manufactured in the past is not practical in terms of cost. Under current conditions in which periodic inspection periods are becoming shorter and performed less frequently, it is necessary to develop inspection technologies to detect damage to rotors quickly and without fail when inspecting actual equipment. Failures that are caused by low cycle fatigue as a result of starting and stopping generators may develop even under smaller loads compared to that before the failures are formed, resulting in breakage. Around rotor parts, centrifugal force acts during operation and very small repeated stress successively occurs due to shaft vibration. Therefore, it is not acceptable to continue operating such generators with a remaining failure for safety reasons. In such a case, it is important to detect an initial crack at an early stage.

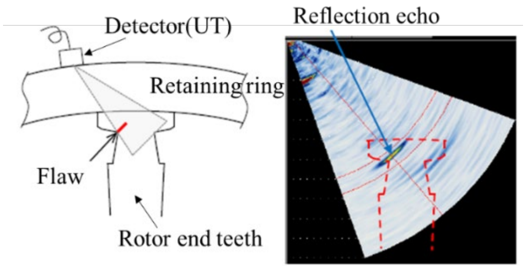
Typical example where low cycle fatigue failure is concerned is rotor end teeth portion as shown in Figure7(a). Visible dye penetrant test (PT) was normally adopted for detecting a minute flaw on the corner of rotor end teeth, stress concentration part covered with the retaining ring. But this existing method takes a long time for judgement of presence of a flaw because disassembling and assembling of the retaining ring, the wedges, and the rotor coils after pulling out the rotor are necessary. Therefore, to minimize outage period of the plant, we have developed a new inspection technology for the rotor end teeth portion with ultrasonic test (UT). Figure 7(c) outlines the new technology that ultrasound is used to detect a failure in a tooth inside a retaining ring from the surface of the ring. This technology enables us to conduct inspections without disassembling the rotor end parts. In other words, the technology can greatly shorten the conventional inspection processes and realize the inspection during a suspension period that was previously impossible to inspect.

A probe of phased-array-UT can only inspect a limited range of angles, and there is an optimum angle of ultrasound against the angle of a flaw. The position where the detector can detect a flaw is limited depending on the angle and length of the flaw, therefore the verification tests were repeated with applying model simulate under various damage condition of the teeth, and we established the appropriate procedure to indicate relationship between locations of the detector and a flaw, corresponding to various rotor structures.



(a)A flaw on the corner of rotor end teeth

(b)Visible dye penetrant test (PT)



(c)Ultrasonic test (UT)

Figure 7 New NDT method to inspect rotor end teeth

Consequently, the rotor end teeth inspection is possible to be carried out in parallel within the period of regular inspection and the inspection opportunity to enhance reliability will be increased. This UT method has also enough detection sensitivity for residual lifetime estimation of the teeth combining with the accurate evaluation by 3D structural analysis described in Chapter 3, so that the owner is possible to plan reasonable inspection frequency.

5. Conclusions

Due to the change of thermal power plant utilization, the number of start and stop cycles of turbine generator tends to increase, and the risk of low cycle fatigue failure of generator rotor parts becomes higher than that initially envisioned. On the other hand, we recognised that there is a possibility that the actual lifetime against low cycle fatigue of the parts may shorter than expected lifetime designed with conventional 2D structural analysis because axial or circumferential asymmetry cannot be taken into account in the 2D model. Therefore, the preventive maintenance for the rotor parts becomes more important to enhance the plant availability, and we have developed and introduced the following technologies.

1. Accurate lifetime evaluation of turbine generator to ensure that a generator rotor runs under DSS operation for 30 years with high reliability over 99.9%.
2. New NDT method to presume residual lifetime of rotor end teeth portion and to plan reasonable inspection frequency.

By using these technologies, we will contribute to stable operation and availability enhancement of thermal power plants.

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