Preventive Maintenance Technology for Enhancing Generator Reliability

Authors: *Kazuaki Ogura** and *Go Kajiwara**

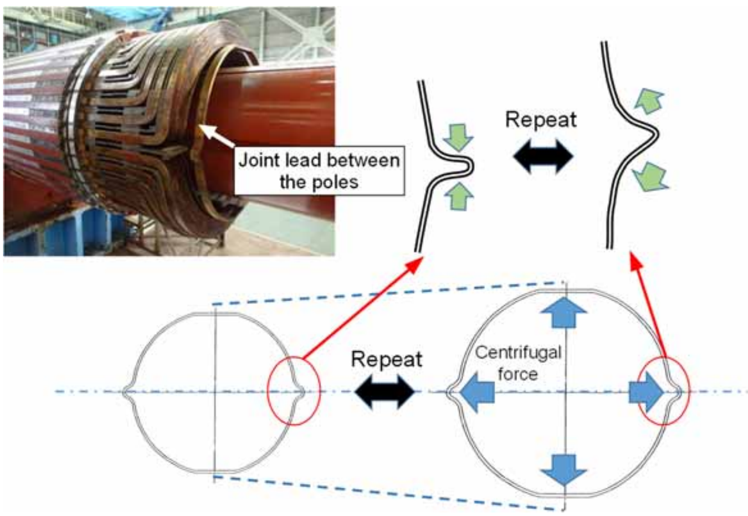
1. Introduction

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. During peak-load operation, generators are operated only for the necessary hours in one day (daily start and stop (DSS)), increasing the number of starts and stops of turbine generators. This in turn increases the number of repeated stress due to centrifugal force acting on each section of the rotor parts in the generators, inevitably increasing the risk of low cycle fatigue failure. Accordingly, to ensure the high reliability of generators in long-term operation in the future, we have been developing technologies for accurately evaluating lifetime using the latest analysis techniques. This paper also introduces a new non-destructive testing (NDT) technology for rotor parts and proposal to add value to preventive maintenance work.(1)

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

In daily start and stop (DSS) operation, a turbine generator is operated only in a certain time of a day for adjustment of power supply, and the 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, centrifugal forces and thermal stresses due to the increase in temperature occur at each section of the rotors. Even if the stress amplitude of rotor parts is lower than the yield point 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 magnitude of stress amplitude, and if the stress amplitude is large, failure may occur after only several thousand cycles.

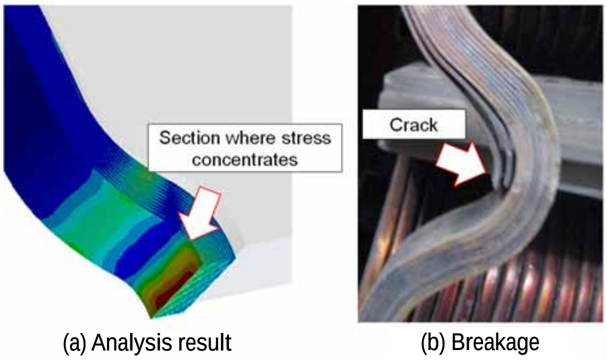
Figure 1 shows an example of repeated stress occurring at the rotor parts during stoppage and operation. Because the joint lead between the poles has a circular structure, circumferential tensile force occurs due to its own centrifugal force during operation. In addition, because the structure absorbs deformation at some sections, stress concentrates at the sections as shown in Fig. 2(a). The parts will not suddenly break when the generator is operated under these conditions. On the other hand, if the number of starts and stops increases under high stress amplitude, failure may occur in susceptible sections. As shown in Fig. 2(b), the section where stress concentrates in the simulation often matches the section that actually broke. Accordingly, when the number of starts and stops of a generator increases, it is important to calculate accurately the stress amplitude at



(a) During stoppage (b) During operation

Fig. 1 Repeated stress occurring at rotor parts due to start and stop

*Energy Systems Center



(a) Analysis result (b) Breakage

Fig. 2 Breakage of a rotor part due to low cycle fatigue

the sections where stress is concentrated to evaluate the strength against low cycle fatigue.

3. Large-Scale 3D Analysis Technique for Rotor Parts

3.1 Structure of the end of a generator rotor

Figure 3 illustrates the cross-section of a turbine generator rotor. A rotor mainly consists of rotor coils, rotor shaft (shaft/teeth), and wedges. The coils and wedges are stored in the slots in 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 to act on the teeth and wedges. When the generator stops, this tensile force is unloaded, and so stress amplitude occurs due to starts and stops. Figure 4 illustrates the structure of the end of a rotor. The retaining rings retain the centrifugal force of the rotor end coils. They are structurally engaged with the shaft and end plates strongly enough by shrinkage fitting such that they will not separate during operation. Therefore, while the generator is not operating, compressive force due to the shrinkage fitting acts on the sections where the retaining rings are coupled with the shaft and end plates. While the generator is operating, tensile force acts due to centrifugal force. In other words, due to start and stop, stress amplitude occurs at the rotor end teeth, end plates, and retaining rings.

In recent years, thanks to the improved performance of computers, the calculation time for models of 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 coils, and other components is now possible. Thanks to this improvement, by re-evaluating verification 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.

3.2 3D analysis results and their appropriateness

Figure 5 shows the structural analysis model of a rotor end. Figure 6 shows the stress amplitude values (difference in stress between the generator under operation and standstill) at each section at the rotor end per start and stop of a generator. The stress concentrates on the sections marked by arrows and they match the sections with a high breakage risk due to low cycle fatigue caused by repeated starts and stops. The stress at the rotor end teeth, end plates, and retaining rings is distributed in the circumferential direction and the tendency in the axial direction is also different from the results of conventional 2D analysis. These results exceed the stress amplitude values assumed initially. 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

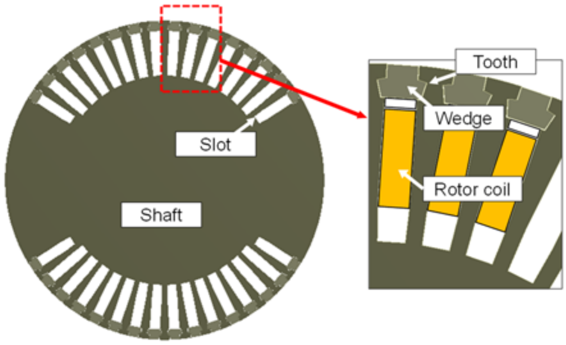


Fig. 3 Cross-section of a rotor

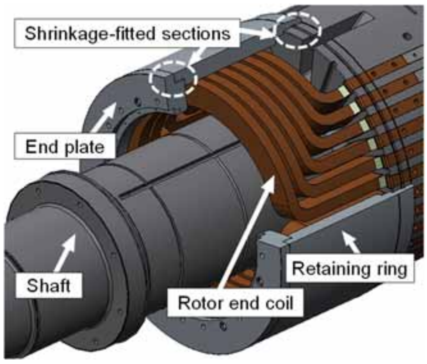


Fig. 4 Rotor end structure

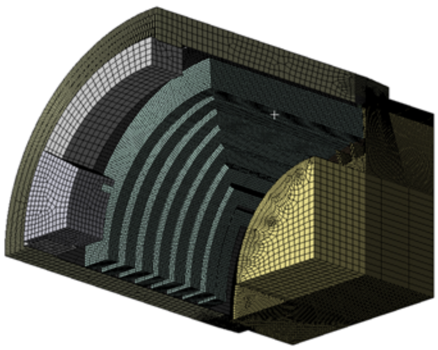


Fig. 5 Structural analysis model for a rotor end (1/4 of the circumference)

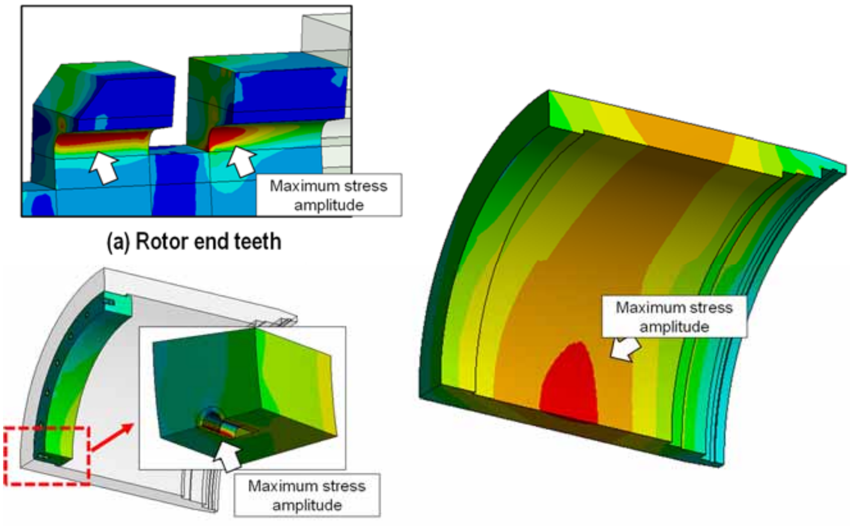


Fig. 6 Stress amplitude at the rotor end when a generator is operating and not operating

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.

Evaluation by comparison with existing data has confirmed that the estimation of the aforementioned 3D analysis is accurate enough for designing. In order to add value 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 7 shows the measured stress on the rotor wedge and retaining ring as examples. The values in Fig. 7 have been normalized by regarding the largest measured value for each rotor wedge and retaining ring as one. 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, enabling highly accurate evaluation of fatigue lifetime.

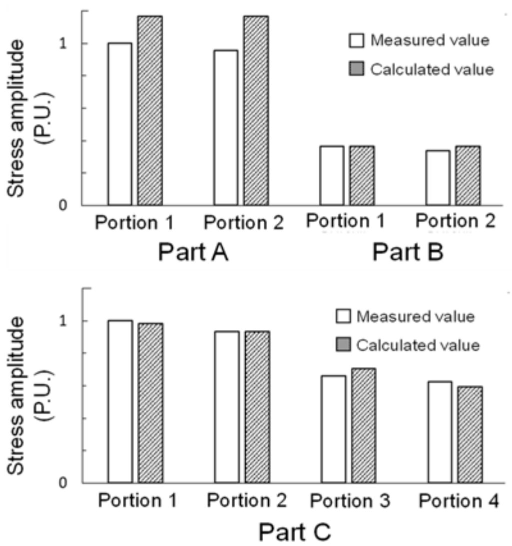


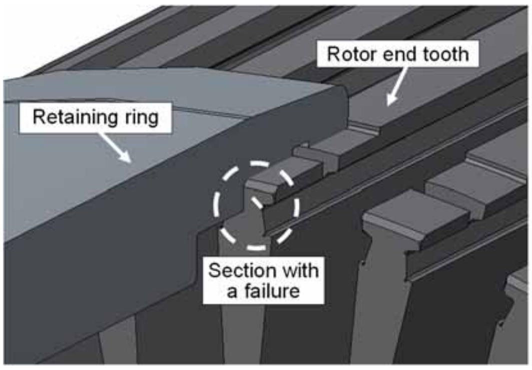
Fig. 7 Measurement results of stress on the rotor wedge and retaining ring

4. Preventive Maintenance Technologies to Create Benefits for Customers

4.1 Non-destructive testing (NDT) technology for rotor parts

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. Conventionally, to detect an initial crack in rotor parts, liquid penetrant inspections are required; for example, if a failure develops at a rotor end tooth as shown in Fig. 8, it is



(a) Section with a failure on a rotor end tooth

(b) Penetrant test

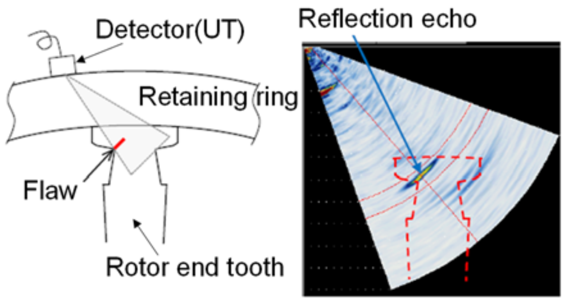
Fig. 8 Penetrant inspection of a rotor end tooth

hidden in the retaining ring due to the structure and cannot be directly inspected. To inspect this section, the rotor needs to be pulled out from the generator and then disassembled into each part, which takes a long time and is unacceptable to customers.

Currently, we have been developing a technology to shorten the inspection procedure. Figure 9 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 inspections to be conducted without disassembling the rotor end parts. In other words, the technology can greatly shorten the conventional inspection processes. It also allows detailed inspections of rotor parts, which used to be impossible in conventional periodic inspection periods, to be included at predetermined periods without problems, thus increasing the opportunities for detailed inspections of rotor parts. We are planning to apply the same technology to inspect each rotor part in the future. We will continue our development efforts to ensure that breakage risks can be detected at an early stage and serious accidents can be prevented without decreasing the availability of thermal power plants.

4.2 Proposal to add value to preventive maintenance work

Accurate evaluation of the fatigue lifetime of each rotor part can enhance the reliability of long-term operation of generators by proposing appropriate timings for inspection and parts replacement. Also, optimizing the strength design standards at the part level can improve the efficiency of generators and reduce costs. As a concrete example, the results obtained this time were incorporated into the design of the cross section of a rotor to optimize its form, which improved the efficiency of the generators by 0.02%. Higher efficiency of generators reduces CO_2 emissions and environmental impact, and also increases the profitability of generation plants by reducing the cost per unit output.



UT: Ultrasonic test

Fig. 9 Ultrasonic test of a rotor end tooth

5. Conclusion

The operation environment of thermal power plants has been changing. For turbine generators in particular, preventive maintenance technologies for rotor parts are becoming more important. Therefore, we have improved the technologies used to evaluate the lifetime of rotor parts by combining the latest analysis techniques with verification using actual equipment and the results of testing of materials. In addition, we have been developing a new inspection technology to detect breakage in rotor parts quickly and without fail in order to shorten periodic inspection periods and improve the availability of generators.

We will use these technologies to propose appropriate maintenance frequencies along with elemental technologies that add value to preventive maintenance work, thus contributing to the reliability of generators in long-term operation and improving profitability.

Reference

(1) Y. Funasaki, et al.: Indirectly Hydrogen-cooled Turbine Generator “VP-X Series” and Application of Element Technologies to Existing Generators, Mitsubishi Denki Giho, 90, No. 11 (2016)