Crack Growth Prediction of the Steam Turbine Generator Shaft

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Abstract. The power network in China is encountering great changes and large-scale network is increasingly implemented for long distance power transmission as well as various kinds of power electronic devices, which bring in the risk of the torsional vibration of the turbine generator shafts, may cause the fatigue damage and cracks in the product life cycle. The paper analyzed the failed coupling of some 600MW steam turbine generator and calculated the local stress of the assembly under torsional load caused by the network disturbance. Then the crack propagation was analyzed with the predicted crack initiation position and crack propagation routine. The assembled coupling contains shaft, coupling and keys with interferences between the parts. Therefore the contact analysis was included. Extended Finite Element Method (X-FEM) is used to calculate the crack propagation and that the mesh needs not to be regenerated with the crack propagation, which is beneficial for engineering applications.

1. Introduction
Crack accidents emerged in several power plants all over the world. Kinds of disturbances were determined to be the causes of cracks, including the stress concentration, alternation loads, the aerodynamic excitation, thermal loads, network disturbances and so on [1-3]. The coupling between the turbine and the generator is one of the mostly observed crack positions [4], with contact stresses due to the interferences between the parts.

In China, the installed capacity of power plants increases greatly in recent years and the network developments partly fall behind the developments of power plants, which cause the problem of electricity transmission. Kinds of devices are used to improve the transmission capacity like series capacitor, Thyristor Controlled Series Capacitors (TCSC), High Voltage Direct Current Transmission (HVDC) and so on [5]. However, another problem emerged, which is the oscillation between the network and turbine generator units including the Subsynchronous Resonance (SSR) and Subsynchronous Oscillation (SSO). Such problems firstly happened in 1970s in USA with severe crack accidents of the turbine generator shafts [6-7]. The shaft crack accidents were also emerged in a power plant in China including two 600MW steam turbine generator units [8]. Torsional interaction phenomena were monitored between the turbine generator and the network in the operation history.

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Several factors are determined to be the root causes including the contact stresses and the network disturbances [8].

To determine the root causes of the crack failures, the stress analysis was analyzed using Finite Element Method (FEM) in many researches as well as the fatigue accumulation of the local part to determine the remaining useful life [4, 8-9]. Furthermore, the crack initiation and propagation are to be analyzed to determine the failure position, extend the useful life and avoid catastrophic failures, which are less researched. This paper concentrated on the crack initiation and propagation of the local shaft, with XFEM, which is a mesh-free method to simulate the crack propagation. The failed coupling in the 600MW steam turbine generator is analyzed with the monitored network disturbances in reality. Under the rated load and the maximal torsional load, the contact analysis using FEM are implemented to determine the local stress. Then the crack initiation and propagation are analyzed with XFEM. This analysis tried to find out the causes of the initial crack and predict the direction and routine of the crack growth.

2. Models and Methods

2.1. FEA Models

The crack, emerged at the power plant with 600MW steam generator, located at the coupling between the low pressure turbine and the generator in figure 1, with the three parts assembled including the shaft, the coupling and the keys in figure 2.

FEM model is established based on the practical size of the three parts, and 1/8 part of the coupling assembly is used according to the Saint-Venant principle in figure 3. Then the meshes are generated with hexahedral meshes, including 139784 elements on the shaft, 79800 elements on the coupling and 10620 elements on the key section in figure 3.

![Figure 1. The cracked position](image1.png)

![Figure 2. The cracked coupling](image2.png)

![Figure 3. The mesh model of the coupling assembly](image3.png)
In the assembling process, the coupling is firstly installed on the shaft. To maintain the connection between the low pressure turbine shaft and generator shaft, and transfer the torques. The shaft and coupling is assembled together through interference fit. The amount of the interference equals to the difference of the radii of the two parts. When the shaft and the coupling are assembled, the keyways are machined to install the keys (as shown in figure 2). The interference exists between the key and the shaft-coupling assembly, where the radius of the keyway is smaller than that of the key. The values of the interferences are in table 1. In the modelling process, the interferences are applied in the solution step.

Table 1. The interferences of the coupling parts

| Position                        | Interference (mm) |
|--------------------------------|-------------------|
| Between Shaft and Coupling     | 0.405             |
| Between Shaft and Key          | 0.03              |
| Between Coupling and Key       | 0.03              |

The coupling assembly is used for transmit the torque from the low pressure cylinder rotor to the generator rotor. The initial stress caused by interferences between the shaft and coupling is significant. However, the local stress at the end of the keyway may be much higher than other positions, the contact stresses under different loads were analyzed in [8], with the elastic material property.

Because a quantity of the interference exists in the assembly, the contact stress is probably high in the contact area. Therefore the material probably reaches the plastic zone. The analysis in the previous study validates that the contact stress is higher than 1000MPa with the elastic material property. Here, the elastic-plastic material property is applied in the model. The stresses under different loads are shown in figure 4, where the SSO loads are the typical conditions when the oscillation occurs between the turbine generator units and the network. Here, the unit used in the torques is p.u., with the definition:

\[ T_{\text{p.u.}} = \frac{T}{T_r}, \]  

Where, \( T \) is the torque in specified case, \( T_r \) is the torque in the rated power.

As the SSO conditions were monitored in operation history of the unit, and the stresses caused by SSO loads are determined to be one of the significant factors that induce the cracks [10]. And High Cycle Fatigue (HCF) was determined as the failure mode of the coupling assembly due to SSO loads.

Compared with the elastic material, the stresses with elastic-plastic material have smaller amplitudes and present nonlinear relation between the stresses and the torques. In different SSO conditions, the equivalent stresses are nearly linear with the elastic-plastic material property, which means that the material is operated in the elastic zone and the plastic strain is small. It validated that the HCF rule is suitable to evaluate the fatigue damage in SSO conditions. In the two phase short circuit condition, the equivalent stresses are large, which presents the nonlinear relation with other conditions, and the plastic strain is obvious. Low Cycle Fatigue (LCF) is therefore to be applied to evaluate fatigue damage in this situation.

The above analyses are discussed in the fatigue damage before the crack initiates using the stress and strain estimates. Once the crack initiates, the relation between the stress and strain may vary and the contact stresses may change. To study the situation after the crack initiation is an important aspect to find out the dangerous position, determine the crack initiation position and acquire the crack propagation characteristics. This is beneficial for practical applications including predicting the remaining useful life of the structure and extending the useful life with optimized operation conditions. Therefore, the crack initiation and propagation analyses are necessary.
2.2. Extended Finite Element Method (XFEM)

To analyze the crack initiation and propagation in the component failure, the conventional FEM has difficulties in modelling the crack area, the meshes need to be regenerated to adapt the changes of crack front, which greatly increases the complexity of the analyse. Some methods are developed to regenerate the meshes automatically, but the quality of the automatically generated meshes needs careful analysis. In general, the FEA using the re-meshing method to study the crack propagation problem is a burdensome job.

In recent years, meshless methods are being proposed to solve the problem. Based on the partition of unity (PU), extended Finite Element Method (XFEM) is one of these meshless methods, which was proposed by Ted Belytschko in 1999–2000 [11], and has been greatly developed in recent years [12]. The basic idea of XFEM is to model the crack front inside the element as some kind of boundaries. The crack-tip enrichment functions \( \gamma_i(r, \theta) \) are applied to acquire the displacement field [11]:

\[
\{ \gamma_i(r, \theta) \}_{i=1}^{4} = \left\{ \sqrt{r} \cos \left( \frac{\theta}{2} \right), \sqrt{r} \sin \left( \frac{\theta}{2} \right), \sqrt{r} \sin \left( \frac{\theta}{2} \right) \sin(\theta), \sqrt{r} \cos \left( \frac{\theta}{2} \right) \sin(\theta) \right\},
\]

(2)

where \( r \) and \( \theta \) are polar coordinates with origin at the crack tip and \( x_1 \) axis parallel to the crack faces.

The approximation takes the form of an extrinsic enrichment and can be written as:

\[
u^h(x) = \sum_{i=1}^{n_1} N_i(x) \left( u_i + \sum_{j=1}^{n_{1,1}} a_{i,j} \gamma_j(r, \theta) \right),
\]

(3)

\[
v^h(x) = \sum_{i=1}^{n_1} N_i(x) \left( v_i + \sum_{j=1}^{n_{1,1}} b_{j,i} \gamma_j(r, \theta) \right),
\]

(4)

where \( (r, \theta) \) is a polar coordinate system with origin at the crack tip and the \( x_1 \) axis parallel to the last segment and \( N_i(x) \) are the standard finite element shape functions. The enrichment coefficients \( a_{i,j} \), \( b_{j,i} \) are determined by solving an auxiliary problem.
and $b_i$ are associated with nodes and $n_e(i)$ is the number of coefficients for node $I$. It is chosen to be 4 for all nodes around the crack tip and zero at all other nodes. More details of XFEM can be referred to [11-12].

The validations of XFEM were implemented in many areas, including the stress intensity factors estimates, the crack growth routine prediction and so on [13-14]. It shows that XFEM has good prediction ability in crack growth without mesh regeneration, and it has been applied in industry [15]. This paper applied the XFEM in the coupling assembly model to simulate the crack initiation and propagation in practical loads, to acquire the failure causes and failure progress.

3. Results and Discussion

To simulate the crack propagation in reality, the contact stresses are to be acquired, which will affect the crack initiation and propagation, as well as the torsional loads. As mentioned in figure 4, the torques under different SSO loads and two phase short circuit are analyzed, using the transient analysis with the coupled turbine generator model and electric network model. The rated torque is:

$$T_n = \frac{60P_n}{2\pi n},$$

where $P_n$ is rated capacity of the turbine generator units, $n$ is the rated rotating speed.

When the two phase short circuit occurs, the torques jump to an instantaneous electrical torque in high amplitude, the maximal torque reaches 8.97 $T_n$ in the analyzed unit based on the coupled analysis between the unit and network. Applied with the maximal torque on the turbine generator shafts, with the rotor model in figure 5, the torque response of the failed coupling can be acquired. The maximal torque acted on the end of the coupling is 4.1 $T_n$. The maximal torque of the failed coupling was acted at the end of coupling side in figure 2.

Figure 5. The rotor model with the equivalent shaft sections

Figure 6. The initial crack in the shaft part of the failed coupling
The crack initiation position was analyzed based on the metallographic analysis and the end of the keyway was determined as the crack initiation position of the shaft. Then the initiation position is modeled in the coupling model with a small size perpendicular to the surface of the shaft in figure 6.

Using the initial crack in perpendicular direction is an attempt to determine the crack propagation direction from the FEA, the initial crack size is small with little impact on the stress distribution of the coupling at the normal contact condition. The calculation result proves that no singular strain filed is presented on the initial crack area at the initial contact condition and the rated torque condition.

When the maximal torque is acted on the coupling with initial crack, the crack propagates in figure 7. The propagation direction has the 45 degree to the normal direction of the surface of the shaft keyway, also 45 degree to the torque direction, which is consistent with the practical situation. The crack propagation routine is along the direction with 45 degree to the torque direction.

**Figure 7.** The propagated crack in the shaft part under maximal torque

4. **Conclusions**

The crack accident is one of the most serious accidents in the rotating machinery operation with the reason that the crack usually occurs without obvious changes in the shaft stiffness, and tiny cracks are difficult to be detected. The cracks emerged in the coupling section is more difficult to be detected as the assembly conceal the crack surface, where the surface detection techniques are not effective.

This paper applied the FEA into the crack analysis with stress estimate, the crack initiation and propagation analysis. The failed coupling in some 600MW steam turbine generator unit in a power plant is analyzed with the typical SSO loads and two phase short circuit load. Using the XFEM, the crack propagation is acquired with the crack direction and the propagation routine. The results can be further analyzed with the amount of crack propagation under fixed loads.

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