Repair Analysis for Low Head Hydraulic Generator Cracking and Rupture

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Received: 18 September 2013 /Accepted: 22 November 2013 /Published: 30 December 2013

Abstract: The generator vibration of the unit is sensitive to the running conditions for the low–head turbine group’s low head, high flow characteristics. The generator local stress concentration often leads to fatigue rupture of the metal structure, which will also affect its reliability. It easily leads the generator bracket of oblique arm structure to cracking and rupture. The reason of the cracking and rupture is proved by numerical analysis and its repair plan has been identified. On-site repair process should be strictly controlled, to ensure the greatest degree of welding quality and the elimination of welding stresses. Running for some time after repair, the main parameters, such as air-gap and other unit operation, have been analyzed. The results are satisfying, and confirm that the analysis of the generator bracket crack repair is objective and reasonable.

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Keywords: Low head, Hydraulic power sets, The generator cracking and rupture, Numerical analysis, Repair.

1. Introduction

Due to turbine’s characteristics of low head and high flow, the unit operating conditions are influenced by hydraulic factors. In addition, local stress concentration often leads to fatigue rupture of the metal structure, which will also affects its reliability [1]. At present there is limited research on the field of crack of low head hydraulic generator rupture. Jianquan Chen worked on the low head hydraulic generator rotor radial plate dynamic stress test. Tianyu Chen studied the causes of rotor bracket crack of low head hydraulic generator. All above focuses on theoretical research of the qualitative, instead of applied analysis. In this paper, a low head turbine hydroelectric power plant was found running up the rotor stud subplate cracks, supporting blocks and the brake ring weld cracking phenomena, and do numerical analysis on the generator rotor crack, set a optimal solution after a comparative analysis with the actual site, and confirm that the analysis of the generator bracket crack repair is objective and reasonable.

2. Introduction to the Generator Structure

2.1. Constitution of the Generator

Generator rated power is 24 MW, the speed is 68.2 rpm (rated) / 219 rpm (runaway), rotor diameter is 7.2 m. Rotor mainly consists of the rotor bracket, field yoke, magnetic pole and some other
components. The rotor bracket consists of the central body, gusset and stud, rotor bracket and field yoke are connected by stud, oblique radial gusset are connected with the central body and the stud [2]. Through the support block, the stud subplate and the brake ring had been welded into one.

2.2. Generator Material and Allowable Stress

Stud subplate of the generator rotor has a thickness of 20 mm, and its material is Q235C, the yield strength is 225 N/mm², the stress limit is 375 N/mm². Central body gusset of the bracket has a thickness of 50 mm, material is Q235C, and the yield strength is 225 N/mm², and the stress limit is 375 N/mm².

3. Preliminary Analysis on Cracking and Rupture

When the unit had run for 2000 h, 33 cracks were found between support blocks and brake ring, and six thirty-thirds rotor stud subplate produce local non-penetrating crack, which are shown in Fig. 1 and Fig. 2. In the original design, the brake ring gravity, centrifugal force and thermal expansion are supported by the pin (88 Φ30 mm). With the rotor rotation, alternating stress produces fatigue damage.

4. Finite Element Analysis on Generator

4.1. Model Setup

Do simulation on magnetic poles, magnetic yokes, brake rings, pins, central body, and support block by solid unit. Do simulation on ally arm by shell unit [3]. Remove the connection between brake ring and the support block, and the braking ring’s centrifugal force is to be on the field yoke plate’s pin. The field yoke model is simulated with solid elements. The material properties and weight of models are as follows: arm elastic modulus is 210,000 N/mm², Poisson’s ratio is 0.3, thermal expansion coefficient is 11.5x10^-6 1/K, a density is 7,850 kg/m³; field yoke modulus Eₓ=150,000 N/mm², Eᵧ=150,000 N/mm², E_z=20,000 N/mm², Poisson's ratio of the field yoke νₓᵧ=0.22, νₓz=0.03, νᵧz=0.03, coefficient of thermal expansion of the field yoke is 11.5x10^-6 1/K; central body mass is 18.5 t, part of the shaft quality is 3.2 t, arm and small gusset quality is 19.7 t, field yoke quality is 49.7 t, brake ring quality is 3.25 t, magnetic pole mass is 42.3 t, other quality is 0.13 t, and total mass is 136 t.

Using ANSYS’s function of intelligent network to size the network division, and the rotor bracket is manually controlled of the local area, the rotor bracket finite element model contains a total of 101,592 units, 124,102 nodes. The model building and solving is completed by ANSYS11.0 [4]. All three displacement nodes of the rotor center body are all constrained [5].

Fig. 1. Welding line between support blocks and control ring.

Fig. 2. Generator cracking and rupture of the rotor stud subplate.

Fig. 3. Generator finite element model.
Fig. 4. The unbalance distribution of magnetic tensile force.

Fig. 5. Generator finite element model under design rated condition.

Fig. 6. Comprehensive stress distribution under design rated condition.

Fig. 7. Generator finite element model under runaway speed condition.

Fig. 8. Comprehensive stress distribution under runaway speed condition.

Rated operating conditions (static load): speed is 68.2 rpm, rated torque is 3360.5 kN·m, field yoke temperature rise is 25 K. Runaway speed condition (static load): runaway speed is 219 rpm. Alternating load condition: gravity is 9.81 m/s². Unbalance magnetic tensile force is 255 kN.

The rotor is loaded with rated torque, centrifugal force, gravity and unbalance magnetic tensile force during operating. The arms average stress is 58 N/mm² in rated operation of the static load condition (see Fig. 5 and Fig. 6) and the arms allowable stress is 75 N/mm². The arm stress is 111 N/mm² under runaway speed condition of the static load and the brake ring stress is 133 N/mm² (see Fig. 7 and Fig. 8) and the arms allowable stress is 150 N/mm².

The stress intensity of welded joint of support block-brake ring is 32.3 N/mm² (see Fig. 9 and Fig. 10). The stress intensity of welded joint of support block-arms is 23.2 N/mm² (see Fig. 9 and Fig. 10). The allowable stress is 15 N/mm².

The generator rotor is bearing alternation stress under operation. According to the conversion of operation time and rotate speed, the breakage cycle index is more than 10⁴ and the breakage belongs to high cycle endurance ration.
Through the calculation of the rotor bracket in the static load, the stress and deformation are lower than the allowable value and the computation results value is more than allowable stress value. The value is due to the stress concentration (in small area) of simplifying the finite element calculation model and less than the material yield limit value, which cannot cause the continuing damage of the rotor bracket in the existing condition. The stress value of the most of the regional rotor bracket is far lower than the allowable fatigue limit value (15 MPa) under the alternating load condition. However, the stress value (32.3 and 23.2 MPa) of the welding parts between the rotor bracket arms side ends and support block-brake ring board is more than the allowable fatigue value (15 MPa), which may mostly cause fatigue damage. According to calculation result and analysis, it is concluded that the rotor bracket crack belongs to high cycle endurance ration.

According to the finite element analysis and checking construction process, it has been found that the welding of support block-brake ring is not conformable with the requirements of welding process. Through the analysis of the results, one of them that causes rotor stud subplate crack is that braking rim and support block are welded together wrongly during field assembly. The weld connected is closer than the pin connected, making the most of the brake ring gravity, centrifugal force and thermal expansion forces transmit to the support arm through the weld, the phenomena of most welding crack of support block and brake ring agrees with finite element analysis.

Based on the finite element analysis of the generator rotor cracking and rupture, it is concluded that the crack of rotor vice board do not extend with the welding disconnection of the rotor stents arms side ends and support block-brake ring board and that brake ring and support block are welded to together wrongly. So at present the rotor crack can be repaired and keep running [8].

4.3. The Analysis Calculation of the Finite Element Repairing Plan

Solution is to eradicate local stress concentration, so that the operation of the alternating stress could evenly be dispersed in the pin, to avoid the braking ring’s weight produce excess load on the rotor ally arm. This makes the alternating stress amplitude stays in the allowable stress of the crack areas.

Simulated by finite element model, the maximum alternating stress amplitude at the connection of the braking ring and the support block is about 32 MPa. The maximum amplitude of alternating stress of the arm and support block at the weld between is about 23 MPa, which is much larger than the allowable fatigue stress (15 MPa). Broken arm and seam also verify the theoretical results.

According to finite element calculations, four kinds of rehabilitation plans are brought out. Plan 1: remove the welding seam between brake ring and the support block, as shown in Fig. 11 and Fig. 12, the calculated maximum amplitude of alternating stress is 11.75 MPa (allowable value is 15 MPa).
Plan 2: remove the welding seam between the brake ring and the support block, and reduce the support block, the radial width is 60 mm, as shown in Fig. 13 and Fig. 14, the calculated maximum amplitude of alternating stress is 10.53 MPa (allowable value is 15 MPa). Plan 3: remove the weld seam between the brake ring and support block, and reduce the support block, the radial width is 60 mm, fill the square hole (20 mm plate, groove welding), as shown in Fig. 15 and Fig. 16. The calculated maximum amplitude of alternating stress is 10.49 MPa (allowable value is 15 MPa). Plan 9: remove support block and fill the square hole (20 mm plate, penetration welding), as shown in Fig. 17 and Fig. 18, its calculated maximum alternating stress amplitude is 10.3 MPa (allowable value is 15 MPa). Based on the above four plan calculations, four kinds of rehabilitation plan are safe in theory. The result is insignificant. But considering the construction process, there are many unknown factors out of consideration, such as inadequate to stress annealing, weld seam defects, etc. We should minimize the alternating stress to obtain greater margin of safety. In Plan 1 alternating stress is below the allowable fatigue stress, but still relatively close to the allowable value.

Plan 4 has the minimum stress, but the support block in the structure and support with the installation of the brake ring locking device the role cannot be canceled. In Plan 2 and Plan 3, the stress is close. In summary of the comparisons, to ensure maximum safety margin and feasibility, Plan 2 is chosen, that removes the weld connection between the brake ring and the support plate, and reduces the radial width of the support block.
4.4. Onsite Construction Process Control

Above calculations are based on theoretical calculations. In order to consist with the actual and theoretical calculations, on-site repair process should be strictly controlled according to welding procedures in accordance with the effective implementation of the welding process, in order to ensure the greatest degree of welding quality and the elimination of welding stresses. On-site processing work. The main control process is as follows:

1) Prior to crack treatment, preheat the weld seam and use dial indicator to control the thermal deformation;

2) Use small current, narrow weld, “trim, segmentation, regression, symmetrical”, welding, with each segment which is not greater than 120 mm;

3) In order to eliminate welding stresses, except the first layer and annealed layer at the weld, hammer the rest of the weld;

4) Monitor the rotor roundness and deformation during weld process at any time. Weld the support block and stud subplate. Local crack treatment of stud subplate is shown in Fig. 19 and Fig. 20.

5. Operating Results

5.1. Air Gap and Roundness of the Stator and Rotor During Full-load Running

Cracks of generator rotor bracket changes in the running process are usually reflected by the generator’s gas gap and roundness of the stator and rotor in the steady-state progress [9, 10], after the repair it is put into the full-load running, the generator air gap, stator and rotor roundness are shown in Fig. 21 and Fig. 22. Air gap +X is in the range of 9.45-9.91 mm, +Y is 12.25-12.38 mm, -X is 11.37-11.70 mm, -Y is 7.70-7.91 mm. Air gap were less than the standard value in Table 1. Stator and rotor’s roundness and eccentricity values change within the standards, as shown in Table 2.
Table 1. Deviation and standards of air gap in all directions [11].

<table>
<thead>
<tr>
<th>Deviation</th>
<th>+X</th>
<th>-X</th>
<th>+Y</th>
<th>-Y</th>
<th>Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical value</td>
<td>-3.1 %</td>
<td>-2.5 %</td>
<td>-3.5 %</td>
<td>-4.2 %</td>
<td>&lt;=8 %</td>
</tr>
<tr>
<td>Minimum</td>
<td>-2.3 %</td>
<td>-2.7 %</td>
<td>-2.1 %</td>
<td>-3.1 %</td>
<td>&gt;4 %</td>
</tr>
<tr>
<td>Maximum</td>
<td>2.5 %</td>
<td>3.0 %</td>
<td>3.5 %</td>
<td>3.6 %</td>
<td>&lt;4 %</td>
</tr>
</tbody>
</table>

Table 2. Roundness and eccentricity of stator and rotor.

<table>
<thead>
<tr>
<th>Item</th>
<th>Stator [mm]</th>
<th>Rotor [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roundness</td>
<td>1.37-1.45</td>
<td>1.6-1.69</td>
</tr>
<tr>
<td>Eccentricity</td>
<td>0.75-0.80</td>
<td>0.35-0.37</td>
</tr>
</tbody>
</table>

5.2. Changes of Magnetic Pole Elongation

In the transient process, the generator rotor bracket crack changes were showing up directly when the magnetic pole elongation changes in the process of increasing speed and excitation, which can be seen in Table 3 and Table 4. The data is very satisfying.

Table 3. The largest 10 magnetic pole elongation changes in the process of raising speed [12].

<table>
<thead>
<tr>
<th>Magnetic pole</th>
<th>Relative elongation in positive direction [mm]</th>
<th>Magnetic pole</th>
<th>Relative elongation in negative direction [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>#48</td>
<td>0.13</td>
<td>#83</td>
<td>-0.08</td>
</tr>
<tr>
<td>#45</td>
<td>0.12</td>
<td>#82</td>
<td>-0.08</td>
</tr>
<tr>
<td>#46</td>
<td>0.11</td>
<td>#84</td>
<td>-0.07</td>
</tr>
<tr>
<td>#47</td>
<td>0.09</td>
<td>#81</td>
<td>-0.07</td>
</tr>
<tr>
<td>#19</td>
<td>0.09</td>
<td>#87</td>
<td>-0.07</td>
</tr>
<tr>
<td>#20</td>
<td>0.09</td>
<td>#75</td>
<td>-0.07</td>
</tr>
<tr>
<td>#49</td>
<td>0.08</td>
<td>#2</td>
<td>-0.06</td>
</tr>
<tr>
<td>#51</td>
<td>0.08</td>
<td>#72</td>
<td>-0.06</td>
</tr>
<tr>
<td>#52</td>
<td>0.08</td>
<td>#11</td>
<td>-0.06</td>
</tr>
<tr>
<td>#78</td>
<td>0.02</td>
<td>#88</td>
<td>-0.06</td>
</tr>
</tbody>
</table>
Table 4. The largest 10 magnetic pole elongation before or after increase field excitation.

<table>
<thead>
<tr>
<th>Magnetic #</th>
<th>Relative</th>
<th>Magnetic #</th>
<th>Relative</th>
</tr>
</thead>
<tbody>
<tr>
<td>#48</td>
<td>0.11</td>
<td>#83</td>
<td>-0.09</td>
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<tr>
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<tr>
<td>#44</td>
<td>0.10</td>
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<td>#41</td>
<td>0.08</td>
<td>#86</td>
<td>-0.07</td>
</tr>
<tr>
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<td>0.07</td>
<td>#1</td>
<td>-0.07</td>
</tr>
<tr>
<td>#43</td>
<td>0.07</td>
<td>#87</td>
<td>-0.07</td>
</tr>
<tr>
<td>#49</td>
<td>0.07</td>
<td>#75</td>
<td>-0.07</td>
</tr>
<tr>
<td>#40</td>
<td>0.07</td>
<td>#74</td>
<td>-0.06</td>
</tr>
<tr>
<td>#66</td>
<td>0.00</td>
<td>#88</td>
<td>-0.06</td>
</tr>
</tbody>
</table>

5.3. Conclusions

By finite element calculation, the reason of bulb-type hydraulic generator rotor stud subplate crack, support blocks and the brake ring weld crack have been found. It is concluded that the rotor stud subplate crack do not extend, and can be repaired and keeps running. By finite element analysis, studied generator rotor bracket crack repair plan, running for some time after repair, the main parameters, such as air-gap and other unit operation, have been analyzed. The results are satisfying, which confirm that the analysis of the rotor bracket crack repair is objective and reasonable. From the researches above, we could get the following conclusion:

1) We have found the initial causes of the bulb generator rotor crack from design ideas.
2) We applied numerical analysis to investigate the causes of crack theoretically, and proposed a detailed method for the repairing.
3) After the analysis on the processed unit operating parameters, the validity of the analysis and treatment to the cracks is proved, and it was tested in the practical applications.

References