The purpose of the paper is to compare the fatigue life expenditure level for turbine shafts and blades due to the excitations of the following six kinds of small disturbances, which are power system unbalance, electrical arc furnace loads, HVDC subharmonic currents, infinite bus voltage sag, load rejection, and mechanical torque pulsation. The results under study could provide the safety comment for the power plants.

II. SYSTEM DESCRIPTIONS

A. System Model

Fig. 1 schematically shows the electromechanical system for study. The steam turbine unit, including a high-pressure (HP) stage and two low-pressure (LP) stage steam turbines, analyzed in this study is a close-coupled and cross-compound reheat unit that operates at a rotational speed of 1800rpm. The rated capacity of the generator is 951MW. Each of LP steam turbines has A and B spindles and uses the shrunk-on rotor. These are eleven rows of blades are sheathed with shrouds and the last two rows of blades are a freestanding structure in which the tip diameter of the longest blade is 4531mm and its length is 1166mm.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>951MW TURBINE-GENERATOR AND SYSTEM PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator (1057MVA, 23.75kV)</td>
<td>Mechanical data</td>
</tr>
<tr>
<td></td>
<td>Mass</td>
</tr>
<tr>
<td>60Hz</td>
<td>( X_r = 1.574 )</td>
</tr>
<tr>
<td>4 poles</td>
<td>( X_r = 1.490 )</td>
</tr>
<tr>
<td>( P_e = 0.90 )</td>
<td>( X_r = 0.168 )</td>
</tr>
<tr>
<td>( Q_r = 0.2334 )</td>
<td>( X_r = 0.190 )</td>
</tr>
<tr>
<td>( V_r = 1.03 )</td>
<td>( X_r = 0.110 )</td>
</tr>
<tr>
<td>Step-up TR1(1057MVA, 24/161kV)</td>
<td>( X_r = 0.15 )</td>
</tr>
<tr>
<td>Transmission line to infinite bus</td>
<td>( X_m = 1.574 )</td>
</tr>
<tr>
<td>1057MVA</td>
<td>( X_r = 0.80 )</td>
</tr>
<tr>
<td>161kV</td>
<td>( R_r = 0.05 )</td>
</tr>
<tr>
<td>Torque distribution (%)</td>
<td></td>
</tr>
<tr>
<td>HP 31</td>
<td>LP1F 13.45</td>
</tr>
<tr>
<td>LP1R 13.45</td>
<td>LP2R 13.45</td>
</tr>
</tbody>
</table>

effect of small power disturbances on turbine-generator mechanism torsional torque and fatigue

Effect of Small Power Disturbances on Turbine-Generator Mechanism Torsional Torque and Fatigue

Jong-Ian Tsai\(^1\), Jin-Tsan Wang\(^2\), Chi-Hshiung Lin\(^3\)
Dep. of \{Electronic\(^1,2\), Electrical\(^3\)\} Engineering, Kao Yuan Institute of Technology, Taiwan
{jitsai1, wang01272, linchsh3}@cc.kyit.edu.tw

Abstract—In this paper, the impact of six kinds of small power system disturbances on the torsional torques and fatigue life expenditure induced in turbine-generator shafts and blades is presented. In this context, investigations have been conducted on a large scale turbine-generator unit connected to the infinite bus feeding various loads. Such power disturbances are power system unbalance, electrical arc furnace (EAF) loads, HVDC subharmonic currents, infinite bus voltage sag, load rejection, and mechanical torque pulsation respectively. The results of these investigations are carried out in the form of typical time-domain responses and frequency-domain response.

I. INTRODUCE

During the last three decades, the torsional impact of large electrical disturbances on the turbine-generator (T-G) shafts and blades has been extensively discussed in many research works [1-3]. Many disturbances impose considerably high stresses on turbine shafts and blades and cause fatigue damage such as network faults, malsynchronization, high-speed reclosing, etc. However, the impact of small electrical disturbances was less studied obviously. In fact, large power disturbances take place rarely whereas the small ones occurs more frequently and even cause long-term fatigue damage in turbine mechanism [4].

On the other hand, the damage on steam turbine blades is significantly affected by impurities in steam, particularly Cl ion [4]. In the more final blade stage, where the transition from dry to wet steam frequently occurs, a saturated solution of salt can be produced from very low levels of steam contaminants. If the considerable torque vibration arising from power disturbances is sustained, it can produce the continuous cyclic stress into the blades operating in the NaCl corrosive environment. The combination of vibratory stresses and corrosive environments provide the necessary conditions for corrosion fatigue to occur.

IEEE ICSS2005 International Conference On Systems & Signals

Effect of Small Power Disturbances on Turbine-Generator Mechanism Torsional Torque and Fatigue

Jong-Ian Tsai\(^1\), Jin-Tsan Wang\(^2\), Chi-Hshiung Lin\(^3\)
Dep. of \{Electronic\(^1,2\), Electrical\(^3\)\} Engineering, Kao Yuan Institute of Technology, Taiwan
{jitsai1, wang01272, linchsh3}@cc.kyit.edu.tw

Abstract—In this paper, the impact of six kinds of small power system disturbances on the torsional torques and fatigue life expenditure induced in turbine-generator shafts and blades is presented. In this context, investigations have been conducted on a large scale turbine-generator unit connected to the infinite bus feeding various loads. Such power disturbances are power system unbalance, electrical arc furnace (EAF) loads, HVDC subharmonic currents, infinite bus voltage sag, load rejection, and mechanical torque pulsation respectively. The results of these investigations are carried out in the form of typical time-domain responses and frequency-domain response.

I. INTRODUCE

During the last three decades, the torsional impact of large electrical disturbances on the turbine-generator (T-G) shafts and blades has been extensively discussed in many research works [1-3]. Many disturbances impose considerably high stresses on turbine shafts and blades and cause fatigue damage such as network faults, malsynchronization, high-speed reclosing, etc. However, the impact of small electrical disturbances was less studied obviously. In fact, large power disturbances take place rarely whereas the small ones occurs more frequently and even cause long-term fatigue damage in turbine mechanism [4].

On the other hand, the damage on steam turbine blades is significantly affected by impurities in steam, particularly Cl ion [4]. In the more final blade stage, where the transition from dry to wet steam frequently occurs, a saturated solution of salt can be produced from very low levels of steam contaminants.

If the considerable torque vibration arising from power disturbances is sustained, it can produce the continuous cyclic stress into the blades operating in the NaCl corrosive environment. The combination of vibratory stresses and corrosive environments provide the necessary conditions for corrosion fatigue to occur.

IEEE ICSS2005 International Conference On Systems & Signals
Fig. 2 shows the mechanical model of the simulated turbine-generator, in which the typical model of a long blade is so complex that it is shown in detail in Fig. 2b. Three types of vibration mode (flexural, axial and torsional) are present in the model, which vibrates in the direction of rotation, perpendicular to rotation and in twist direction, respectively. Among them, the flexural mode has lower resonant frequency and is usually chosen to study the vibration mode shapes of blades. The electrical and mechanical data with the final row (L0) and next-to-final row (L1) of the blades are given in Table I. All the parameters are in the per unit system, based on generator ratings.

II. FREQUENCY-DOMAIN RESPONSE BY FREQUENCY SCANNING

The vibration modes of the turbine system can be computed by using the frequency-scanning approach. Suppose that the terminal of generator rotor is a shake with electromagnetic torque (E/M torque) of one per unit, the frequency inspects the natural frequencies of steam turbines from 0.01Hz to 140Hz with the interval of 0.01Hz. The scanning results for the predominate shaft and blades are shown in Fig. 3, which also reveals the turbine vibration modes as depicted in Table II. It is found that the modes 1–4 and 9–10 are shaft torsional mode, modes 5–8 are the flexural mode for the L0 blade, and modes 11–14 are the flexural mode for the L1 blade. These modes have been avoided from the forbidden frequency bands defined as 60Hz ±5% and 120Hz ±5%. The bandwidth for the each mode is so narrow that the response on vibration modes has very high quality factor (Q).

Based on the frequency domain analysis, the torsional stresses on turbine shafts or blades are easily deduced from the induced E/M torque by power system disturbances.

<table>
<thead>
<tr>
<th>Mode</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>951MW</td>
<td>19.11</td>
<td>36.35</td>
<td>40.23</td>
<td>46.07</td>
<td>49.80</td>
<td>49.82</td>
<td>51.80</td>
<td>52.69</td>
<td>102.35</td>
<td>104.61</td>
<td>126.92</td>
<td>127.08</td>
<td>133.44</td>
<td>134.47</td>
</tr>
</tbody>
</table>

TABLE II
VIBRATION MODES FOR THE 951MW UNIT (HZ)

951MW unit: LP2R-GEN SHAFT

951MW unit: LP2R-L0 BLADE
IV. TIME-DOMAIN RESPONSE BY NONLINEAR MODELING

For time-domain simulation investigations, the entire nonlinear studied system is modeled by Matlab-Simulink/Power System Blockset software [11]. The excitations owing to six kinds of common power disturbances will be discussed.

A. Power system Unbalance

In this case, the point A of the studied system is open in Fig. 1. It has been known that the component of induced E/M torque due to unbalance negative currents (I2) is double-system frequency (120Hz) [4]. As seen from Fig. 3, there are low torque responses for both the shafts and the L0 blades at 120 Hz. However, there is considerable high response of -29.3dB for the LP2R-L1 blade, which leads to supersynchronous oscillation (SPSO).

Fig. 4 demonstrates the transient time behaviors subject to typical I2 = 0.06 pu by uneven load distributions [4]. Each phase current is controlled not to exceed 1.05 pu, the overcurrent protection setting for the studied system. Before 0.3 seconds, the transient E/M torque comprises both system frequency (60Hz) component and double system (120Hz) component. The vibrations of the turbine mechanism are governed by such two forced excitations. Until a steady-state condition is reached, the remaining torque is imposed by the E/M torque of 120 Hz component only. The results for the LP2R-L1 blade with the considerable torque vibrations and the shaft with insignificant torque vibrations agree with the frequency domain analysis.

B. Electrical Arc Furnace Load

In this case, the point A is connected to a steel plant through a step-down transformer and an EAF purpose-used feeder line as shown in Fig. 5, where several local loads are considered. The steel plant is consisted of a 50-ton electrical arc furnace (EAF) load and a thyristor Q compensator (TQC) in service. All parameters of the EAF system are listed in [5].

From the investigation of [5], since the induced E/M torque during the heating operation is mainly composed of the subsynchronous frequency components (<60Hz), the operation of an EAF load viewed from a generator is a subharmonic disturbance. Accordingly the excited torsional torque in the L0 blade will be higher than in the L1 blade due to the subsynchronous vibration mode of the L0 blade. From the simulation result in Fig. 6, the EAF with TQC is precisely modeled by dynamic load model feeding field measured raw data from the MOF of the steel plant. To observe the common impact to the turbine generator, the voltage flicker AV10 at PCC is kept to the standard limit 0.45% [8]. As can bee seen, both the amplitude and the frequency of the E/M torque are stochastic also, caused by the randomly dramatic real power fluctuation at the MOF during the boredown and meltdown period. Thus, the most onerous shaft or blade torque vibrations are induced at about 111 second whereas the maximum fluctuating E/M torque doest not appear at the same time. This is because the maximum torque vibration is excited by either the short-time resonant effect or the torque additive effect due to the excitation in phase with the previous excitation. Because the frequency of the E/M torque is stochastic, the torque amplification phenomenon due to the sustained resonance is not easily excited. Overall, the shaft and blade torsional torque are still considerable.
C. HVDC Subharmonics

In this case, the point A is connected to an asynchronous 50/60Hz HVDC link as given in Fig. 7. The 12-order variable-frequency ripple currents superimposed on DC currents in asynchronous HVDC links results in the subharmonic current at the inverter. Supposing that the sum of the frequency of the harmonic current and the frequency of the turbine vibration mode exactly equals to the system frequency, the subsynchronous resonance (SSR) phenomenon would be introduced [9, 10].

According to the investigation [10], the typical maximum E/M torque due to the subharmonic current has amplitude of 0.002 pu and the frequency distribution for the induced E/M torque is within 0–13Hz for the 60Hz machine and within 6.6–35.2Hz for the 50Hz machines. The SSR will impossibly be occurred because no vibration mode for the 951MW unit is within these ranges. However, there is a very good possibility for the 50Hz machines.

Because the excitation of the harmonic disturbance is a steady-state excitation, the torque response analysis following such a disturbance can easily be calculated using the frequency scanning method. Provided that the terminal of generator rotor is a shaker with the E/M torque excitation of 0.002 pu, the fluctuating peak-to-peak sympathetic torques in turbine shafts and blades are extremely violent as illustrated in Table III.

Fig. 6. The current and real power at the MOF, and vibration torques caused by electrical arc furnace system

Fig. 7. The studied 50/60Hz asynchronous HVDC link

D. Voltage sag at the infinite bus, Load Rejection and mechanical torque pulsation

The investigation associated with large power system excitations on the turbine generator torques such as network faults has been illustrated. In this section, the more frequent small disturbance such as the remote faults or malsynchronization momentarily is considered. Such impact could be equivalent to a voltage amplitude sag, phase sag or frequency drifting at the infinite bus as shown in Fig. 8.

One the other hand, another more common small disturbance such as large-scale motor trip or load shedding can be treated as a resistive load with the CB from ON to-OFF action as described in Fig. 9. The real power fluctuation for the selected load is identical to the case B. The transient responses are shown in Fig. 10. The transient responses due to impulse mechanical torque pulsation are also indicated in Fig. 11.

As depicted in Fig. 8 and Figs. 9–11, it is clear that the transient E/M torques due to above transient disturbances comprise either unidirectional or system frequency component. The responses of the turbine shafts and blades to the two kinds of excitations determine their vibration behaviors, which are not sustained and significant due to no resonant conditions.
IV. DISCUSSION

As discussed in the last section, the amplitude deviation between the maximum and the minimum torques is defined as the peak-to-peak torque. The induced peak-to-peak torques in all cases are summarized in Table III. It is found that the most onerous torque in both shafts and blades is excited by the HVDC subharmonics under resonant excitation. Since the blade torques due to negative current and an EAF load are almost identical and persistent, the long-term fatigue life expenditure (within 30 years) is noticeable. However, the others which are neither
resonant nor sustained lead to very little fatigue life expenditure. From the simulation results, the transmission torque for each blade is 0.0252 pu. The fluctuating torque level of 0.01 pu accompanied corrosion fatigue at the critically stressed locations in blade root would destroy the blade after several years’ services [4]. That means that if the ratio of the fluctuating torque to the transmission torque exceeds 0.3968, the long-term corrosion damaging effect will be earlier occurred on turbine blades. Therefore, compared with Table III, the turbine blade damaging effect due to an EAF load makes more possibly even under the flicker limit at the PCC. In other words, the typical flicker limit may not guarantee turbine blade against fatigue damage.

The transmission torque for the LP2R-GEN shaft section is 0.9 pu. The onerous fluctuating torque due to above two disturbances is 0.2728 pu. Because the ratio of the fluctuating torque to the transmission torque is 0.3031, lower than 0.3968, and no corrosion fatigue occurs on turbine shaft, the shaft would not be damaged during its lifetime.

Although the HVDC subharmonics is a sustained disturbance, the persistently resonant probability is very low because of the twofold reasons. First, for the very high Q characteristic of the vibration mode, if the excitation frequency is a little apart from the resonant mode frequency, the response will be decayed substantially. Secondly, the torque amplification must be excited by the sustained excitation with precise resonant frequency. The excitation frequency in an asynchronous link is time-varying though. Roughly, the long term fatigue effect of the turbine-generator is still noticed [9].

<table>
<thead>
<tr>
<th>Disturbance</th>
<th>$T_{LP2R-G}^{EN}$</th>
<th>$T_{LP2R-L}^{EN}$</th>
<th>$T_{LP2R-G}^{0}$</th>
<th>$T_{LP2R-L}^{0}$</th>
<th>$T_{LP2R-G}^{1}$</th>
<th>$T_{LP2R-L}^{1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unbalance I; current&lt;sup&gt;1&lt;/sup&gt;</td>
<td>0.043</td>
<td>&lt;1e-5</td>
<td>&lt;1e-5</td>
<td>&lt;1e-5</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>EAF load&lt;sup&gt;2&lt;/sup&gt;</td>
<td>0.2728</td>
<td>0.012</td>
<td>0.011</td>
<td>0.008</td>
<td>0.007</td>
<td></td>
</tr>
<tr>
<td>HVDC subharmonics&lt;sup&gt;3&lt;/sup&gt;</td>
<td>&lt;1e-2</td>
<td>&lt;1e-5</td>
<td>&lt;1e-5</td>
<td>&lt;1e-5</td>
<td>&lt;1e-5</td>
<td></td>
</tr>
<tr>
<td>HVDC subharmonics&lt;sup&gt;4&lt;/sup&gt;</td>
<td>2.436</td>
<td>0.251</td>
<td>0.303</td>
<td>0.235</td>
<td>0.284</td>
<td></td>
</tr>
<tr>
<td>Vinf amplitude sag&lt;sup&gt;5&lt;/sup&gt;</td>
<td>0.0616</td>
<td>0.0079</td>
<td>0.0071</td>
<td>0.0057</td>
<td>0.0052</td>
<td></td>
</tr>
<tr>
<td>Vinf phase sag&lt;sup&gt;6&lt;/sup&gt;</td>
<td>0.1103</td>
<td>0.0093</td>
<td>0.0083</td>
<td>0.0065</td>
<td>0.0058</td>
<td></td>
</tr>
<tr>
<td>Vinf frequency drift&lt;sup&gt;7&lt;/sup&gt;</td>
<td>0.5534</td>
<td>0.0070</td>
<td>0.0070</td>
<td>0.0055</td>
<td>0.0053</td>
<td></td>
</tr>
<tr>
<td>Load rejection&lt;sup&gt;8&lt;/sup&gt;</td>
<td>0.0445</td>
<td>0.0019</td>
<td>0.0016</td>
<td>0.0007</td>
<td>0.0015</td>
<td></td>
</tr>
<tr>
<td>Torque disturbance&lt;sup&gt;9&lt;/sup&gt;</td>
<td>0.1385</td>
<td>0.011</td>
<td>0.010</td>
<td>0.007</td>
<td>0.005</td>
<td></td>
</tr>
</tbody>
</table>

Remark: 1. $I_2=0.06$ pu under the steady-state condition, 2.$\Delta V_{10}=0.454$ & $\Delta P_{avr}=0.0556$ pu, 3a. E/M torque=0.002 pu (non-resonant case), 3b. E/M torque=0.002 pu (resonant case), 4a. Voltage amplitude sag of 0.01 pu, 4b. Voltage phase sag of 0.05 degree, 4c. Ramp frequency variation of voltage with 3Hz/sec, 5. $\Delta P_L=0.0556$pu, 6. $\Delta P=0.0556$pu mechanical torque pulsation.

V. CONCLUSIONS

From the studied results, the specific conclusions of this paper are summarized as follows.

1. The long-term fatigue life expenditure on turbine mechanism due to the intermittent disturbance such as voltage sag, load rejection, mechanical torque pulsation, etc can be ignored.

2. The long-term corrosion fatigue life expenditure in turbine blade root due to the sustained off-resonant disturbance such as unbalance negative current and the sustained random-resonant disturbance such as an arc furnace load must be received more attention. The blades may be damaged within their whole lifetime even under the normal operation but the shafts would not.

3. The sustained intermitted-resonant disturbance such as the HVDC subharmonic currents may damage the turbine shaft and blades

REFERENCES


