Fatigue life loss and countermeasure for turbine blades owing to harmonic excitations of slip energy recovery drives

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Abstract

The long-term effect of noncharacteristic harmonic currents arising from slip energy recovery drives (SERD) on fatigue life expenditure in turbine-generator blades is presented in this paper. When such an induction motor drive is adopted by a feedwater pump (FP) in power plants, many advantages are obtained due to its static converter cascade with the wound-rotor. Because the frequencies of the three main harmonic terms of the recovery currents are subsynchronous and offer a probability distribution due to the adjustable speed operation, a systematic fatigue estimation approach was devised to investigate the long-term impact for the low-pressure turbine blades. From the simulation result, it is clear that the sustained excitation of these harmonics becomes a cause of blade failure even though the harmonic current is still normal for only one generator connected to the SERD. By the effect analysis of uncertainty, the countermeasure for the turbine integrity was then found.

Keywords: Slip energy recovery, Harmonics, Torsional Vibration, Turbine, Blade, Fatigue Life.

1. Introduction

Torsional vibrations on large-scale steam turbine generators have been extensively investigated in many research works in the past. Earlier, a series of researches are focused on the unstable subsynchronous resonance issue due to series compensation scheme [1]. Subsequently several publications conducted on the overstress concern arising from large-signal disturbances such as network faults, even without series compensation [2]. Therefore, aimed at these problems, numerous countermeasures have been proposed.

Recently, intermittent subsynchronous resonance caused by noncharacteristic harmonics was gradually received attention such as the asynchronous HVDC link [3]. The HVDC scheme can produce subsynchronous resonance (SSR) currents in the inverter AC side through the variable-frequency ripple currents superimposed on DC currents. This is able to result fatigue damage in nearby large-scale generator shafts or blades for long-term operations [3].

In the same manner, slip energy induction motor drives that utilizes the converter connected to the wound-rotor serve FP of auxiliary equipments in a few power plants. Then the slip energy is recovered to the grid through the converter cascade. Consequently, the harmonic currents with subsynchronous frequency components could be modulated out at the inverter and they could excite SSR vibrations in turbine shafts and blades randomly. For long-term operations, this may become a cause of the shaft or blade failure.

The main purpose of this paper is to develop an approach to effectively predict the long-term fatigue life loss containing the adjustable speed uncertainties, the
operating time, and the material strength of blades. The modified fatigue life loss program based on the report in a three-year project of General Electric Co. [7, 8] will be employed to predict the actual fatigue loss. Fatigue life loss estimations prove the potential risk in turbine blades due to the SERD harmonic currents. Countermeasure will be studied from the electrical parameter sensitivity analysis.

![Fig. 2 (a) studied system; (b) turbine mode](image)

2. System descriptions

2.1 Studied system

The turbine-generator electromechanical system used for the investigations in this study is shown in Fig. 2(a). A steam turbine generator connected to an internal reactor feedwater pump fed by an SERD and via a step-up transformer to the infinite bus through a double-circuit transmission line. An induction machine employs a wound-rotor connected to its incoming grid through a static converter cascade that comprises a 6-pulse diode rectifier, smoothing reactor, 6-pulse inverter, and recovery transformer. The practical nuclear unit, consisting of a high-pressure (HP) stage and two low-pressure (LP) stages steam turbine, is a close-coupled and cross compound reheat unit that operates at a rotational speed of 1800 rpm. The generating capacity of the turbine-generator and the pressure water type of steam system and is 951 MW and 2785 MW, respectively. Each of the LP steam turbines has A and B spindles, and uses the shrunk-on rotor with eleven stages of each spindle, including rotary and stationary blade stages. There are eleven rows of blades in the LP steam turbine.

Figure 2(b) illustrates the mechanical model of the turbine-generator, in which the typical model of a long blade is so complicated. The flexural, axial and torsional modes vibrate in the same direction as rotation, perpendicular to the rotation direction and in a twist direction, respectively. Among them, the flexural mode has lower resonant frequency and is usually chosen for investigation. The electrical and mechanical data are given in Table I. All of the parameters of this system are in the per unit system, based on generator ratings.

Table 1 951 MW turbine generator and system parameters (pu.)

<table>
<thead>
<tr>
<th>Generator (1057MVA, 23.75kV)</th>
<th>Mechanical data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>144.15</td>
</tr>
<tr>
<td>Inertia</td>
<td>159.50</td>
</tr>
<tr>
<td>Damping</td>
<td>1584.9</td>
</tr>
<tr>
<td>Stiffness</td>
<td>325.28</td>
</tr>
<tr>
<td>s, K</td>
<td>206.0</td>
</tr>
<tr>
<td>HP</td>
<td>0.1787</td>
</tr>
<tr>
<td>LP1F</td>
<td>0.6546</td>
</tr>
<tr>
<td>LP1R</td>
<td>0.6486</td>
</tr>
<tr>
<td>LP2F</td>
<td>0.6575</td>
</tr>
<tr>
<td>LP2R</td>
<td>0.6676</td>
</tr>
<tr>
<td>GEN</td>
<td>1.1616</td>
</tr>
<tr>
<td>REC</td>
<td>117.16</td>
</tr>
<tr>
<td>EXC</td>
<td>1.61</td>
</tr>
<tr>
<td>6p REC/6p INV Lp=4mH</td>
<td>144.15</td>
</tr>
<tr>
<td>6p REC/6p INV Lp=4mH</td>
<td>159.50</td>
</tr>
<tr>
<td>6p REC/6p INV Lp=4mH</td>
<td>1584.9</td>
</tr>
<tr>
<td>6p REC/6p INV Lp=4mH</td>
<td>325.28</td>
</tr>
<tr>
<td>LP1F, 1R, LP2F, 2R Blade-L0 0.0344 36.2</td>
<td>B1F, 1R, 2F, 2R - L1 0.0387 41.8</td>
</tr>
<tr>
<td>B1F, 1R, 2F, 2R - L0 0.0344 36.2</td>
<td>B1F, 1R, 2F, 2R - L1 0.0387 41.8</td>
</tr>
</tbody>
</table>

2.2 Steady-state harmonic current source

For a general 6-pulse rectifier in the SERD, the output DC current contains mainly a set of harmonics for integer multiples of 6 as follows:

\[ I_d(t) = I_d + a_6 \sin(6\omega_2t + \beta_6) + a_{12} \sin(12\omega_2t + \beta_{12}) + \ldots \]  

(1)

where \( \omega_2 = \omega_0 \). Here, \( \omega_2 \) represents the fundamental
angular frequency of rectifier AC side, which is equal to rotor frequency of the induction motor in Fig. 2a; s and \( \omega \) are per unit slip, 377 rad/sec respectively. For a 6-pulse inverter, the switching function \( s_n(t) \) comprises a series of expansions of the multiple of (6N±1):

\[
s_n(t) = k[\cos(\omega t) - \frac{1}{5}\cos(5\omega t) + \frac{1}{7}\cos(7\omega t) - \frac{1}{11}\cos(11\omega t) + \frac{1}{13}\cos(13\omega t) - +...]\tag{2}
\]

where \( k = 2\sqrt{3}/\pi \). By modulation theory [6], the output AC current of the inverter can be given by

\[
I_{ac}(t) = I_{dc}(t) \times s_n(t) = I_{ac0}(t) + I_{ac1}(t)
\]

where \( I_{ac0}(t) = kI_0 \cos \omega t \) is the AC fundamental current, terms of 3(A)–(D) are the integer harmonic current, and the other terms are referred to as noncharacteristic harmonic currents. As can be seen from Fig. 3a, all the frequencies of harmonics vary with the operating rotor speed except for integer harmonics.

2.3 The analysis of the excitation frequency of rotor

All electrical disturbances give rise to generator electromagnetic torques (E/M disturbing torques) which impose torsional stresses in the turbine-generator blades. The frequency of the E/M disturbing torque equals the rotor frequency of the disturbance. Provided that the rotating magnetic field (MMF) produced by the stator harmonic current is forward such as the harmonic multiple of (3N+1), the corresponding rotor frequency is

\[
f_r = f_s - 60
\]

Conversely, if it is backward such as the harmonic multiple of (3N+2), the rotor frequency is

\[
f_r = f_s + 60
\]

Accordingly, for the harmonic term of 3(A,B), the frequency of their combining E/M disturbing torque are 6 multiples of system frequency, as indicated in Fig. 3b. This can be further deduced to other harmonic terms in the figure. Through inspecting the subsynchronous frequencies of the E/M disturbing torque, Fig. 4 shows that only three terms are noticeable. The other terms with very super-synchronous frequencies or negligible amplitudes put nearly no risk the generator. By way of combining Figs. 3b and 4 (rotor speed distributions), the individual probability distribution of the frequency of the E/M disturbing torque is listed in Table 2.

2.4 The Calculation of Subharmonic Currents

An SERD drives a FP of 20MW rating in this paper. The phase voltage for a blocked rotor is

\[
E_{br} = \frac{V_s}{a_M} = 23.75kV/1.732/0.5 = 2.74kV
\]
Table 2 Frequency range of the Predominant E/M Disturbing Torques and Their Corresponding p.d.f

<table>
<thead>
<tr>
<th>term</th>
<th>Disturbing frequency ((s=0.5)~0.02)</th>
<th>p.d.f</th>
</tr>
</thead>
<tbody>
<tr>
<td>3(i,ii)</td>
<td>7.2~180</td>
<td>0.0058</td>
</tr>
<tr>
<td>3(I,II)</td>
<td>14.4~360</td>
<td>0.0029</td>
</tr>
<tr>
<td>3(IV,VI)</td>
<td>0~345.6</td>
<td>0.0029</td>
</tr>
</tbody>
</table>

\(+\): nominal rotor speed range \(n_\text{r}=50\%~98\%\sim \text{U}(0.74,0.0192)\)

U: (Uniform distribution)

\[ V_{\text{d0(rec)}} = 2.3394 \times sE_{\text{br}} = 2.3394 \times 0.125 \times 2.74k = 8019.5V \quad (7) \]

Under the assumption of neglecting the loss of the smoothing reactor and the rated recovery slip power of \(P_{\text{recov}}\) equal to 3MW, the DC pole current is

\[ I_d = \frac{P_{\text{recov}}}{V_{\text{d0(rec)}}} = 374.09A \quad (8) \]

Assume a ripple at the inverter of 9\% at the 6\textsuperscript{th} harmonics [10], i.e. 721.7kV. Assume also that the DC reactor is 4 mH. This will give a 6\textsuperscript{th}-harmonic current of

\[ \frac{8019.5 \times 0.09}{(2\pi60)(6)(0.004)} = 79.77A_{\text{RMS}} = 112.81A_{\text{PEAK}} = a_6 \quad (9) \]

According to Eq. 3, a direct current of 347.09A will give a fundamental alternating current of

\[ I_{ac0} = kI_d = 412.49A_{\text{PEAK}} \quad (10) \]

Similarly, the modulation product produced by term (i) in Eq. 3 has an amplitude of

\[ I_{3(i)} = \frac{ka_6}{2} = 62.20A_{\text{PEAK}} \quad (11) \]

This is approximately 0.1508 pu. Due to the specification for speed variation range being 50\%, the designed inverter AC side-to-the recovery transformer line side turns ratio is [9]

\[ a_{\text{recov}} = s_{\text{max}}/(aM \times (\cos\alpha_{\text{max}})) = 0.5/(0.5 \times 0.866) = 1.155 \quad (12) \]

where \(\alpha_{\text{max}}\) is the maximum inverter firing angle of 150 degree. Based on the studied generator rating, the per unit harmonic current of 3(i) term penetrating to generator grid is derived by

\[ I_{3(i)} = I_{3(i)(A)} \times a_{\text{recov}}/(1057M/(\sqrt{3} \times 23.75k)) = 0.28\% \quad (13) \]

In the same manner, the other two harmonic terms can be given as tabulated in Table 3.
Table 3 Predominant Harmonic Current Levels for a 20MW FP Driven by an SERD

<table>
<thead>
<tr>
<th>Term</th>
<th>$S_{Rb}$</th>
<th>$S_{Pb}$</th>
<th>1.22</th>
<th>$V_{Pb}$</th>
<th>$I_{600}$</th>
<th>$I_{20}$</th>
<th>$I_{400}$</th>
<th>$I_{400}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(%)</td>
<td>(%)</td>
<td>(%)</td>
<td>(%)</td>
<td>(%)</td>
<td>(%)</td>
<td>(%)</td>
<td>(%)</td>
<td>(%)</td>
</tr>
<tr>
<td>(SV, II)</td>
<td>6</td>
<td>9</td>
<td>72.2</td>
<td>76.9</td>
<td>62.8</td>
<td>9.8</td>
<td>15.9</td>
<td>15.95</td>
</tr>
<tr>
<td>(%)</td>
<td>(%)</td>
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<td>(%)</td>
<td>(%)</td>
<td>(%)</td>
<td>(%)</td>
<td>(%)</td>
<td>(%)</td>
</tr>
<tr>
<td>(SV, II)</td>
<td>12</td>
<td>5.6</td>
<td>44.0</td>
<td>0.9</td>
<td>35.99</td>
<td>19.55</td>
<td>6.9</td>
<td>6.9</td>
</tr>
<tr>
<td>(%)</td>
<td>(%)</td>
<td>(%)</td>
<td>(%)</td>
<td>(%)</td>
<td>(%)</td>
<td>(%)</td>
<td>(%)</td>
<td>(%)</td>
</tr>
<tr>
<td>(SV, II)</td>
<td>12</td>
<td>5.6</td>
<td>44.0</td>
<td>0.9</td>
<td>35.99</td>
<td>19.55</td>
<td>6.9</td>
<td>6.9</td>
</tr>
</tbody>
</table>

*: Based on SER system rating ($S_{Pb}=20$ MVA, $V_{Pb}=23.75$ kV)
**: Based on 951MW generator rating ($S_{Pb}=1057$ MVA, $V_{Pb}=23.75$ kV)

2.5 FP operating characteristics

Motor speed is controlled in accordance with process requirements such as water flow or airflow. By controlling flow directly with motor speed, it is possible to eliminate valve controls, damper controls and vane controls. These throttling control systems have been widely used in power plants in the past for pumps and fans. However, throttling control systems are inefficient and in cases of large pressure drops, throttling systems not only dissipate power unnecessarily, but lead to unnecessary maintenance costs as well [11].

The consumption of the power system loads is time varying. The power fluctuation causes the variations of steam flow, pressure, temperature, etc. For the purpose of normal liquid level in the reactor drum, the FP is speeded up to supply the feed-water as the flow augments whereas the FP is decelerated on the contrary. As mentioned in [12], the nominal speed range of the application is limited to half speed to nearly full speed. Under the assumption of the nominal distribution speed, the mean and variance of the speed are 0.74 and 0.0192 respectively.

3. Using Frequency-Scanning Method to Calculate the Fluctuating Torque

The steady-state fluctuating torque on the k-th blade is given by

$$T_k = [I_{em}] \times [SSF] \times [GSF] \times R_{E/M} \times R_{E/M}$$

$$= [E/M \text{ disturbing torque}] \times R_{E/M}$$

(14)

The ratio of the SERD output current impressed on the generator to the total SERD one is defined as the System Scaling Factor (SSF) [13]. It can be determined from the symmetrical fault currents following three-phase short-circuit at the converter station bus. Besides, the ratio of the SERD output current impressed on the generator to the E/M disturbing torque is defined as the Generator Scaling Factor (GSF), which is approximately 1.1 [13]. Because the excitation of the harmonic current is a steady-state excitation, the response ratio ($R_{E/M}$) of the torque of the blade to E/M torque can easily be derived using the frequency scanning method. Supposing that the terminal of generator rotor is a shaker with the worst-case excitation (0.004 pu) of E/M torque, the frequency-scanning inspects the frequency responses of the turbine mechanical system from 0.01Hz to 140Hz with an interval of 0.01Hz.

The frequency scanning results for final lows of blades is plotted in Fig. 5. This demonstrates that the subsynchronous resonant torque of blades is

![Fig. 5. The frequency-scanning response and the frequency distribution of different terms for the E/M disturbing torques (a) for the LP2F blade (b) for the LP1R blade.](a)

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considerably higher than supersynchronous one. All the frequencies of vibration modes are summarized in Table 4. Fig. 6 depicts the more onerous resonance torque values among the excitation frequency range. It is shown that the majority of fatigue life loss of LP turbine blades are caused by the mode 2 (36.84Hz) except LP1R. The steady-state fluctuating torque versus the E/M disturbing torque with the dominant vibration mode frequency is illustrated in Fig. 7.

4. Fatigue theorem

4.1 The characteristics of the blade materials

The results obtained from the three-year project developed by General Electric Co., under the auspices of EPRI, reveal the properties of the alloy steel of which steam turbine generators are usually made. Fig. 8a shows the lower bound S-N curves for AISI 403 alloy. The monotonic cyclic stress-strain curve can be formulated as

\[
\varepsilon_a = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{H}\right)^{\frac{1}{s}}
\]  

(15)

where \(\varepsilon_a\) and \(\sigma_a\) are strain and stress amplitude, E is the elastic modulus, H is cyclic strength coefficient and s is cyclic strain hardening exponent. The cycles-to-failure \(N_f\) is a function of total strain amplitude

\[
\varepsilon_a = A(2N_f)^{\alpha} + B(2N_f)^{\beta}
\]  

(16)

where the constants A, \(\alpha\), B and \(\beta\) are determined by the elastic and plastic components of strain.

4.2 Fatigue life expenditure

The fatigue damage, associated with the closed stress-strain loop counted in the rain-flow technique, is determined from a stress-life (S-N) diagram in combination with the linear damage rule. The Palmgren-Miner formula measures the accumulated fatigue damage in terms of a loss percentage, D, defined as

\[
D(\%) = \sum_i \left(\frac{n_i}{N_{f_i}}\right) \times 100\%
\]  

(17)

where \(n_i\) is the number of cycles at the \(i^{th}\) stress level, and \(N_{f_i}\) is the number of cycles to failure at the \(i^{th}\) stress level. When D equals 100, the accumulated linear damage predicts failure for the material.

4.3 Stress distribution and mean stress

In addition to discontinuity of shape, the material
properties also ought to be considered to determine the stress distribution on the blade. Thus, as the stress concentration factor is so large that the stress exceeds the yielding point of the materials, the stress distribution must be rearranged due to plasticity. An approximate method known as Neuber’s rule was used for estimating the stresses and strains in a notch. The theoretical stress concentration factor \( K_t \) is

\[
K_t^2 = \frac{\sigma_a \epsilon_a}{\sigma_{0u} \epsilon_{0u}}
\]

where \( \sigma_a \) and \( \epsilon_a \) are, respectively, the maximum stress and strain amplitudes in the notch, \( \sigma_{0u} \) and \( \epsilon_{0u} \) are the stress and strain amplitudes, respectively, on the outer surface of the nominal section adjacent to the notch.

As for the effects of mean stress, Goodman line is often used to approximately calculate the equivalent stress. Suppose that the mean stress is \( \bar{\sigma}_m \) and the ultimate tensile strength is \( \sigma_f \), when blades are forced by the alternating stress \( \sigma_a \), the equivalent stress \( \sigma_{eq} \) can be obtained as

\[
\sigma_{eq} = \sigma_a \left( 1 - \frac{\sigma_m}{\sigma_f} \right)
\]

5. Fatigue life simulation results

Under the normal operating point of 951MW unit, the bending torque of last stage blade on each LP steam turbine is 0.0252 pu. According to the parameter of the generator, the value of blade centrifugal stress is 0.0344 pu. Thereby the working stress of the turbine blade, under normal conditions, is 0.0427 times of the machine base. The material softening point is at about 100,000 cycles to failure [8], which is used as the base of blade torque with safety factor (SF) at 1. The relationship between the torques against logarithm value of cycles can be obtained in Fig. 8b. The time interval for estimating the cumulative fatigue expenditure is 30 years as the design lifetime.

5.1 Effect of the E/M disturbing torque

To prevent the bearing stress from exceeding the material yielding point following a three-phase fault at the power plant terminal, the lowest safety factors for different blades are evaluated in Table V [2]. The corresponding critical E/M disturbing torques which damage the blades are also listed in the table. It is seen that the LP2F blade corresponding to the lowest critical disturbing torque dominates the fatigue damage behavior of LP turbine blades. The fatigue results of the one as well as LP2R blade for the possible SF are indicated in Fig. 9.

If only one generator is connected to SERD (neglect the coupling with the infinite bus), the SSF equals 1. In this scenario, the main harmonic current, depicted in Table 6 and Fig. 9, appears to have destroyed the turbine blades. However, the blades may accumulate less fatigue life loss because of the actual dispersion effect of the currents as plotted in Fig. 2a. Thus especially for the generators connected to a weak power system, the inevitably high magnitude of the injecting harmonic currents will be adequate to harm this machine even under normal operations. Therefore if there is potential for blade damage through estimation,

Table 5 Critical E/M Disturbing Torque that Begins Damaging the Blade

<table>
<thead>
<tr>
<th>Blade</th>
<th>LP1F</th>
<th>LP1R</th>
<th>LP2F</th>
<th>LP2R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evaluated SF</td>
<td>4</td>
<td>4</td>
<td>5.5</td>
<td>5.5</td>
</tr>
<tr>
<td>E/M torque of damage</td>
<td>0.00279</td>
<td>0.00316</td>
<td>0.000955</td>
<td>0.00108</td>
</tr>
</tbody>
</table>
Table 6 E/M Disturbing Torque for Only One Generator Connected to the SERD and Corresponding 30-year Usage Factor (%) for the LP2F Blade

<table>
<thead>
<tr>
<th>SF</th>
<th>5.5</th>
<th>6.0</th>
<th>6.5</th>
<th>7.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure</td>
<td>Failure</td>
<td>Failure</td>
<td>Failure</td>
<td></td>
</tr>
</tbody>
</table>

The harmonic current of term (3,i,ii) is 0.0028 pu.

Æ The E/M disturbing torque of term (3,i,ii) 0.00294pu.

SF=5.5 SF=6.0 SF=6.5 SF=7.0

Studied E/M torque

0.5 1 1.5 2 2.5 3

loss percentage of 30 years

x 10-3

E/M disturbing Torque (p.u.)

0 20 40 60 80 100

(a)  (b)

Fig. 9 30-year loss percentage (a) for the LP2F blade; (b) for the LP2R blade

we suggest taking safety precautions. (e.g. special relaying and monitoring systems, or countermeasure)

6. Countermeasure

According to the above deduction, the long-term impact on the fatigue life loss of turbine blades cannot be neglected. The unique countermeasure mentioned in [4-5] is to pass the critically resonant speed ranges of the FP rapidly with a specific speed controller. However, for a general power station, there are a number of parallel connected turbine-generators, which contains numerous non-identical frequencies of vibration modes. Most of frequencies of the shaft torsional modes are subsynchronous while some of the blade mode (e.g. L0-2nd, L1-2nd mode) frequencies are supersynchronous (less than 150Hz generally) as evidenced from the Campbell diagram in Fig. 10 Consequently, the rapidly passing speed controller may not be carried out easily.

In this section, a novel countermeasure is proposed. This scheme is applicable for whatever power stations. The fundamental concept is to include no vibration modes within the excitation frequency range of E/M torque. Firstly, Table 7 illustrates the corresponding frequencies of the remaining subharmonic terms under different pulse configurations of the converter as deduced from Eq. 3. Then the relationship between the rotor speed and excitation frequency can be plotted in Fig. 11. Secondly, if adopting 24-pulse rectifier for the SERD and shifting the rotor speed maximum value (n, max) less than 0.9 pu as seen from the figure, the excitation frequency range corresponding to the entire speed (>150Hz) will contain no vibration modes. This countermeasure effectively prevents the turbine-generators from resonant accidents.

Table 7 The Frequencies of All the Subharmonic Current Terms for Different Pulse Configurations

<table>
<thead>
<tr>
<th>Pulse number</th>
<th>6p rec</th>
<th>12p rec</th>
<th>18p rec</th>
<th>24p rec</th>
</tr>
</thead>
<tbody>
<tr>
<td>6p inv</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12p inv</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequencies</td>
<td>360s, 360-720s, 720s, 1080s, 1440s</td>
<td>720s, 1080s, 1440s</td>
<td>1440s</td>
<td></td>
</tr>
<tr>
<td>Subharmonics</td>
<td>Remark: s denotes per unit slip</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 10 The Campbell diagram of long turbine blades for the 951MW unit

Fig. 11 The relationship between rotational speed and the corresponding excitation frequencies of the subharmonic terms under various pulse configurations.

7. Conclusions

The induction motor of FP can be treated as the
largest load in power stations. The economic benefits of using the SERD must be weighted against the potential damage to the turbine generator blades. From the studied results, the following conclusions can be drawn:

1. The turbine blades may not be guaranteed to be out of danger if a high level of SERD subharmonic currents penetrates this generator. Connecting to the weak power system contributes to this effect more significantly.

2. Safety precaution should be undertaken on all generators in close proximity to the FP driven by the SERD to ascertain whether or not a generator might be at risk.

3. The proposed countermeasure, instead of rapidly passing speed approach, is applicable to any power station with SERD system and ought to be employed for fear of potential risk in nearby generators.

References


