Fatigue Life Expenditure of Turbine-Generator Shafts Excited by Harmonics of Slip Energy Recovery Induction Motor Drivers

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Abstract
In this paper, the long-term fatigue life loss of steam turbine-generator shafts owing to noncharacteristic subharmonic currents of a slip energy recovery induction motor drive (SERIMD) is analyzed. An SERIMD has many advantages and is an adequate candidate of the feedwater pump (FP) in power plants for the purpose of variable speed control. However, it gives rise to sustainable variable frequency subharmonics which may induce electromechanical subsynchronous resonance (SSR) in turbine shafts. Accordingly, the author has determined that the long-term effect of these subharmonics is a cause of fatigue damage on turbine shafts even under normal operating conditions through fatigue life estimation.

Keywords
Torsional Vibration, Turbine Generator, Shaft, Slip Energy Recovery

1. INTRODUCTION

Slip energy drives are different from most induction motor drives in that the converter is connected to the rotor instead of the stator. The converter can be rated at a fraction of the motor rating for limited speed range of applications. This is unlike conventional drives where the converter rating must at least equal that of the motor. This results in a cost saving of power electronics components. High efficiency, low cost, and simplicity of control establish the SERIMD as a superior candidate for high power pumps, fans, and blowers.

In contrast, this drive has its own drawback. Since the rectifier is fed by rotor winding, the variable-frequency ripple currents are superimposed on DC currents as the speed varies. This modulates a variable low frequency harmonic source at the inverter AC side and may excite SSR in nearby T-G shafts.

Dr. H. Fick first reported this phenomenon of sub-synchronous frequency stimulus from the torsional stress analyzer in a power plant in Germany [1]. Professor R. Yacamini then intimated that the concept of torsional oscillations is due to the SERIMD scheme [2]. However, faithfully evaluating the long-term cumulative fatigue life expenditure involving the resonance torque, operating time and variable subsynchronous speed etc. becomes a complicated problem that has not yet been investigated. Solution of this problem is the motivation behind the development of our proposed method. Fatigue life loss sensitivity under the uncertainty of the electrical as well as parameters will then be performed.

2. SYSTEM DESCRIPTIONS

2.1 System Model

Fig. 1 schematically shows the electromechanical system under study. A steam turbine generator is connected to a local reactor FP driven by an SERIMD via a step-up transformer to the infinite bus through a double-circuit transmission line. An induction machine employs a wound-rotor connected back to its incoming bus through a slip energy recovery converter, which comprises a 6-pulse diode rectifier, smoothing reactor, 6-pulse inverter, and recovery transformer. The practical steam turbine unit including a high-pressure (HP) and two low-pressure (LP) steam turbines analyzed in this study is a close-coupled and cross-compound reheat unit that operates at a rotor speed of 1800 rpm. The generating capacity of T-G is 951 MW. Each of the low-pressure steam turbines has A and B spindles, and uses the shrinked-on rotor with eleven stages of each spindle, including rotary and stationary blade stages. All of the parameters of this system are in the "per unit" system, based on generator ratings.

2.2 Steady-State Harmonic Current Source

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

\[
I_{dc}(t) = I_s + a_1 \sin(6\omega t + \beta_1) + a_2 \sin(12\omega t + \beta_2) + \ldots
\]

where \( \omega = \frac{\pi}{L} \). Here, \( \omega_2 \) represents the fundamental angular frequency of rectifier AC side, which is equal to rotor frequency of the induction motor for SERIMD connection in Fig. 1; \( s \) 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):

\[
s_n(t) = k \left[ \cos(\omega_2 t) - \frac{1}{5} \cos(5\omega_2 t) + \frac{1}{7} \cos(7\omega_2 t) - \frac{1}{11} \cos(11\omega_2 t) + \frac{1}{13} \cos(13\omega_2 t) - \ldots \right]
\]

where \( k = 2\sqrt{3}/\pi \). By modulation theory [7], the output AC current of the inverter can be given by

\[
I_{ac}(t) = I_{dc}(t) \times s_n(t) = I_{dc}(t)^n
\]
where $I_{ac0}(t) = k_1 \cos \omega t$ 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. 2, all the frequencies of harmonics vary with the operating rotor speed except for integer harmonics. If their frequency is lower than the system frequency, they are defined as subharmonics. Otherwise, they are defined as superharmonics.

2.3. The Analysis of the Frequency of E/M Disturbing Torque

All electrical disturbances give rise to electromagnetic disturbing torques (E/M disturbing torques) which impose torsional stresses in the T-G shaft. 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, the correspond rotor frequency is

$$f_r = f_s - 60$$

Conversely, if it is backward, the rotor frequency is

$$f_r = f_s + 60$$

Accordingly, all the harmonic terms can be deduced in Fig. 3. It is emphasized that most of the natural frequencies for the large scale T-Gs are inevitably subsynchronous. If the rotor frequency of the harmonics coincides with one of those frequencies, the sympathetic torque in the turbine shafts will be excited. Through inspecting the subharmonic E/M disturbing torque, Fig. 4 shows that only three terms are noticeable. The other terms with either supersynchronous frequencies or negligible amplitudes place almost no risk on the generator. By way of combining Figs. 3 and 4 (rotor speed distributions), the individual probability distribution of the frequency of the E/M disturbing torque under nominal speed ranges is listed in Table 1.

![Fig. 1. Studied system](image1)

![Fig. 2. The frequency of the harmonic currents in the viewpoint of stator.](image2)

![Fig. 3. The frequency of the harmonic currents in the viewpoint of rotor.](image3)
Fig. 4. The frequency distribution of the main three terms of subharmonic E/M torques and the probability distributions of the rotor speed.

<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,III)</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>

Table 1. Frequency range of the Predominant E/M Disturbing Torques and Their Corresponding p.d.f

2.4. The Calculation of Subharmonic Currents

Assume that an SERIMD drives a FP of 20MW rating. The phase voltage for a blocked rotor is

\[ \text{E}_{br} = \left( \frac{\sqrt{3}}{3} \right) \frac{V_s}{\alpha_M} = 23.75kV / 1.732 / 0.5 = 2.74kV \quad (6) \]

where \( \alpha_M \) of 0.5 is the stator-to-rotor turns ratio of the machine. Assume also that the rotor speed is 1575 rpm (s=0.125). Then the DC pole voltage is [4]

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

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

\[ I_{d0} = \frac{P_{rec}}{V_{d0}} = \frac{3MW}{8019.5V} = 374.09A \quad (8) \]

Assume a ripple at the inverter of 9% at the 6th harmonic, i.e. 721.7kV. Assume also that the DC reactor is 4 mH. This will give a 6th-harmonic current of

\[ I_{6h} = \frac{721.7kV}{6} \times I_{d0} = 62.20A \quad (9) \]

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

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

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

\[ I_{3(i)} = \frac{62.20A}{2} = 62.20A \quad (11) \]

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 [4]

\[ a_{rec} = \frac{S_{max}}{a_{rot}} = 0.5(0.5*0.866) = 0.28 \quad (12) \]

where \( a_{max} \) 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

\[ I_{3(i)} = \frac{I_{3(i)}(A) \alpha_{rec} \sqrt{3}}{1057M} = 0.28 \quad (13) \]

In the same manner, the other two harmonic terms can be given as tabulated in Table 2. As mentioned in [5], the nominal speed range of the application is limited to half speed to nearly full speed. Under the assumption of the nominal speed distribution, the mean and variance of the speed are 0.74 and 0.0192 respectively.

<table>
<thead>
<tr>
<th>Harmonic order, n</th>
<th>Harmonic current (A)</th>
<th>Inverter current (%)</th>
<th>Inverter current (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3(i)</td>
<td>9</td>
<td>721.76</td>
<td>112.81</td>
</tr>
<tr>
<td>3(ii)</td>
<td>9</td>
<td>62.20</td>
<td>15.08</td>
</tr>
<tr>
<td>3(iii)</td>
<td>6</td>
<td>449.09</td>
<td>55.097</td>
</tr>
<tr>
<td>3(iv)</td>
<td>7</td>
<td>35.097</td>
<td>19.35</td>
</tr>
<tr>
<td>3(v)</td>
<td>9</td>
<td>4.69</td>
<td>0.09</td>
</tr>
<tr>
<td>3(vi)</td>
<td>12</td>
<td>449.09</td>
<td>3.87</td>
</tr>
<tr>
<td>3(vii)</td>
<td>12</td>
<td>0.94</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Table 2. Predominant Harmonic Current Levels for a 20MW FP Driven by an SERIMD

3. CALCULATING TORSIONAL TORQUES BY FREQUENCY SCANNING

The ratio of the inverter output current impressed on the generator to the total inverter output current is defined as the System Scaling Factor (SSF) [3]. The ratio of the converter 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 [3]. Because the excitation of the harmonic disturbance is a steady-state excitation [3], the torque response analysis following such a disturbance can easily be calculated using the frequency scanning method. Provided that the terminal of the generator rotor is a shaker with the excitation of 0.004 per unit E/M torque, the frequency scanning based on electromechanical analogy theory inspects the frequency responses of the turbine mechanical system from 0.01Hz to 140Hz with an interval of 0.01Hz. The steady-state torque on the \( k \)-th shaft section is given by

\[ T_k = [I_{harmonic}] \times [SSF] \times [GSF] \times R_{k/g} \quad (14) \]

where the response ratio \( R_{k/g} \) of the shaft torque to E/M torque can be derived using this method as shown.

Fig. 5. The frequency-scanning response and the frequency distribution of different terms for the E/M disturbing torques (a) for the LP2R-GEN shaft (b) for the LP1R-LP2F shaft.

Table 3. Vibration Modes for the 951 MW Unit (Hz)
in Fig. 5. This demonstrates that the turbine system offers a very high Q characteristic. All the vibration modes are indicated in Table 3.

![Cyclic stress amplitude (MPa)](image)

Fig. 6. S-N diagrams of three widely used shaft materials.

### 4. Fatigue Theorem

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 [6], [7]. The analytical fatigue life equations can be formulated according to metal fatigue theory. Typical softening between monotonic and stable cyclic are represented as

\[
\gamma_{oa} = \frac{\tau_{oa}}{G} + \left[\frac{\tau_{oa}}{H'}\right]^\gamma
\]

(15)

where \(\gamma_{oa}\) and \(\tau_{oa}\) are strain and stress amplitude, \(G\), and \(H'\) and \(s'\) are constants.

The material fatigue properties in the form of a strain-life diagram are presented as a function of the total strain amplitude against cycles-to-failure

\[
\gamma_s = A'(N_f')^\alpha + B'(2N_f')^\beta
\]

(16)

where the constants \(A'\), \(\alpha'\), \(B'\) and \(\beta'\) are determined by the elastic and plastic strain components. According to these equations, Fig. 6 depicts the relationship between stress and the life of the shaft materials A469 and A470 and A471.

The fatigue damage, associated with the closed stress-strain loop counted in rain-flow technique, was determined from stress-life (S-N) diagrams in combination with the linear damage rule. The Palmgren-Miner formula measures the accumulated fatigue damage in terms of a usage factor, \(D\) (%), defined as

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

(17)

where \(n_i\) is the number of cycles at the \(i\)th stress level, and \(N_{fi}\) 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.

### 5. Fatigue Life Loss Simulation

Under the normal operating point of 951MW unit, the working stresses are 0.28, 0.59 and 0.9 times of the machine base respectively for the HP-LP1F, LP1R-LP2F and LP2R-GEN shafts. The time interval for estimating the cumulative fatigue expenditure is 30 years. The stress corresponding to 100000 cycles-to-failure in the S-N curve was used as the base of the shaft working stress with the safety factor (SF) at one [7]. When the designed SF is more than one, the equivalent working stress must decrease by 1/SF degrees.

Through the fatigue life loss simulation, as seen from Table 4, the corresponding critical E/M disturbing torque at which shaft damage begins is given. As can be seen, the LP2R-GEN shaft with the lowest E/M torque of damage dominates the whole fatigue life expenditure of the T-G.

For the worst-case excitation of the harmonic currents, it can be assumed that a 951MW generator is solely connected to the inverter output bus (SSF=1). The per-unit value of the maximum E/M disturbing torque due to the main subharmonic currents is described in Table 5. Comparing the 30-year usage factor as shown in the table or Fig. 7 with E/M disturbing torque line, it appears that the all the shafts have been damaged in their lifetime, owing to such subharmonic disturbances. Nevertheless, the actual inverter output bus should be connected to a power network instead of one generator only. The actual shunt effect would reduce the level of the E/M disturbing torque in the machines. In other words, the shafts may accumulate little fatigue life loss, even no loss, because of the dispersion effect of the inverter output currents. Thereby, especially for the generator connected to a weak power system, the evitable high amplitude of the injecting SERIMD subharmonic currents could be adequate to harm this machine even under normal operations. If there is potential for shaft damage through safety estimation, we suggest taking safety precautions. (e.g. installations of a speed controller which rapidly passes the critically resonant speed ranges of the FP, special relaying systems, or substitutions of the higher SF material).

<table>
<thead>
<tr>
<th>Shaft</th>
<th>HP-LP1</th>
<th>LP1-LP2</th>
<th>LP2-GEN</th>
<th>GEN-REC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evaluated SF</td>
<td>2.5</td>
<td>4.5</td>
<td>3.5</td>
<td>2.5</td>
</tr>
<tr>
<td>E/M torque of damage</td>
<td>0.00161</td>
<td>0.00154</td>
<td>0.001059</td>
<td>0.001429</td>
</tr>
</tbody>
</table>

Table 4. Critical E/M Disturbing Torque that Begins Damaging the Shaft

<table>
<thead>
<tr>
<th>SF=3.5</th>
<th>SF=4.0</th>
<th>SF=4.5</th>
<th>SF=5.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure</td>
<td>Failure</td>
<td>Failure</td>
<td>Failure</td>
</tr>
</tbody>
</table>

Table 5. E/M Disturbing Torque for Only One Generator Connected to the Inverter bus and Corresponding 30-year Usage Factor (%) for the LP2R-GEN Shaft
6. CONCLUSIONS

The economic benefits of using the SERIMD must be weighted against the potential damage to the turbine generator shafts. From the studied results, the specific conclusions of this paper are summarized as follows.

1. Studies should be undertaken on all machines in close proximity to the FP driven by the SERIMD to ascertain whether or not a machine might be at risk.

2. The T-G shafts may not be guaranteed to be out of danger as long as a high level of SERIMD subharmonic currents penetrates this generator. Connecting to the weak power system contributes to this effect more significantly. Therefore, monitoring and relaying systems, or a special speed controller for a quick pass around critical speed should be employed, to protect the machines that are indicated at risk in studies.

References


