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PRACTICAL GUIDELINES FOR OIL&GAS PLANT DESIGN AGAINST SUB-SYNCHRONOUS TORSIONAL INTERACTION PHENOMENA

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ABSTRACT

Variable Frequency Drives (VFDs) are widely used in the Oil&Gas industry to enable variable speed operation of motors. These drives use power electronic devices, which produce current and voltage harmonic distortion. They can also interact with other units connected to the same electrical grid (i.e. turbine-generators) via a phenomenon called Sub-Synchronous Torsional Interactions (SSTI). This can lead to a restriction of plant operation, and in the worst case, to major damage of machinery.

This paper provides a comprehensive evaluation of the SSTI phenomenon and gives practical guidelines to enable the following: a proper design of the plant and the system, an optimization of plant operability, and a strategy for mitigation of potential problems.

Field test results and simulation analyses are presented, emphasizing the importance of a proper SSTI evaluation and management in the early engineering phase.

INTRODUCTION

System integration is becoming more and more critical for complex Oil&Gas applications in particular considering increasing power rating of VFDs that are now reaching about 100 MW. These VFDs share the same grid as turbine-generator units and other devices.

There are many aspects that can influence the torsional response of generator units: grid events, torsional interaction with large power system unit controls, harmonics produced by power electronics devices, sub-synchronous resonances (i.e. typically with series capacitor-compensated lines), and load variations.

Experience indicates that large power-electronic systems can pose a risk of shaft-line torsional vibrations. As schematically shown in Figure 1, VFDs can electromechanically interact with torsional modes of turbine-generators connected to the same grid leading to torsional instability. This instability can produce network blackout and/or damage on rotating machines impacting Oil&Gas plant availability.

Basically, any turbine-generator unit tends to torsionally vibrate at its torsional natural frequencies (TNFs); normally the first torsional mode is the most involved one. Speed oscillations ($\Delta\omega$) of the shaft-line at that frequency (1st TNF) can cause voltage oscillations (Δv) in the grid through the electric generator itself. These voltage oscillations are seen as a disturbance by a VFD (or by any other power electronic load), which reacts injecting current oscillations (Δi) into the grid. Those current oscillations become electrical torque oscillations (ΔT_e) through the generator electromagnetic field, establishing the SSTI phenomenon.

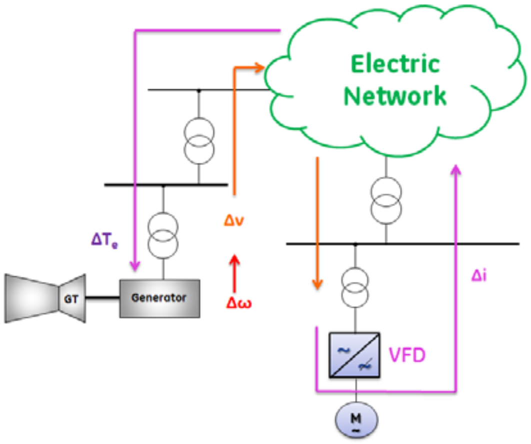

Figure 1: SSTI phenomenon schematization

Based on the authors' site experiences, the main drivers of the SSTI phenomenon for Oil&Gas plants are:

- ✓ Grid configuration (i.e. island electrical grid operation)
- ✓ Available short circuit power levels evaluated at the connection bus of power electronic loads operating on the same grid Generator ratings and location in the grid
- ✓ Generator torsional natural frequencies and relevant mode shapes
- ✓ Rating, topology and control settings of power electronic loads (i.e. VFDs) connected to the electrical grid

After a theoretical overview and conceptual explanation, site experiences are presented showing how different plant configurations can impact the SSTI phenomenon. This emphasizes the actual applicability of the SSTI theory to real cases in the Oil&Gas industry.

Simulation analyses are carried out to demonstrate concepts and assumptions driving the SSTI studies. Test results are compared with simulations to highlight how an SSTI assessment and analysis performed in both the early and detailed engineering phases can help mitigate and manage potential SSTI risk at site.

SSTI BACKGROUND AND THEORY

Different approaches and methods to evaluate the SSTI phenomenon are hereafter presented based on project engineering phases and data availability. Relevant theoretical concepts are also provided.

Preliminary Risk Assessment

In the early plant design phase and when only high level engineering data are available, a useful method to perform a preliminary SSTI risk assessment is the calculation of the Unit Interaction Factor (UIF). This factor has been introduced in the past to assess the interactions between generators and High Voltage Direct Current (HVDC) systems (Piwko and Larsen, 1982).

The UIF is calculated for several plant configurations (to be defined with plant owners): when the UIF is greater than a defined threshold, the risk of sub-synchronous torsional interactions is significant for that plant configuration and precautions should be taken. All possible plant conditions should be analyzed including commissioning, start-up and any potential contingency.

For each power generation train the UIF is calculated considering one VFD at the time. When the UIF is bigger than 0.1 the related configuration shows a potential risk of SSTI as described by R.J. Piwko and E.V. Larsen in 1982.

The UIF is a function of the given VFD rated power and the rated power of the i-th generator under analysis:

$$UIF_{G,i} = \frac{MVA_{VFD}}{MVA_{G,i}} \cdot \left(1 - \frac{SC_{G,i}}{SC_{TOT}}\right)^2 \tag{1}$$

where:

$UIF_{G,i}$ is the unit interaction factor for the i-th generation train;

MVA_{VFD} is the rating of the VFD;
$MVA_{G,i}$ is the rating of the i-th generator;
$SC_{G,i}$ is the short circuit capacity at the VFD bus excluding the i-th generator;
SC_{TOT} is the total short circuit capacity at the VFD bus.

Based on Equation (1), keeping the VFD and generator ratings ($MVA_{VFD}/MVA_{G,i}$ ratio) constant while connecting more generators to the grid will cause the ratio $SC_{G,i}/SC_{TOT}$ to approach 1 and UIF to approach 0. Summarizing, the plants in island configuration with few power generation trains are the most critical.

Nevertheless, the UIF calculation is an approximate method that provides an indication of the risk of sub-synchronous interactions. When the detailed plant data are available and the preliminary assessment shows a potential SSTI risk, a more detailed analysis should be carried out.

SSTI Detailed Analysis

Before talking about the SSTI detailed analysis, the concept of electrical damping must be introduced including its effect in the mechanical behavior of the train.

The Electrical Damping (D_E)

The general torsional mechanical equation:

$$J\ddot{\vartheta} + D_M\dot{\vartheta} + K\vartheta = T \tag{2}$$

where J is the inertia, D_M the mechanical damping, K the stiffness, and T the external torque applied to the system. The system is always stable since D_M is always positive.

In a power generation system, an electrical damping (D_E) is also acting on the generator shaft, which is due to the interaction with the electrical network through the generator magnetic flux. The electrical damping can be either positive or negative. Negative damping reduces the damping effect in the train.

For small oscillations, the electrical damping can be modeled as an equivalent rotational viscous damper acting on the electric generator shaft windings section, for which an oscillating electrical torque ΔT_e at a given frequency f_n is proportional to a speed oscillation $\Delta\omega$ at the same frequency. The electrical damping, D_E, is influenced by the network and by the loads connected to the network; in combination with the mechanical damping, D_M, it determines the equivalent damping of the whole system. This is a key point to understand the SSTI phenomenon.

Mathematically, the electrical damping is a function of the frequency and it is defined as the real part of the derivative of the electrical torque versus the rotating speed. Practically, considering a mechanical system that is oscillating at its natural frequency f_n, the corresponding electrical damping can be calculated as follows:

$$D_E(f_n) = -Re\left[\frac{\Delta T_E(f_n)}{\Delta\omega(f_n)}\right] \tag{3}$$

where $\Delta\omega(f_n)$ is the speed phasor representative of the speed oscillation at the frequency f_n and $\Delta T_E(f_n)$ is the corresponding electrical torque phasor. The negative sign indicates a positive damping effect when torque oscillations are opposing speed oscillations.

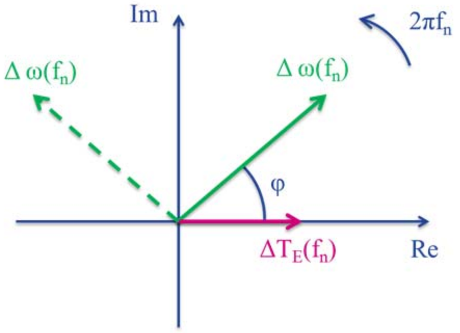

Figure 2: ΔT_E and $\Delta\omega$ phasor diagram

The previous equation can be written as:

$$D_E(f_n) = -\frac{|\Delta T_E(f_n)|}{|\Delta\omega(f_n)|}cos\varphi \tag{4}$$

where φ is the phase between ΔT_E and $\Delta\omega$ as shown in Figure 2. Therefore D_E can either be positive or negative depending on the φ value:

$$for\ \varphi \in \left[\frac{3}{2}\pi, \frac{\pi}{2}\right] \Rightarrow D_E(f_n) \leq 0 \tag{5}$$

$$for\ \varphi \in \left[\frac{\pi}{2}, \frac{3}{2}\pi\right] \Rightarrow D_E(f_n) \geq 0 \tag{6}$$

The following simple example is proposed to better clarify this concept. A turbine-generator mechanical torsional model has been built including the first mode only, considering a mechanical damping equal to 0.

A transient event is created applying a step on the mechanical torque, and the related dynamics are determined through simulations.

Two cases have been analyzed imposing the electrical torque out-of-phase or in-phase with respect to the speed variation, with the intent to demonstrate the previous relations.

Calculating the electrical torque as the ratio between a constant power and the actual speed, the resulting torque is 180° shifted with respect to the speed (Figure 3). In this case, the response at the 1st TNF is stable (refer to the plot in Figure 4).

Shifting 180° the speed (Figure 5), the electrical torque and speed are forced in phase and the resulting electrical damping is negative, with the same amplitude of the previous case, and the response at the 1st TNF is unstable (Figure 6).

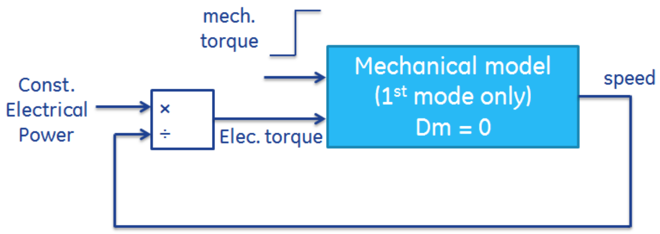

Figure 3: Electrical damping example 1 block diagram

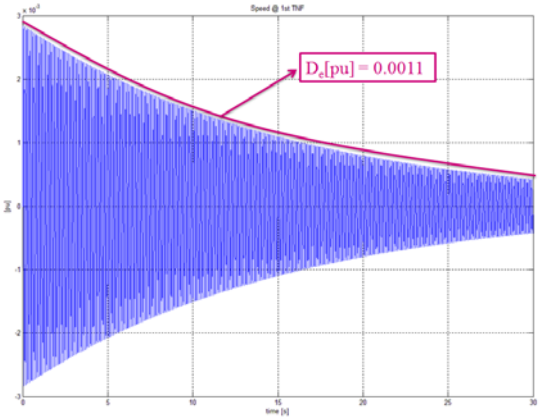

Figure 4: Electrical damping example 1 with $D_E > 0$

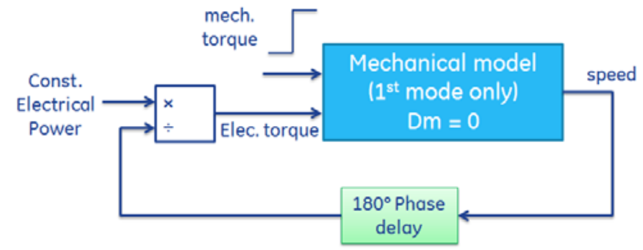

Figure 5: Electrical damping example 2 block diagram

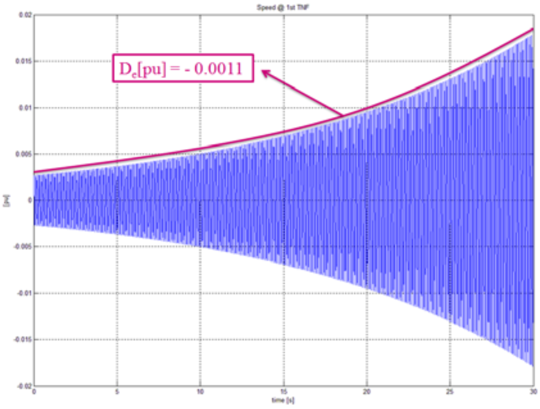

Figure 6: Electrical damping example 2 with $D_E < 0$

Contribution of the Torsional Mode Shape on the SSTI

In order to quantify the effect of the electrical damping on the train response at its torsional natural frequencies, it is useful to introduce the modal approach. The generic 2nd order system of differential equations which describe the shaft torsional dynamic behavior is:

$$[J]\underline{\ddot{\vartheta}} + [D]\underline{\dot{\vartheta}} + [K]\underline{\vartheta} = \underline{T} \tag{7}$$

where equation (7) is the multi-degree-of-freedom representation of equation (2). It can be represented in the modal reference through the following coordinate transformation:

$$\underline{\vartheta} = [\Phi] \cdot \underline{q} \tag{8}$$

where q is the vector of the modal coordinates and [Φ] is the mode-shapes matrix (calculated as the eigenvectors of $[J]^{-1}\cdot[K]$ matrix). Combining the above equations results in:

$$[\Phi]^T[J][\Phi]\underline{\ddot{q}} + [\Phi]^T[D][\Phi]\underline{\dot{q}} + [\Phi]^T[K][\Phi]\underline{q} = [\Phi]^T\underline{T} \tag{9}$$

Since the damping matrix [D] is difficult to characterize, it is directly defined in modal form, based on modal amplification factor values coming from field experience. Therefore the modal equations can be represented as:

$$[M_{EQ}]\underline{\ddot{q}} + [D_{EQ}]\underline{\dot{q}} + [K_{EQ}]\underline{q} = \underline{T_{EQ}} \tag{10}$$

where all the modal matrices (M_{EQ}, D_{EQ} and K_{EQ}) are diagonal. The effect of the electrical torque at the frequency of a generic mode n can be represented as a damping effect according to the rules explained in the former section. Considering only the first mode and applying the electrical torque on the generator windings section, the equivalent torque becomes:

$$T_{EQ} = \beta \cdot T_E \tag{11}$$

where β is the normalized amplitude of the first torsional mode corresponding to the electric generator windings mid-section (ref. to Figure 7).

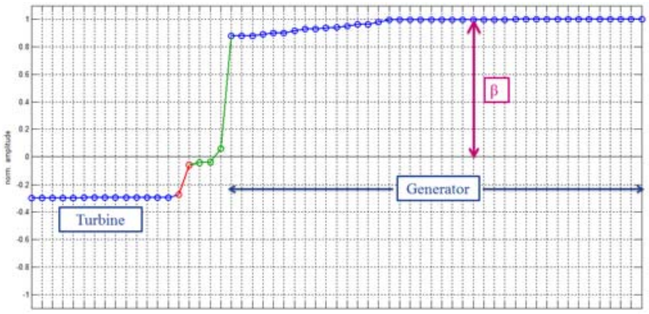

Figure 7: 1^{st} torsional mode shape example

Analyzing small oscillations across a linearized condition at the frequency of the first mode, the electrical torque can be written as:

$$\Delta T_E = D_E \cdot \Delta\omega = -\beta \cdot D_E \cdot \Delta\dot{q}_1 \qquad (12)$$

The equivalent torque can therefore be defined as:

$$T_{EQ} = \beta \cdot \Delta T_E = -\beta^2 \cdot D_E \cdot \Delta\dot{q}_1 \qquad (13)$$

The total damping for the first torsional mode can thus be calculated as:

$$D_{tot} = D_M + \beta^2 \cdot D_E \qquad (14)$$

where D_M is the mechanical modal damping.

The contribution of the torsional mode shape relative amplitude β is therefore fundamental in defining the SSTI system response. For modes where β is small, β^2 is very small and therefore even a negative electrical damping will be unlikely to drive a system into instability.

The Detailed Study

In the detailed study, a simulation model of the complete network is built including generators and active components (e.g. LCI drives). All operating configurations of the plant, from commissioning to normal operation, must be identified by the customer and evaluated in the study.

An effective method to perform these simulations is to create a transient event (e.g. a load step) into the torsional mechanical model of the turbine-generator. Depending on the entire network system model, the induced perturbation will become stable or unstable depending on the sign of the equivalent damping. The equivalent damping (mechanical and electrical) can then be calculated as the logarithmic decrement of the generator speed response. In this way, the effect of torsional mode shape as previously described will be inherently considered.

An alternative method of evaluation is to apply a sinusoidal speed variation at the frequency of interest f_n (typically only for the first mode) located at the shaft of the generator producing an electrical torque pulsation in the machine.

The electrical torque pulsation is then filtered at the frequency of the speed variation in order to obtain the component relevant for the damping calculation. The electrical damping is then calculated as follows:

$$D_E(f_n) = -\frac{|\Delta T_E(f_n)|}{|\Delta\omega(f_n)|} cos\varphi \qquad (15)$$

As described in the previous section, the above electrical damping is multiplied by the β^2 of the corresponding torsional mode shape.

By evaluating the turbine-generator mode shapes for a given study, only the modes with a significant β (and with basically a flat shape in correspondence of the generator windings sections) shall be included in the analysis. Conditions where the equivalent damping is negative or close to zero will represent a high risk of SSTI.

It is important to highlight that the above mentioned study only has the purpose of identifying potential instabilities due to the SSTI phenomenon. Other methods should be used to evaluate the forced response impact of VFDs inter-harmonics direct excitations on any other machine (generators, DOL motors, etc.) connected to the same grid. In these cases the resulting torque responses on the impacted machines should be evaluated as consequence of such current pulsations injected into the network by any power electronic device.

FIELD EXPERIENCE

Over the last years several SSTI phenomena have been experienced at site by the Authors. In all these cases, the main causes of the SSTI were observed: island network, large VFDs loads, GTG 1st mode shape highly involved in the electric generator sections, relatively low short circuit power at the generators bus bars. One of the most significant site experiences hereafter described happened during the commissioning phase of an LNG Oil&Gas plant.

A description of a typical LNG train configuration and operating philosophy has been described in the literature, as for example by Schramm S. in 2010.

CASE 1: LNG train start-up with two GTGs feeding the plant

The network configuration is represented in Figure 8 below:

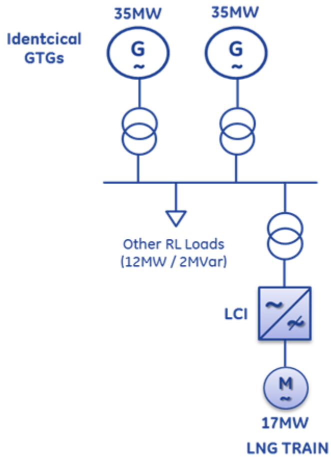

Figure 8: Case 1 network configuration

The field scenario is summarized below:

- ✓ Two identical gas turbine driven electric generators (GTGs, rated 35 MW each) were feeding an island network;

- ✓ An LCI drive (starter/helper) was starting up an LNG train;
- ✓ Some resistive/inductive (RL) loads (approx. 12 MW) were connected to the grid.

At about 95% speed of the LCI start-up, phase one GTG tripped for high lateral vibrations on its gearbox causing the other GTG to take the complete network load. After a few seconds, this second GTG also tripped for the same reason before completing the LCI start-up sequence, leading to a plant black-out.

Figure 9 shows a full spectrum plot of the GTG gearbox shaft vibration (high speed side) when the trip occurred. As highlighted by the measurements, the main vibration component is sub-synchronous at about 10 Hz. This frequency is the GTG first torsional natural frequency.

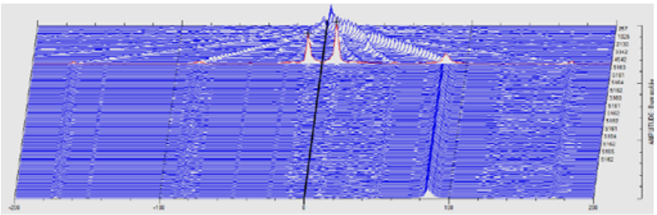

Figure 9: GTG gearbox high speed shaft full spectrum (2 GTGs in operation) - Case 1

The measured DC link current of the LCI drive at the same timeframe was also available. Data vs. time and waterfall plots during the last portion of the start-up phase are shown in Figure 10 and Figure 11. The 1st TNF of the GTG train is clearly visible in the LCI drive DC link current and it increases in amplitude while the gearbox vibrations are increasing as well. The gearbox vibration exceeded the trip threshold and the machine tripped.

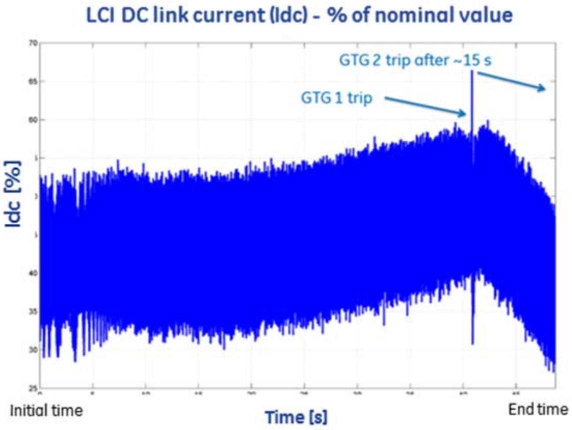

Figure 10: LCI DC link current, last portion of the start-up phase (2 GTGs in operation) - Case 1

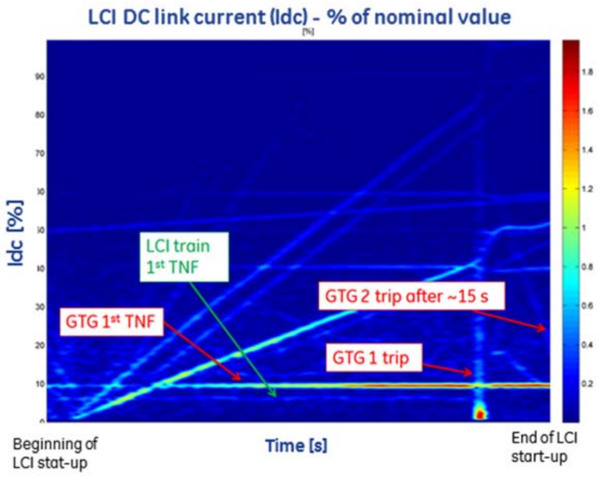

Figure 11: LCI DC link current waterfall, entire start-up phase (2 GTGs in operation) - Case 1

This is the typical behavior of an SSTI phenomenon, where the torsional oscillations of the GTG are translated into electrical quantities that finally show up in the VFD DC link current. In this case the GTG integrity was preserved only because the gearbox translated torsional oscillations into lateral vibrations, leading to the machine trip.

It is important to note that torsional vibration measurements on the GTGs were not available for this event since no torsional measurement probe was installed at that time.

CASE 2: LNG train start-up with three GTGs feeding the plant

After understanding that an SSTI phenomenon occurred, it was suggested to the plant owner to add in another GTG that was available. This action increased the short circuit power at the generator bus bar to reinforce the network against sub-synchronous oscillations.

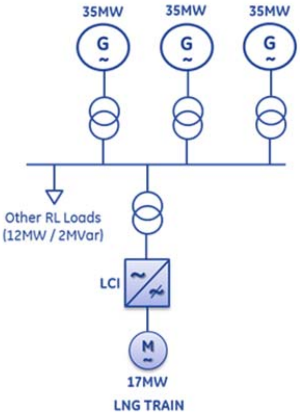

Figure 12: Case 2 network configuration

In addition, a torsional vibration monitoring system was installed while going ahead with the commissioning activities.

In this configuration, the LCI train was able to start-up without any trip on the GTGs. Figure 13 to Figure 16 below show the corresponding torsional measurements and DC link current data vs. time and waterfall plots during a complete LCI start-up.

The torsional monitoring system measured the alternating angular oscillation (in degrees) from a speed measurement on the gas turbine tooth-wheel. Additional details can be found in the lecture presented by L. Naldi in 2011.

A conservative threshold of intervention (manual trip) was set to 0.5 degrees, calculated from the maximum allowable alternating torque of the weakest element of the shaft-line. The measured maximum alternating angular oscillation was lower than 0.1 degrees, thus well below the allowable limit.

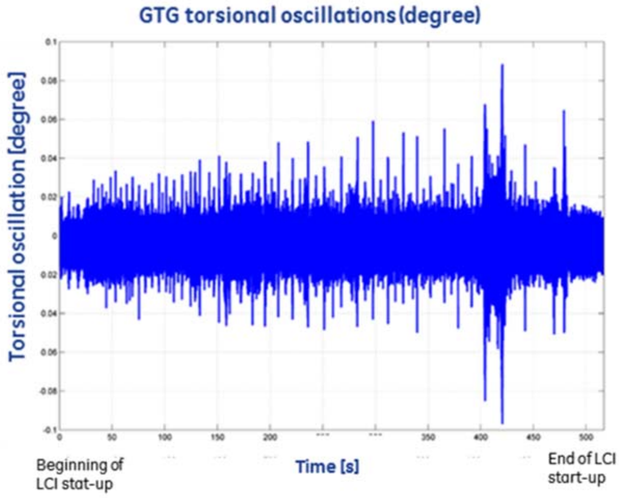

Figure 13: GTG torsional measurement (alternating angular oscillation), entire start-up phase (with 3 GTGs in operation) - Case 2

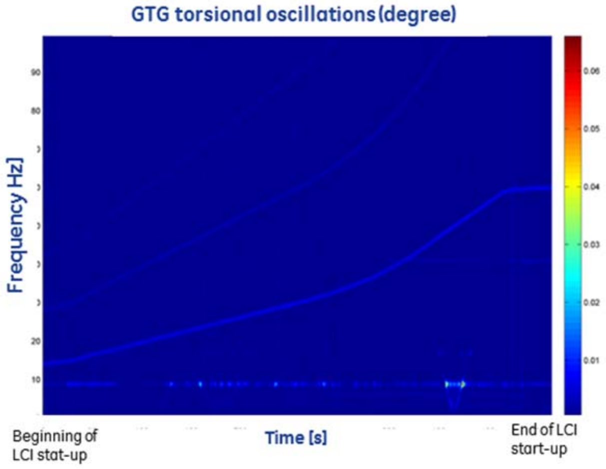

Figure 14: GTG torsional measurement waterfall (alternating angular oscillation), entire start-up phase (with 3 GTGs in operation) - Case 2

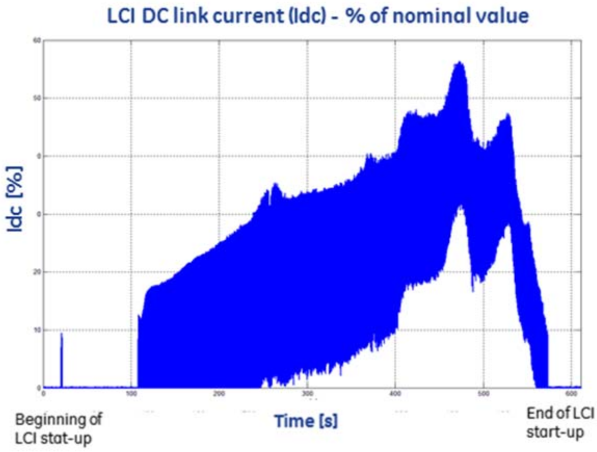

Figure 15: LCI DC link current, entire start-up phase (with 3 GTGs in operation) - Case 2

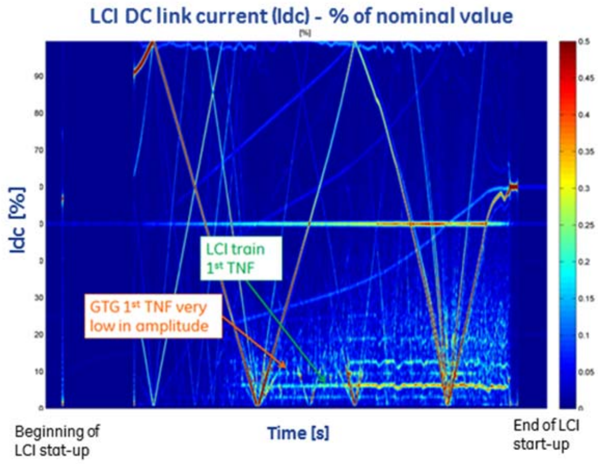

Figure 16: LCI DC link current waterfall, entire start-up phase (with 3 GTGs in operation) - Case 2

CASE 3: Unplanned event leading to SSTI phenomenon

In addition to the start-up scenarios analyzed in the previous paragraphs, another interesting SSTI case involving an LNG train at rated speed is hereafter described. The network configuration was composed of three GTGs feeding two LNG trains as shown in Figure 17.

The gas turbines of the LNG trains were powering the compressors, while the LCI drives were unloaded. The torsional monitoring system was already in place.

At a certain moment some contingencies occurred. The sequence of the events is summarized below:

1. The fuel gas pressure of all turbines dropped because of a leak.
2. The power delivered by the two gas turbines of the LNG trains decreased because of the fuel gas leakage and the turbine controller started requesting toque to the LCI helpers.

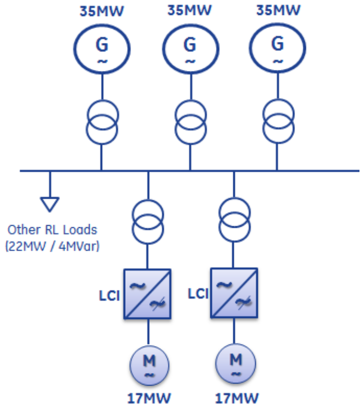

Figure 17: Case 3 - unplanned event network configuration

3. The three GTGs had to increase the delivered power to follow the LCI helpers demand.
4. When the helpers set points were respectively about 100% and 60% of their rated power one of the three GTGs tripped for low fuel gas pressure.
5. Tripping of this GTG caused the isolation of the fuel gas leakage, thus the fuel gas header pressure kept increasing up to the normal value.
6. When the fuel gas pressure returned back at its nominal value, the two gas turbines driving the LNG trains were again able to deliver the power requested by the compressors therefore the turbine controller decreased the power demand to the helpers unloading them completely.

During this contingent scenario, when the GTG tripped, there were only two GTGs feeding both the LCI drives that were requesting power simultaneously. This started an SSTI phenomenon, leading to a torsional vibration increasing on both the GTGs. Figure 18 shows the alternating angular oscillation on one of those GTGs starting from the GTG trip event.

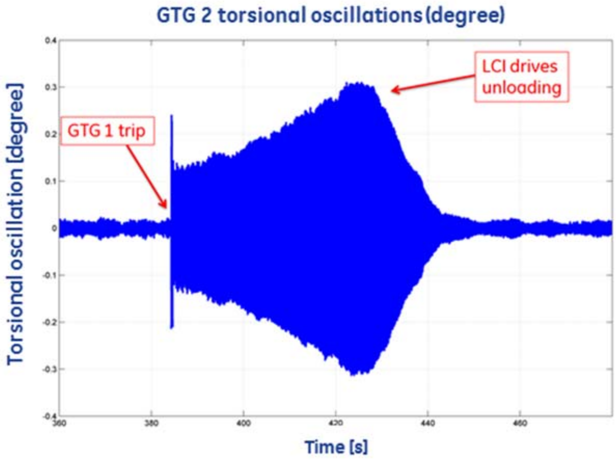

Figure 18: GTG 2 torsional measurement (alternating angular oscillation) during the unplanned event – Case 3

Unfortunately the LCI DC link current was not stored during this unplanned event. It was clear that loading both helper motors simultaneously with only two GTGs connected to the entire network was an unstable condition due to the SSTI phenomenon. When the helpers were unloaded again the torsional oscillations on the GTGs stabilized.

It is important to remark that the torsional oscillation on the GTGs reached a maximum value of about 0.3 degrees, with a threshold at 0.5. The gearbox vibrations during this condition overcame the alarm threshold and were close to the trip limits.

CALCULATIONS, SIMULATIONS AND ANALYSIS

The main target of this paragraph is to understand the SSTI predictability considering network data and available system information of the whole plant. Simulation results will be shown. First of all the UIF has been calculated for Case1, Case 2 and Case 3 analyzed in the section above.

Scenario	UIF
Case 1 (2 GTG, 1 LCI)	0.24
Case 2 (3 GTG, 1 LCI)	0.16
Case 3 (2 GTG, 2 LCI)	0.48

Table 1: UIF calculation for 3 plant configurations

The UIF values calculated for both Case 1 and 2 are greater than the threshold of 0.1 (as well as for the contingent scenario presented in Case 3). Normally in this condition an SSTI detailed analysis is highly recommended to drilldown the phenomenon. The UIF only provides an indication of the SSTI potential risk. For example, instabilities have not been observed at site with 3 GTGs in operation (Case 2) even though the related UIF is above the threshold limit.

Detailed simulations have been carried out first of all to reproduce the SSTI phenomenon during LCI start-up, then to demonstrate the stability with 3 GTGs in operation.

The entire system has been simulated in MATLAB/Simulink® environment. The GTG shaft line has been modeled to reproduce site measurements; the model includes gas turbine governor, excitation system and mechanical characteristics. The mechanical dynamics of the GTG have been implemented with its torsional model considering the rigid and 1st torsional modes. The step-up transformer is also included.

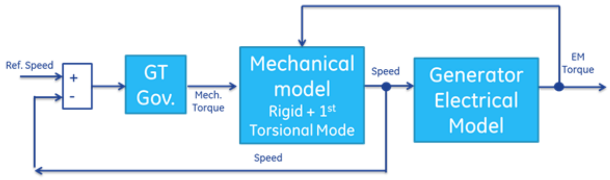

Figure 19: GTG model block diagram

The VFD is modeled with two independent bridges fed by a phase shifted (30°) step down transformer. On each bridge there are 6 thyristors for the rectifier side. The firing angle is modulated by a PI controller using the DC link current as feedback.

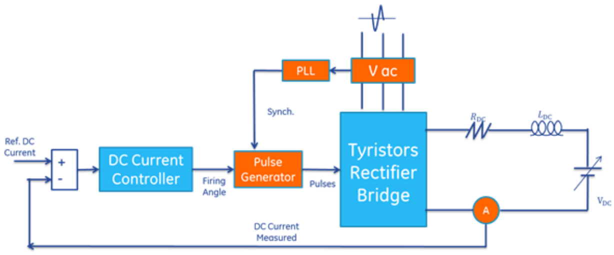

Figure 20: VFD Model block diagram

The implementation of the control logic and circuit is done according to project data. The inverter side is modeled as a DC variable voltage source. This model is suitable to describe the SSTI main dynamics even though more details can be added to refine the analysis. The model matches the test results.

Simulation results and parameter variation sensitivity analysis are presented in the following sections to reproduce and describe the SSTI criticality recorded in the field. Specifically the LCI start-up has been deeply investigated since this condition caused GTG torsional instabilities at site.

CASE 1: LCI start-up with 2 GTGs (ref. to Figure 8)

As shown in the field experience section, the Case 1 configuration with only 2 GTGs connected to the grid led the system to become unstable and the generator trains tripped due to high radial vibration on the gearbox. The aim of this simulation is to replicate the same system behavior as observed at site and to evaluate the torsional oscillations on the generator shafts.

The LNG train start-up has been reproduced giving a ramped DC link current reference that simulates a torque demand to the LCI helper motor. Then the LCI is unloaded according to the standard LNG train start-up logic.

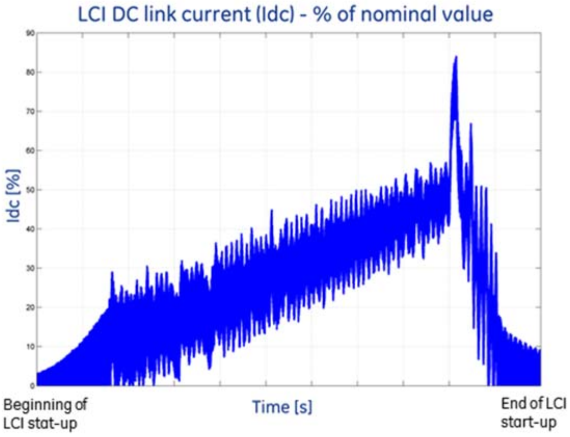

Figure 21: LCI helper motor start-up simulations with 2GTGs LCI DC link current trend [%] - Case 1

Figure 21 shows the LCI DC link current during the simulated start-up and Figure 22 shows its waterfall (extraction of the final start-up portion).

A component around 10Hz (1st torsional mode of the GTGs) is present (Figure 22) in the LCI DC link and its amplitude is consistently growing.

The practical meaning of this observation is that the torsional oscillation at the 1st TNF of the GTG unit is coupled with the VFD DC link through the oscillation of voltage on the electrical grid. The DC link current controller can have an influence on this coupled phenomenon and it can add some additional system damping if well-tuned. Once this SSTI phenomenon started, the speed and the torque of the generators started to oscillate at 10 Hz as shown in Figure 23 and Figure 24. In order to be congruent with field measurements shown in the previous section, the shaft torsional oscillation is provided as an alternating angular oscillation (in degrees) on the turbine section shown in Figure 24. That torsional resonance caused high gearbox vibration and consequent trip of the unit.

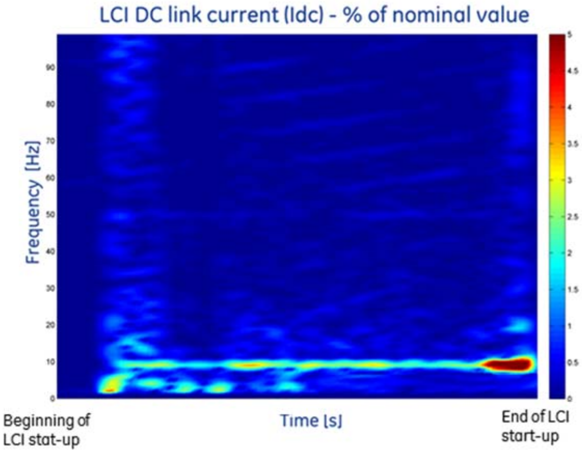

Figure 22: LCI helper motor start-up simulations with 2GTGs LCI DC link current waterfall [%] - Case 1

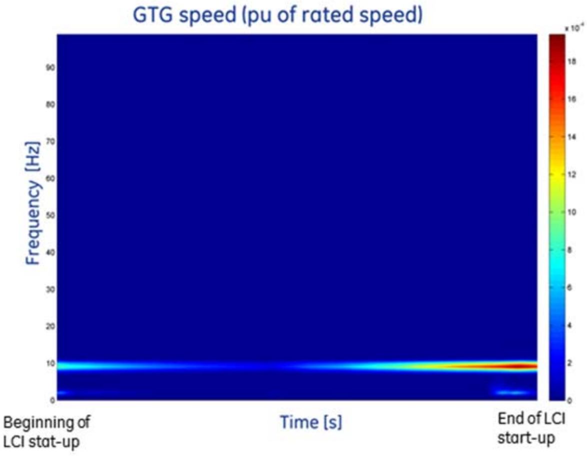

Figure 23: LCI helper motor start-up simulations with 2GTGs GTG speed waterfall [pu] - Case 1

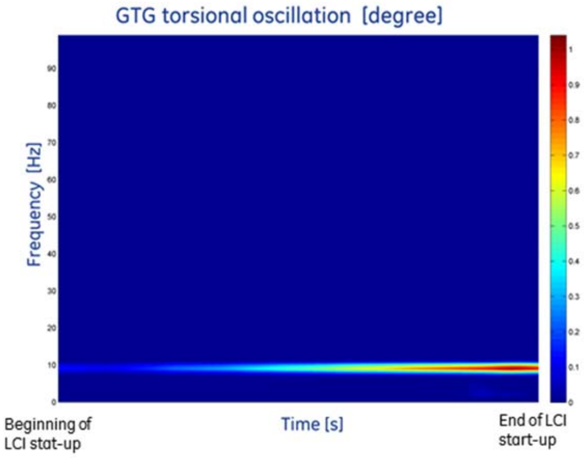

Figure 24: LCI helper motor start-up simulations with 2GTGs GTG angular oscillation [deg] - Case 1

CASE 2: LCI start-up with 3 GTGs (ref. to Figure 12)

In Case 2, the LCI start-up with 3 GTGs connected to the grid did not show SSTI issues at site as described in the field experience section. The LCI correctly started without leading to high GTG vibration. The aim of this section is to replicate by simulation the proper behavior of the coupled system and to demonstrate by analysis that the torsional oscillations on GTGs are lower for Case 2 than for Case 1. The LCI start-up has been simulated as for the previous case. The main simulation results are showed in the following Figure 25 to Figure 28.

As per Case 1, the waterfall in Figure 26 shows a component around 10Hz (1st torsional mode of the GTGs) in the DC link current. Also, the generator speed starts to oscillate at 10 Hz as shown in the waterfall in Figure 27, but the main difference between the case with 2 GTGs and 3 GTGs is the amplitude of the vibration. In this Case 2, the GTGs torsional oscillations are well below the alarm threshold and this perfectly matches the field experience.

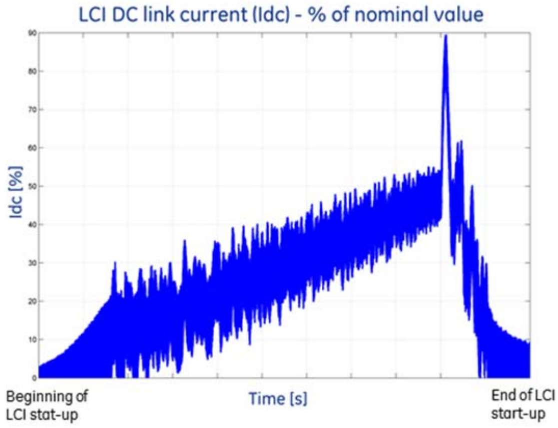

Figure 25: LCI helper motor start-up simulations with 3GTGs LCI DC link current trend [%] - Case 2

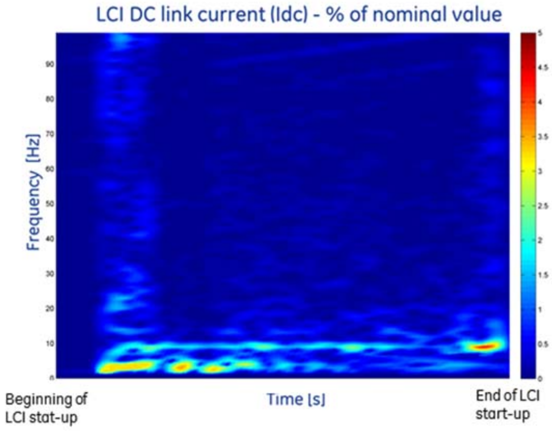

Figure 26: LCI helper motor start-up simulations with 3GTGs LCI DC link current waterfall [%] - Case 2

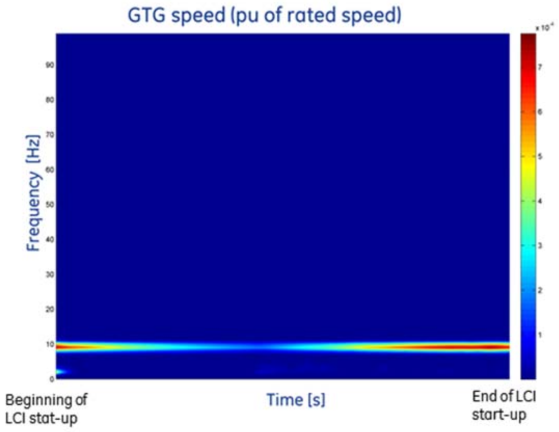

Figure 27: LCI helper motor start-up simulations with 3GTGs GTG speed waterfall [pu] - Case 2

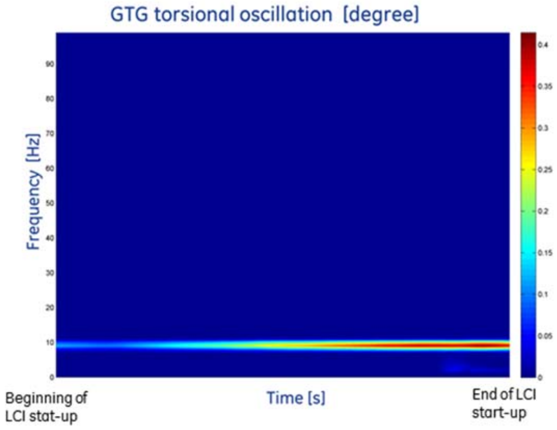

Figure 28: LCI helper motor start-up simulations with 3GTGs GTG angular oscillation [deg] - Case 2

SSTI Stability Sensitivity Analysis

One of the main concepts behind the SSTI phenomenon is that the torsional response is not only due to the mechanical damping and the excitation at shaft TNFs but also to the electrical damping as discussed in the theory section. The scope of this section is to study the stability of the generator torsional behavior versus the number of generators feeding the grid, connected passive loads and mechanical amplification factor.

Sensitivity Analysis versus GTG Number

A load variation from 50% to 100% is applied to the LCI helper motor. Figure 29 and Figure 30 show the resulting GTG speed with 2 or 3 generators connected to the grid respectively. The case with 2 generators connected is unstable, but becomes stable with 3 generators.

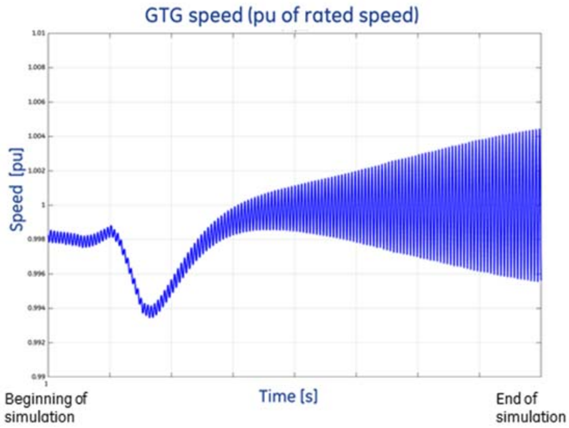

Figure 29: 2GTGs – LCI load step – GTG speed response [pu]

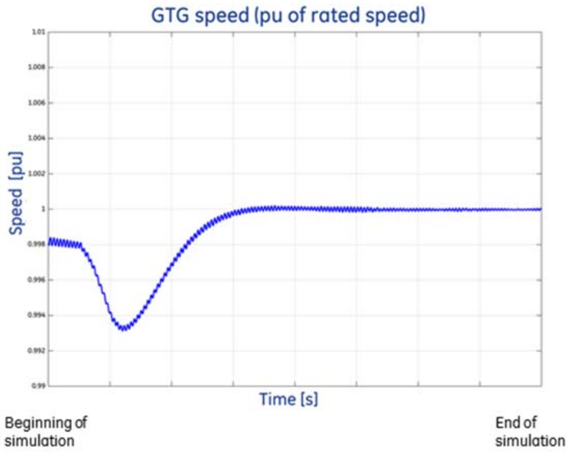

Figure 30: 3GTGs – LCI load step – GTG speed response [pu]

Sensitivity Analysis versus Passive Load Variation

The equivalent RL load considered in the previous analysis (ref. to Figure 29) has been doubled to demonstrate that passive loads can have a relevant influence in the SSTI.

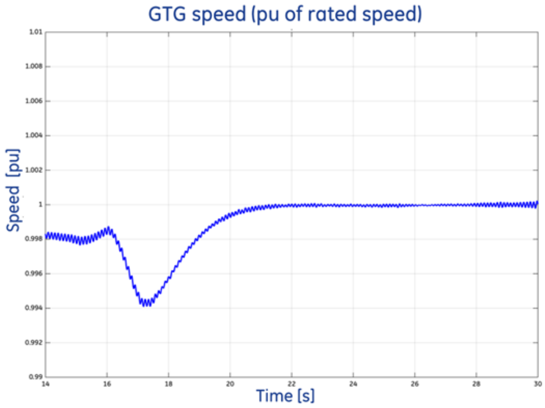

Figure 31: 2GTGs – LCI load step – GTG speed response [pu] with doubled RL load

In fact increasing the passive load helped to move the overall electrical damping in the positive direction reducing and containing the oscillations within acceptable limits. Figure 31 shows the GTG speed response with 2 generators connected and 24 MW/4 MVAR passive loads.

Sensitivity Analysis versus Mechanical Damping (DM)

Mechanical Damping is positive per its nature. It is a common practice to define a certain value of amplification factor (AF) given by experience and calculate the D_M starting from that. Scope of this simulation is to highlight the effect on plant stability doubling the D_M.

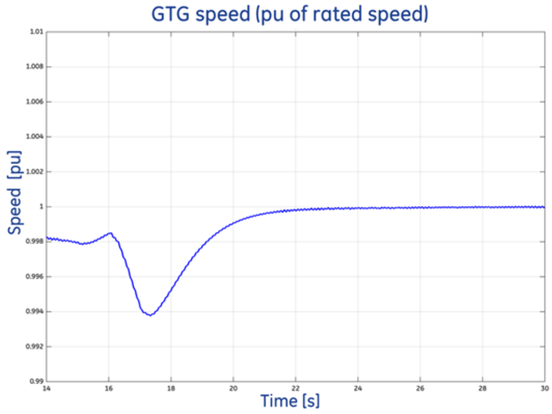

Figure 32: 2GTGs – LCI load step – GTG speed response [pu] with doubled D_M

Sensitivity Analysis versus VFD Control Parameters

Another very important concept to highlight is that VFDs control settings can have a large influence on the SSTI phenomena. For example the VFD tuning is performed generally by the VFD supplier based on several boundary conditions that generally do not include the SSTI phenomenon.

An evaluation should always be requested in case VFD control modifications are needed at site because this could impact SSTI response. It is always difficult to identify an effective tuning of the control parameters that make the system immune to torsional interaction in all possible scenarios. Therefore the control parameters are always a compromise between fast response of the control and system stability. The margin to play with is not boundless as discussed by P. Joerg in 2013.

SSTI MANAGEMENT GUIDELINES

The analysis of torsional interaction is very important in Oil&Gas facilities because this phenomenon can directly affect the operation of the system. In some cases SSTI effect is not detected until generator shaft lines are damaged. The reason is mainly the unknown stress in the mechanical shaft because of lack of appropriate sensor connected to the shaft.

As shown in the Field Experience section, the key drivers of the SSTI phenomenon are the following: island network, large VSDS loads, power generation trains 1st mode shape highly involved in the electric generator sections, and relatively low short circuit power at the generators bus bars.

The short circuit power at the generator bus bars needs some additional considerations. This power is governed by the equivalent sub-transient reactance (xd”) of the generators connected to that bus. The greater the short circuit power, the greater are the benefits from the SSTI point of view. But too high short circuit power can have a negative impact on fault torques that can lead to a shaft line oversizing. Generally, case-by-case evaluation has to be carried out for a suitable design trade-off.

In addition to the torsional analysis performed according to international standards, several actions can be taken to properly manage SSTI risk.

First of all, a risk assessment needs to be done in the early stage of plant definition leading to major engineering potential mitigation actions in order to avoid contingencies leading to critical UIFs (i.e. increase number or rate of generators, optimize VFDs load versus other loads). All possible scenarios should be investigated: not only normal operations but also contingencies and plant start-up. For example during plant start-up and when VFDs are in commissioning phase limited number of generators is typically in operation. This will commonly lead to higher UIF values than normal operating conditions.

When the SSTI risk becomes real, other actions can be taken in order to avoid site impacts. A detailed SSTI study should be performed to evaluate the critical scenarios and quantify the system damping effect on each generator shaft line. Sensitivities to load variations and VFDs control parameters tuning should also be included to both demonstrate robustness of the analysis and optimize plant behavior.

Detailed SSTI studies can lead to several mitigation options that should be analyzed in depth and properly implemented:

- ✓ Planning-based Operational Strategies to avoid configurations identified as likely to cause generator high torsional vibration and to avoid operating conditions not evaluated for SSTI study;
- ✓ Real-time Operational Strategies:
  - Process Adjustments: modify compressor speed or VFDs power if generator high torsional vibrations are detected;
  - Trip pre-selected VFDs before generator trips based upon generator torsional vibration different thresholds;
- ✓ Tuning of VFDs’ controllers to reduce impact on generator torsional behavior (negative damping and/or direct excitations). Real time simulations can also be used to pre-tune VFDs real controller in order to avoid time impact during site commissioning phase.

It is important to highlight that the tuning of the VFD control parameters is not always the ultimate action to mitigate SSTI and should not be performed at site without a full understanding and analysis of the plant (detailed/mitigation study). In fact the change of VFD parameter settings have an impact also on the train performances and stability. For this reason a trial and error approach should be strictly avoided at site to minimize the risk of issues and damages.

In case of very critical plant configurations where the VFDs control settings and plant operational strategy optimizations are insufficient to reduce the SSTI risk under a level accepted by the operability team, other options can be customized and implemented such as additional VFDs algorithms and active dampers as described by R.J. Piwko and E.V. Larsen at the beginning of the 1980s and by C. Sihler (2006, 2009) more recently.

In any case and as also shown in the Field Experience section, an unplanned scenario can always happen and it is very important to equip Oil&Gas train shaft lines with proper torsional vibration sensors and a monitoring system to detect any potential high torsional vibration that could otherwise lead to shaft line damage.

CONCLUSIONS

The increasing trend of VFDs load implementation in Oil&Gas plant is enhancing the potential of SSTI phenomena and relevant impact on plant operability.

Starting from real site experiences, the theory behind the SSTI issues has been described. Simulation results led to a comprehensive understating of the main drivers of this phenomenon leading the authors to provide a set of practical guidelines to properly manage SSTI risk since early plant definition phase. Figure 33 provides a schematic summary of the practical guidelines described in the paper.

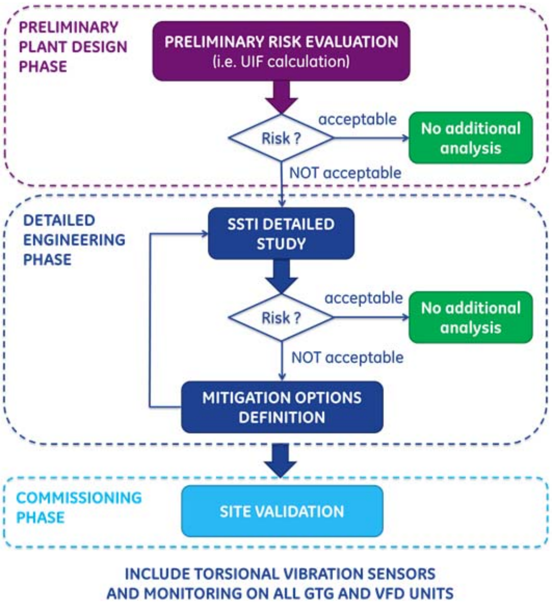

Figure 33: Summary of SSTI practical guidelines for Oil&Gas plants

NOMENCLATURE

VFD = Variable Frequency Drives
SSTI = Sub-Synchronous Torsional Interactions
PCC = Point of Common Coupling
UIF = Unit Interaction Factor
HVDC = High Voltage Direct Current
LCI = Load Commutated Inverter
GTG = Gas Turbine Generator
LNG = Liquefied Natural Gas
DC = Direct Current
TNF = Torsional Natural Frequency

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