Gas turbines in a carbon-neutral society
10th International Gas Turbine Conference
11-15 October 2021

Paper ID Number: 49-IGTC21

THE IMPORTANCE OF TORSIONAL VIBRATIONS IN THE ENERGY TRANSITION

Frits Petit, Felipe Vergara, Filip Verbinnen and Sébastien Grégoire
ENGIE Laborelec
Rodestraat 125, 1630 Linkebeek, Belgium
+32 (0) 2 382 02 28
Frits.petit@engie.com

ABSTRACT

This paper aims at introducing torsional vibrations with a focus on the energy production sector. Although considerable effort has been devoted to the subject leading to a profound understanding since decades, important damage to shaft lines still occurs. The main reason is that for energy production units (e.g. gas turbine power plants, wind turbines…), the excitation primarily comes from interaction with the energy grid. Consequently, changes to the electricity grid like the introduction of High Voltage Direct Current stations (HVDC) stations, heavily consuming arc furnaces, series capacitor banks … could potentially lead to excessive torsional vibrations which were not accounted for in the design stage of the unit. With the upcoming energy transition, more than ever torsional vibrations may not be overlooked.

Along with some key aspects of torsional vibrations in the energy production sector including measurement results, some important known grid interaction phenomena will be outlined such as SubSynchronous Resonance, interaction with HVDC stations and heavy consuming arc furnace plants.

INTRODUCTION

The electricity grid is drastically changing. Offshore wind farms, large solar plants and a lack of storage are important drivers in the transition of the grid. An increasingly number of active components (e.g. High-Voltage DC stations) and large-distance connections in between neighbouring countries is being put into place all over the world. In Europe, the grid frequency regulations will be relaxed resulting in larger and faster grid frequency variations (ENTSOE, 2018). All these changes on the electrical side have a direct impact on the mechanical side of a conventional electrical power plant (Adrees, 2017). More specifically, grid interaction can lead to excessive torsional vibration amplitudes of a turbo-generator shaft line.

Although the risk of damage due to torsional vibration is generally well assessed at the design stage of a power generation system, later adjustments to the shaft line, or modifications to the external power system, can create the perfect conditions for certain phenomena to develop. Different catastrophic failures have occurred, recent as well as in the past, in which rotors were found destroyed due to torsional vibrations (Anderson, Agrawal, & Ness, 1999).

While shaft lines are generally well protected against lateral vibrations (typically caused by well-known phenomena such as unbalance, rub, fluid instability etc.), monitoring and protection against torsional vibrations remain an exception. In fact, as torsional vibrations are not transmitted to the foundation, power plants are completely blind and do not capture torsional vibrations with their standard monitoring system. Consequently, a shaft line can suffer from excessive torsional vibration amplitudes leading to a fatigue failure of the shaft line (e.g. a cracked rotor) without any warning. Moreover, as torsional vibrations are very lightly damped, fatigue damage accumulates very fast such that irreversible damage can be caused in a matter of minutes.

In the remainder of this paper, insight into the torsional vibration dynamics of turbomachinery will be given as well as how the torsional vibrations are typically measured. The most important grid interaction phenomena will be outlined along with some examples from the field.

NOMENCLATURE

HVDC – High Voltage Direct Current
LCC – Line Commutated Convertor
VSC – Voltage Source Convertor
SSR – Subsynchronous Resonance
SSTI – Subsynchronous Torsional Interaction
PSS – Power System Stabilizer
DFIG – Doubly Fed Induction Generator

TORSIONAL VIBRATIONS

The torsional vibration natural frequencies of interest for a turbo-generator shaft line are the subsynchronous modes and the modes close to 1x and 2x grid frequency. The other modes are typically not excited in operation.

The subsynchronous modes, i.e. modes with a frequency below 1x grid frequency, are the most important ones for what grid interaction concerns and are typically quite straightforward in terms of mode shape. For these modes, all the torsional twisting motion typically happens in the intermediate shafts in between the main rotors (steam turbines, gas turbines and generator) while the main rotors themselves can be regarded as rigid bodies. Consequently, besides the inertia of the main rotors which is typically available, more detailed information of these more complex rotors is not required and only the geometry of the intermediate shafts and couplings is needed to assess the severity of the torsional vibration amplitudes.

Mode shape examples of a gas turbine unit and a steam turbine unit are shown in Figure 1 and Figure 2 respectively. For a gas turbine unit, typically only the first mode is subsynchonous while for a steam turbine unit multiple subsynchronous modes exist. A simplified lumped-mass model with 2 to 7 lumped masses is typically sufficiently accurate to describe the subsynchronous dynamics.

In some cases, the dynamics of the L-0 and L-1 blades need to be considered for the modes near 2x grid frequency. The blade dynamics are for instance clearly visible in mode 5 of Figure 2 where they are represented as single degree of freedom systems. For the subsynchronous modes, the blade dynamics do not play a role and the blades can typically be regarded as an inertia lumped to the rotor, also referred to as a concentrated mass.

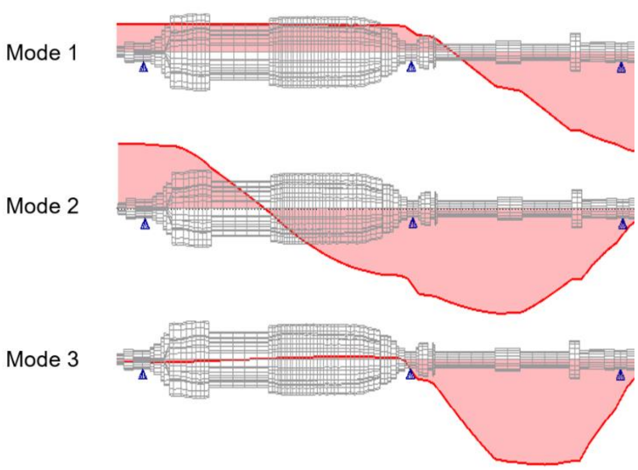

Figure 1: Lowest 3 torsional vibration modes of a gas turbine unit. Only mode 1 is subsynchronous.

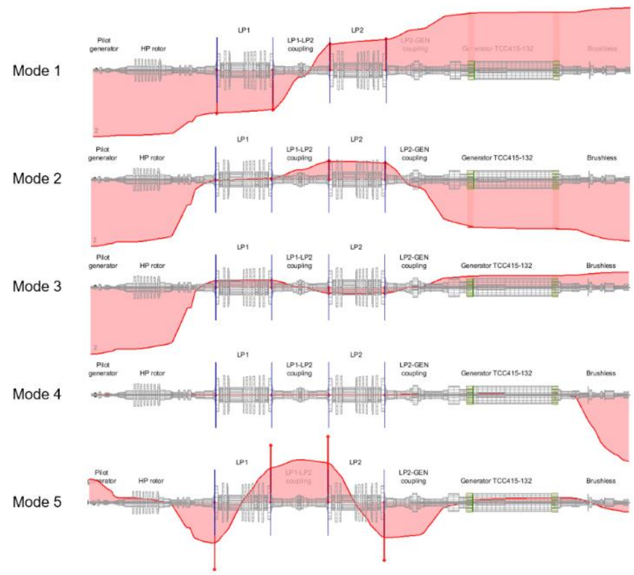

Figure 2: Lowest 5 torsional vibration modes of a steam turbine unit. Modes 1 to 4 are subsynchronous.

MEASUREMENT TECHNIQUES

The most used technique in the power generation sector is Time Interval Measurement. Typically, a hall-effect sensor facing a toothed wheel (e.g. around 60 teeth) is used which generates a pulse every time a tooth passes underneath the sensor. The time in between two pulses is determined using a clock with a very high sampling rate (MHz order).

In most cases the existing speed sensors for speed control or over-speed purposes are enough for what the subsynchronous modes concerns. Given the accurate prediction obtained with the theoretical model (error with respect to measured values typically less than 1%), a single axial location is generally enough to assess the torsional vibration behavior of the entire shaft line.

Sometimes optical sensors facing a zebra-tape or reflective tape are added on top of the existing ones for temporary measurement campaigns or for validation of the theoretical model. This validation is sometimes required, for instance when the existing sensor is too close to a nodal point for one of the subsynchronous modes.

Other techniques like encoders, magneto-strictive sensors or strain gauges are also possible but less widely used due to installation and/or calibration issues. Some examples are shown in Figure 3.

Torsional vibrations of turbomachinery are also visible on the electrical side due to the electro-mechanical coupling provided by the generator. However, assessing the fatigue damage due to torsional vibrations purely based on the electrical measurements (generator 3-phase current and voltage) is difficult as the mechanical-electrical transfer function is not known a priori.

Figure 3: A couple of measurement techniques for torsional vibrations in turbomachinery. From left to right: Hall-effect sensor facing toothed wheel, optical sensor facing zebra-tape, encoder at shaft end, magneto-strictive sensor.

Torsional vibrations of turbomachinery are also visible on the electrical side due to the electro-mechanical coupling provided

EXCITATION OF TORSIONAL VIBRATIONS

Torsional vibrations are typically grid-induced and therefore the excitation source is external to the power plant (EPRI, 2005). Sometimes however, the excitation is internal to the power plant.

Internal excitation

Examples of internal excitation are mainly due to control instability issues. A typical example is speed control instability which can occur when the fuel valve of a gas turbine is not well tuned and interacts with the lowest torsional natural frequency of the shaft line. Other known examples are voltage control instabilities involving the Power System Stabilizer (PSS) (Grigsby, 2012) and excitation due to power electronic harmonics, for instance during the so-called static start of a gas turbine before synchronizing to grid where the generator is used as a motor (see Figure 4). As the excitation is internally to the power plant, it can be more easily mitigated than external excitation, for instance by changing the control parameters.

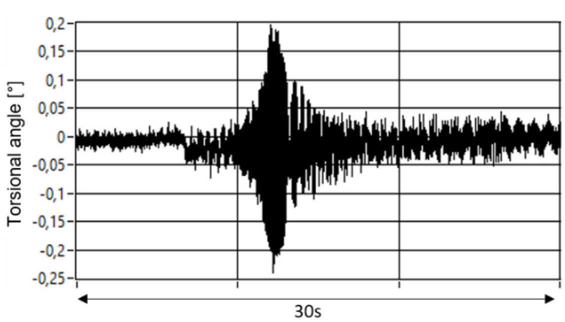

Figure 4: Transient resonance passage during a static start of a gas turbine. The lowest natural frequency at 17Hz is excited at 170rpm by the 6th harmonic.

External excitation

External excitation involves interaction with the electricity grid. The coupling between turbo-generator shaft line and the electricity grid is provided by the generator. Consequently, only modes with sufficient mode shape amplitude at the generator are excitable. When regarding Figure 1 and Figure 2, mode 2 and 3 of the gas turbine and mode 4 of the steam turbine are not susceptible to important grid interaction as the mode shape amplitude is nearly zero along the entire generator resulting in an overall torque which is also nearly zero.

Excitation at 1x and 2x grid frequency

The main excitation frequencies are 1x and 2x grid frequency. Every transient grid event excites the mechanical shaft at 1x grid frequency, while any 3-phase unbalance introduces excitation at 2x grid frequency. In design, exclusion zones for the torsional natural frequencies are therefore imposed around 1x and 2x grid frequency to avoid any dynamic amplification (ISO/FDIS, 2009).

An example of a transient event is shown in Figure 5 in which a crane caused a short circuit of a high voltage transmission line close to the power plant. As the fault is cleared in less than 100ms and no natural frequencies are present close to 1x and 2x grid frequency, torsional amplification does not occur. The response is dominated by the lowest natural frequency around 7.5Hz. The resulting torsional vibration amplitudes remained well below the static angle imposed by the nominal torque and did not cause important fatigue damage.

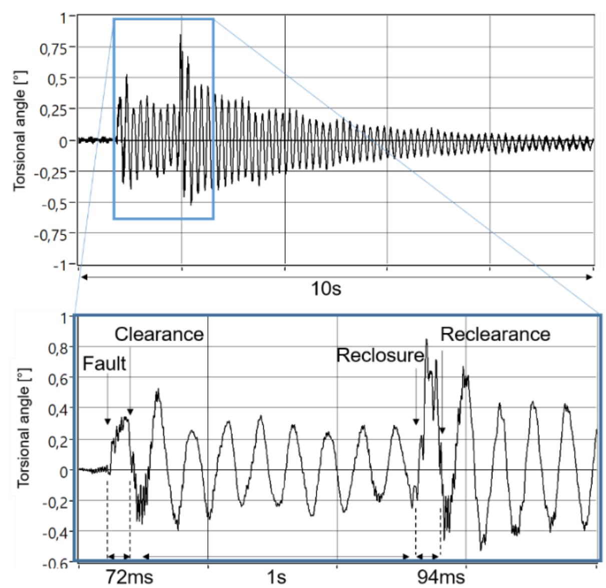

Figure 5: Torsional angle [°] between both shaft ends during a transient event.

Subsynchronous Resonance

SubSynchronous Resonance (SSR) is the term mainly used for torsional interaction of turbo-generator shafts with series-compensated transmission lines. A series capacitor bank is installed in long transmission lines (typically >200km) in order to compensate for its inductance. Doing so, the transmission line becomes an RLC-circuit introducing an electrical resonant frequency in the system which can interact with the torsional resonant frequency and drive the system unstable. Although this is a well-known phenomenon, failures still occur when not accounting for before commissioning of the power plant or the series capacitor bank. Typically, a screening is performed by means of a frequency scan (Grigsby, 2012) in which potential interaction is assessed by modelling the grid under different grid configurations.

Recent catastrophic failures in Vietnam and Peru have raised the awareness in those regions. Frequency scans are being performed for all power plants which are electrically close to the series capacitor bank and torsional vibration monitoring and protection systems are being installed in the power plants at risk. An example is shown in Figure 6. The electrical resonances are clearly visible for the different grid configurations. The shaft line torsional frequency (complement of grid frequency) of interest is shown as well. Sufficient frequency margin exists for all grid configurations.

Recently, a new type of SSR without series compensated lines is described based on reported incidents in China in which a doubly fed induction generator (DFIG) wind farm interacts with the shaft line of a conventional power plant resulting in growing torsional vibration amplitudes (Du, Chen, & Wang, 2017).

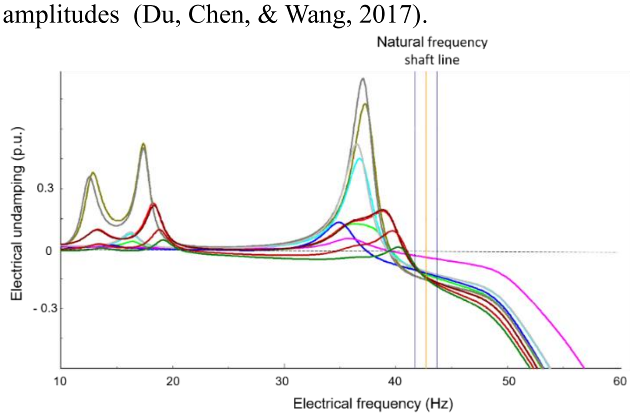

Figure 6: Frequency scan to assess potential SSR condition

Subsynchronous Torsional Interaction

Large-distance connections are most cost-effective using DC transmission in combination with High-Voltage DC (HVDC) stations to convert from AC to DC and vice-versa. HVDC stations are also used to connect isolated wind farms with the AC grid. In the past, subsynchronous torsional interaction (SSTI) has been observed between a Line Commutated Converter (LCC) type HVDC station and a turbo-generator shaft line.

An increasingly number of Voltage Source Converter (VSC) type HVDC stations are being deployed all around the world. In Europe alone, more than 15GW VSC converter stations have been deployed since 2015 and more than 25GW are planned or under construction. The size of the converter stations is also increasing. With currently 1GW stations deployed and 2GW stations in the pipeline, their relative importance compared to the MVA rating of conventional power plants is increasing as well. The relative rating is considered in the Unit Interaction Factor (UIF), a low-level screening concept defined in the 80's following the first observation of HVDC interaction in the Square Butte project (Piwko & Larsen, 1982). More detailed time-domain simulations are used when the UIF exceeds a certain threshold. Up to date, no instances of torsional interaction with turbomachinery have been reported. Some incidents with wind farms though have recently occurred. An improved insight can be gained by measuring both the mechanical and the electrical part during the commissioning of the HVDC station.

Electric arc furnace

The expected effect of HVDC stations can also be assumed from past measurements showing the influence of an electric arc furnace located near the power plant. Indeed, an electric arc furnace introduces a large amount of perturbation on the grid. Power electronics are therefore typically implemented to improve the power quality. This in turn, can introduce effects like those seen for other large power electronic equipment currently used in the energy transition like HVDC systems. If the electrical distance between the arc furnace and the power plant is small, important interaction can occur leading to accumulating fatigue damage. Instances of cracking of the generator retaining ring due to fretting fatigue have been reported. An example of the typical large-varying response is shown in Figure 7 in which the lowest two torsional vibration modes are excited.

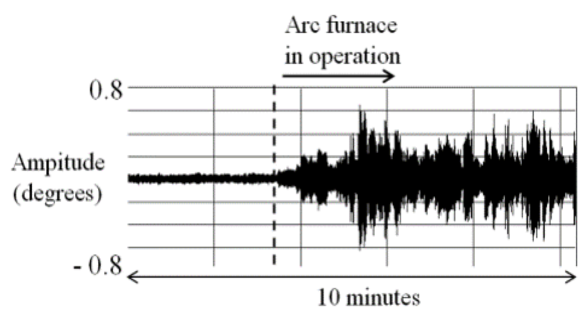

Figure 7: Torsional angle [°] in between both shaft ends is strongly excited when arc furnace is put into operation

CONCLUSIONS

Although torsional vibration issues are typically well addressed in the energy production sector, the increasingly number of grid changes in the current energy transition introduces new phenomena not known a priori. As torsional vibration monitoring systems remain an exception, fatigue damage can accumulate in time and result in shaft cracking without warning. Permanently installed torsional vibration monitoring seems therefore indispensable considering the ongoing energy transition.

REFERENCES

Adrees, A. (2017). *Risk based assessment of subsynchronous resonance in AC/DC systems.* Springer.

Anderson, P., Agrawal, B. L., & Ness, J. E. (1999). *Subsynchronous resonance in power systems.* IEEE Press.

Du, W., Chen, C., & Wang, H. (2017). Sub-synchronous Interactions Induced by DFIGs in Power Systems Without Series Compensated Lines. *IEEE Transactions on Sustainable Energy*.

ENTSOE. (2018). Rate of Change of Frequency (ROCOF) whitstand capability.

EPRI. (2005). *Steam Turbine-Generator Torsional Vibration Interaction with the Electrical Network: Tutorial.*

Grigsby, L. L. (2012). *Power System Stability and Control.*

ISO/FDIS. (2009). *22266-1, Mechanical vibration - Torsional vibration of rotating machinery.*

Piwko, R., & Larsen, E. (1982). HVDC System Control for Damping of Subsynchronous Oscillations. *IEEE Transactions on Power Apparatus and Systems.*