A1 – 834 Session 2022
Study Committee SCA1 / Rotating Electrical Machines
Preferential subject PS1 / Generation Mix of the Future

Robust Design of Nuclear Turbine-Generators and AVRs for increased penetration of renewables and HVDC lines in transmission grids

Mohamed BERRIRI,
Hervé BIELLMANN*
Arnaud BUGUIN
GENERAL ELECTRIC

Stephane BRAEM
Valentin COSTAN
Vincent FERNAGUT
EDF (CNEPE & R&D)

FRANCE
mohamed.berriri@ge.com, herve.biellmann@ge.com, arnaud.buguin@ge.com,
stephane.braem@edf.fr, valentin.costan@edf.fr, vincent.fernagut@edf.fr

SUMMARY

The power transmission grids are evolving towards an ever-greater share of renewable energies, such as wind and solar. In parallel, numerous HVDC transmission lines are being developed worldwide.

The large high-power electronic converters used to connect HVDC transmission lines and most of the renewable power sources are sometimes connected close to nuclear turbine-generators. Transmission System Operators (TSOs) therefore need, in such cases, to perform specific studies to detect any potential resonance interaction phenomena between these high-power electronic converters and the nuclear turbine-generator shaft-lines, and to define appropriate mitigation and/or protection strategies.

This paper provides the reader with explanations about this Sub-Synchronous Torsional Interactions (SSTI) phenomena and their possible consequences on the lifetime of turbine-generator shaft-lines.

It provides explanations about the different mitigation and protection methods that can be implemented by TSOs and utilities at the plant level to mitigate these risks. This includes specific shaft-line mechanical design rules, a review of different monitoring and protection systems, and appropriate design and setting of the excitation control system.

A possible improvement of the AVR control system in order to reduce torsional interactions between nuclear shaft-lines and the power-electronic converters of HVDC stations and windfarms is presented. Based on a typical study case, the effectiveness of a SEDC (Supplementary Excitation Damping Control) is demonstrated.

<u>Sub-Synchronous Torsional Interactions (SSTI) and their possible consequences on turbine-generator shaft-lines:</u>

Initiated by an unbalance between the generator air gap torque and the torque of the steam turbine shaft, the variations in torsional stress excite the natural vibration modes of the shaft-line.

These torsional oscillations may result from different types of grid perturbances:

- Transient (due to synchronization, line switching, load rejection, faults…),
- Continuous (due to unbalanced loads, negative sequence currents…),
- Caused by system interactions between turbine-generator sets and large power electronic converters, or series capacitor compensated lines.

Torsional oscillations can cause torsional stresses at critical locations along the shaft-line, which may consume lifetime of the shaft-line or can in very worst-cases lead to damages.

As early as the 1980s, incidents highlighted the risk of Sub-Synchronous Torsional Interactions (SSTI) between the converter stations of HVDC links and turbine-generator units.

Mitigation methods (shaft-line mechanical design rules, shaft-line monitoring and protections, improvement of the control of the generator excitation currents)

Specific analysis and shaft-line design rules are applied to avoid any risks for the shaft-line resulting from SSTI.

In addition, different types of protections can be installed on shaft-lines that may be exposed to such phenomena. A wide range of protection and monitoring systems is available, from basic technics based on frequency/acceleration measurements, to advanced systems using digital twin technics capable of providing accurate estimations of the constraints at different locations of the shaft-line in real-time.

The optimal control of the generator excitation currents can also play a significant role in the reduction of these torsional oscillations. Indeed, if the action of the PSS (Power System Stabilizer) function of the AVR proves to be insufficient to dampen oscillations, more sophisticated solutions can be evaluated, such as adding numerical notch filters on some of the resonance frequencies measured in the AVR.

Case study: Assessment of SEDC AVR control strategy to reduce SSTI between a nuclear shaft-line and a HVDC conversion station

The goal of this case study is to highlight the performances of certain AVR control modifications on the net damping of torsional modes. An active control strategy of the AVR known as Supplementary Excitation Damping Control (SEDC) is investigated.

For this purpose, an EMT (Electro-Magnetic Transient) model of a simplified test system is developed. It includes detailed models of synchronous turbine-generator, transformers, transmission lines and power electronic converters. The turbine-generator unit is modelled in detail as a lumped parameter model where the coupling between the mechanical and electrical systems is considered. The EMT model includes also a detailed description of turbine-generator protection and power converter control.

EMT simulations are performed and demonstrate the effectiveness of these countermeasures by comparison of net damping. Simulations are conducted considering various operating points of the power plant, in weak and strong grid conditions.

KEYWORDS

Nuclear Turbine-Generator, Increased penetration of renewables, SSR (Sub-Synchronous Resonances), SSTI (Sub-Synchronous Torsional Interactions), SEDC (Supplementary Excitation Damping Control).

1. INTRODUCTION

The power transmission grids are evolving towards an ever-greater share of renewable energies, such as wind and solar. These renewable energy sources, which did not exceed some years ago a very limited percentage of the energy mix of a given country, can today reach in some country's penetration ratios as high as 70% to 80% of the generated power. Several countries even target now 100% renewable energies at long term. These renewable power sources are most of the time connected to the grids by means of very high-power electronic converters.

In parallel, numerous HVDC transmission lines are being developed worldwide. For example, in Europe, expanding electrical interconnections is a pillar of the energy policy. Indeed, by taking advantage of the complementarity of energy situations in different countries, these interconnections are essential to integrating renewable energies. As an illustration of this impressive evolution, France's national Ten-Year Network Development Plan assumes that France's interconnection capacity will double over 15 years, from around 15 gigawatts today to close to 30 gigawatts by 2035, most of these interconnections using HVDC lines and consequently high-power electronic converters [1].

With more and more electrification of the industry, other high-power energy consumers such as big industries sometimes also use high-power electronic converters for their processes. For example, it is expected that the massive need for hydrogen production may require in the future hundreds of gigawatts of electrolysers to be supplied from the grids worldwide.

These very high-power electronic converters are sometimes connected close to conventional synchronous generators, including close to nuclear turbine-generators.

Transmission System Operators (TSOs) therefore need to perform specific studies to detect any potential resonance interaction phenomena between these high-power electronic converters and the nuclear turbine-generators, and to define appropriate mitigation and/or protection strategies.

Since this risk of interactions exists as soon as large renewable power sources such as wind farms are connected close to conventional generator units, TSOs and utilities have started working again actively on this re-emerging topic, in order to write new specifications and recommendations to mitigate this risk.

This paper is structured as follows:

- Section 1: Introduction
- Section 2: Basics of Sub-Synchronous Torsional Interactions (SSTI) and their possible consequences on turbine-generator shaft-lines
- Section 3: Mitigation methods: Shaft-line mechanical design rules
- Section 4: Mitigation methods: Shaft-line monitoring and protections
- Section 5: Mitigation methods: Improvement of the control of the generator excitation currents to reduce risks of SSTI
- Section 6: Case study: Assessment of SEDC AVR control strategy to reduce SSTI between a nuclear shaft-line and a HVDC conversion station

2. BASICS OF SUB-SYNCHRONOUS TORSIONAL INTERACTIONS (SSTI) AND THEIR POSSIBLE CONSEQUENCES ON TURBINE-GENERATOR SHAFT-LINES

Nuclear steam turbines generally include a shaft-line comprising several turbine stages and a generator, forming a complex system.

In normal operation, the shaft-line rotates at a given synchronous frequency, for example 25 Hz, 30 Hz, 50 Hz or 60 Hz depending on the grid frequency and the number of poles of the generator.

However, when rotating, the shaft-line may also be subjected to torsional oscillations.

What are the origins of shaft torsional oscillations?

Shaft torsional oscillations are generated by grid disturbances. As explained in [2], the steady-state operation of a turbine-generator unit is characterized by the equality of the mechanical power collected on the turbine-shaft and the electrical power delivered by the generator to the grid. An electrical disturbance on the grid results in a sudden change in the electromagnetic torque applied on the rotor of the generator. The possible actions on the turbine torque are too slow to be able to instantly compensate for the variations in the electromagnetic torque. A transient imbalance torque therefore appears, which can generate torsional oscillations of the shaft-line. These oscillations can take several seconds to dampen as only few elements contribute to their damping.

These torsional oscillations may result from different types of grid perturbances:

- Transient (due to synchronization, line switching, load rejection, faults,…),
- Continuous (due to unbalanced loads, negative sequence currents,…),
- Caused by system interactions between turbine-generator sets and large power electronic converters (such as HVDC links, large wind farms, arc furnaces,…), or series capacitor compensated lines (this last category being called SSR, for ‘Sub-Synchronous Resonances).

Torsional oscillations cause torsional stresses at critical locations along the shaft-line, which may result, in the case of high amplitudes, in fatigue, fretting-fatigue of shafts, couplings and low-pressure blades. In the worst cases, this may even result in the breakage of the shaft-line.

When do we speak of SSTI (Sub-Synchronous Torsional Interactions) between turbine-generators and HVDC conversion stations or high-power electronic converters of renewable power sources?

The CIGRE Working Group JWG C4_B4_52 (Guidelines for Sub-Synchronous Oscillation Studies in Power Electronics Dominated Power Systems) [3] is currently working on the classification of sub-synchronous resonances between turbine-generators and other equipment connected to the grid, based on the analysis of recent incidents. The report of this working group is scheduled to be published in January 2022.

Sub-Synchronous Torsional Interactions (SSTI) refer to those torsional interactions that may appear when a turbine-generator unit is close to large power electronic converters, such as the conversion stations of HVDC links or large wind farms.

As explained in chapter 6 of [4], this arises because the stator magnetic field resulting from the sub-synchronous currents flowing from the grid into the generator armature winding, interacts with the main magnetic field produced by the turbine-generator rotor. Torque pulsations are thereby produced on the turbine-generator rotor.

How could SSTI result in damages on turbine-generator shaft-lines?

In certain grid conditions, when the electrical resonance is close to a resonance frequency of the shaft-line, these torsional oscillations may occur.
When these oscillations occur at frequencies lower than the synchronous frequency of the shaft-line, they are called Sub-Synchronous Resonances (SSR).

The difficulties for the power plant designers and machine manufacturers come from the fact that these interactions can't always be sufficiently handled on the power station level. As the turbine-generator rotor may interact with the regulating system of the DC power converters or wind-generators, the net torsional oscillation damping (representing coupled electro-mechanical system) can become very low or even negative. In such cases, the damaging fatigue cycles of the shaft-line parts accumulate much faster than assumed in the design. In the worst case, this sub-synchronous instability may even lead to immediate failure of shaft-line parts.

As early as the 1980s, incidents highlighted this risk of sub-synchronous torsional interactions.

This risk has for example been examined deeply in France for the Gravelines nuclear power plant in [5]. On this plant, investigations highlighted a possible risk of torsional interactions between the six 900MW generators in Gravelines and the 2000MW conversion station of the IFA2000 HVDC-LCC link located at 30km. In certain network configurations resulting in low short-circuit power, if no mitigation strategy had been implemented, these interactions could have resulted in a reduction of the damping of the oscillations such that the consumption of the lifetime of the shaft-line would have been significantly increased in case of certain grid events (for example short-circuits close to the generators).

And so, what is the situation today with the rapid increase in the penetration of renewables and HV-DC lines in transmission grids?

Since this period in the 1980s, Transmission System Operators (TSOs) have been used to perform specific studies to identify any potential risks and implement appropriate mitigation and/or protection strategies.

It is worth noting that this topic is more and more current and will be further evidenced in the coming years. Indeed, this risk of interactions exists as soon as large renewable power sources such as wind farms or large HVDC transmission lines are connected close to conventional generator units.

As a consequence, TSOs and other expert groups have, in the past years, started working again actively on this re-emerging topic, in order to write new specifications and recommendations to mitigate risks resulting from these Sub-Synchronous Torsional Interactions.

One may refer for examples to:

- In Europe, the ‘Commission Regulation (EU) 2016/1447 of 26 August 2016 establishing a network code on requirements for grid connection of high voltage direct current systems and direct current connected power park modules (NC HVDC)’ [6],
- In Germany, the ‘VDE/FNN: VDE-AR-N 4131 Technical Connection Rule for the connection of HVDC systems and generation plants connected via HVDC systems’ [7],
- In Germany, the VDE white Paper ‘SSTI Consideration of possible impacts of the operation of HVDC systems in the grid on the shaft trains of turbine-generator sets in power plants’ [8].
- In France, the collaboration initiated between the national TSO (RTE) and EDF in order to develop a method for studying the risks of SSTI [9].

3. MITIGATION METHODS (SHAFT-LINE MECHANICAL DESIGN RULES)

The design of the shaft trains is currently deeply focused to minimize the risk of torsional vibration problems. Torsional vibrations issues are today covered by specific design criteria.
Design rules for torsional vibrations of large steam turbine generators are based on general design philosophies. These rules consist of restricted ranges for torsional natural frequencies and limits for torsional stresses in shaft sections for the load cases "normal operation" and "electrical disturbances in the generator system".

The reason for establishing the torsional natural frequency rule is to avoid resonance of torsional vibrations in normal operation and in the case of electrical disturbances. Torsional vibrations are very lightly damped and therefore a small restricted range is sufficient.

Torsional vibrations are mainly excited by the electrical system of the generator with single and double electrical grid frequency. Torsional vibration modes close to the exciting frequencies, which cannot be excited by the dynamic generator torque, can therefore be accepted if the torsional shaft stress levels at electrical disturbances with variation of the electrical grid frequency are checked.

The allowable torsional stress level for the nominal operation torque should be fulfilled. The guideline value will be used for first dimensioning of the shaft journal diameters. These limits are based on stress amplification factors for electrical short-circuits, experienced in normal operation, short-circuit at generator terminals and mal synchronization. In the case of electrical short-circuits the torsional stress limit is set while yield limit Re(T) on the shaft journal surface is reached.

The design criteria for torsional vibrations of steam turbine generators are such that the torsional natural frequencies should be outside of the frequency range 90% to 110% of the nominal grid frequency fgrid and 180% to 220% nominal grid frequency fgrid.

A torsional frequency value in the ranges of 90% to 94% and 106% to 110% of the nominal grid frequency fgrid or 180% to 184% and 212% to 220% may be acceptable if the stress levels in the shaft journals are allowable for the electrical standard disturbances with an applied grid frequency of 94% fgrid or 106% fgrid, whichever is nearer the natural frequency concerned (with fgrid ... nominal grid frequency).

A particular attention should be taken for potential coupling with large blade stages which may induce coupled modes with the rotor shaft-line associated with deformed shapes that can be excited by torsional excitation.

Special customer specifications or contract requirements can confirm or go beyond these general design rules. This may include for example:

- All natural torsion frequencies for the shaft-line shall have a minimum margin of +/-5% as compared with the frequency of the electrical network and its multiples; To witness this specification, the manufacturer shall provide a forecast study of the natural torsion frequencies of the shaft-line. This study takes into account any excitability that may exist for the flexible blades.
- The manufacturer shall forward an evaluation of the integrity of the main blades due to shaft line torsional excitation under electrical faults.

- The manufacturer shall forward an evaluation of the resistance shown by the rotors and coupling to torque level due to torsional (and rotary flexion) fatigue, taking normal operation as well as exceptional (exceptional load ramp up, house load, network faults normally eliminated,…) or accidental (accidental generator operating conditions including out of phase synchronization, short circuit,…) conditions defined by the customer. That assessment is provided in the form of an estimation of the consumption for the service life. This assessment considers preexisting defects in the forgings and the welds originated from the manufacturing process with a size just below the resolution limits used for ultrasonic testing, and then not detected during inspection.
- The manufacturer shall provide manufacturing inspection plan in coherence with such hypothesis.
- A rotor inspection procedure shall be forwarded to be executed during plant shutdowns, searching for any defects in the sensitive zones.
- The customer may request a check on site of the torsional behavior of the shaft line, mainly for the first of a kind shaft line train design.

4. MITIGATION METHODS (SHAFT-LINE MONITORING AND PROTECTIONS)

A typical nuclear turbine-generator is equipped with appropriate instrumentation to monitor lateral vibrations. However, this lateral vibration instrumentation is incapable of measuring the torsional response of a turbine-generator resulting from sub-synchronous resonances. Consequently, significant torsional vibration can be occurring for a turbine-generator without any warning from the lateral vibration instrumentation prior to a significant failure. [4]

Different types of monitoring and protection systems have consequently been developed, with different levels of complexity and accuracy, to protect shaft-lines that may be subject to high sub-synchronous resonance constraints.

It has originally been proposed to monitor the strain on the shaft-line by means of strain gauges placed on the shaft. However, this solution is not widely used, since it is complicated to install, it has low reliability over time, and so it is usually used only for punctual assessments and not for permanent monitoring of the shaft.

For permanent monitoring, different alternative solutions to the strain gauges have been developed, using different methods to protect the shaft-line against torsional constraints.

Here below are given some examples of such protection systems based on different measurement and protection methods. Depending on its mitigation and protection strategy, the utility may select the most appropriate solution:

A: Torsional Stress Relay (TSR), using shaft-line speed measurement [10],

B: Generator protection relay, using phase voltage and/or current measurements at the generator terminals [11],

C: Model-based monitoring systems, using shaft-line speed measurement [12&13],

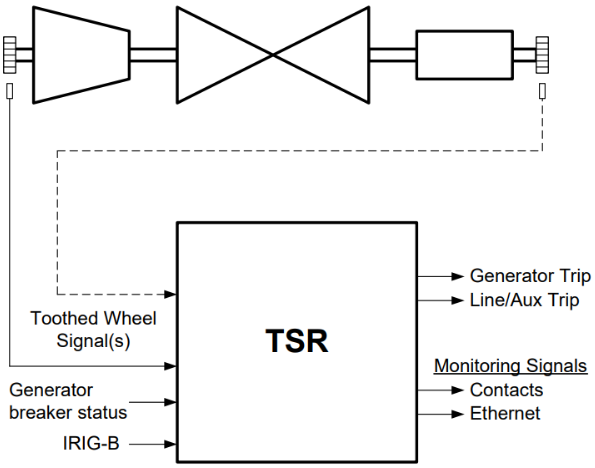
D: Combination of both electrical method (B) and model-based method (C).

E: Protective solutions integrated with the turbine controller, using shaft-line speed measurement [14],

A. Turbine-Generator Torsional Stress Relays (TSR)

One may refer to **[10]** for an example:

This is a basic, proven, and reliable solution, that has now been implemented for decades. Below pictures show a typical equipment scope for such a protection:



Typical configuration of TSR for one turbine-generator, with either one or two toothed wheels

The equipment includes toothed wheels and associated sensors to allow **speed measurements** at one or several locations of the shaft-line. Measurement signals are sent to the dedicated protection cubicle, in which they are sampled at a high rate and digitally band-pass filtered at each torsional frequency to produce signals proportional to the magnitude of vibration for each mode. Each “modal speed” signal can then be used in with different protection logic strategies such as ‘inverse time fatigue trip’ or ‘steady-state instability trip’.

B. Generator protection relays with embedded sub-synchronous protection function

One may refer to **[11]** for an example:

Here, a different approach consists in measuring the **phase voltages and/or currents** at the generator terminals, and use them to provide protections such as a sub-synchronous protection of the generator or a detection of sub-synchronous interactions between HVDC links and the generator. These protections are generated by means of advanced algorithms embedded and tunable in the generator protection relay software.

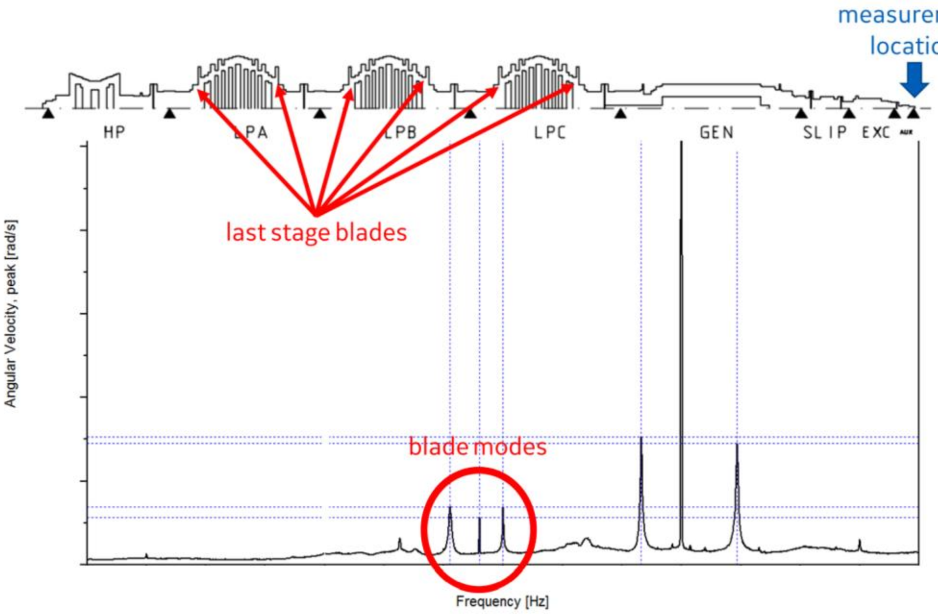
This type of protection does not require additional measurement sensors or equipment. But its implementation for an accurate torsional protection of the whole shaft-line needs to be carefully evaluated since it does not include any accurate estimation of the real torsional torque constraints over the whole shaft-line length.

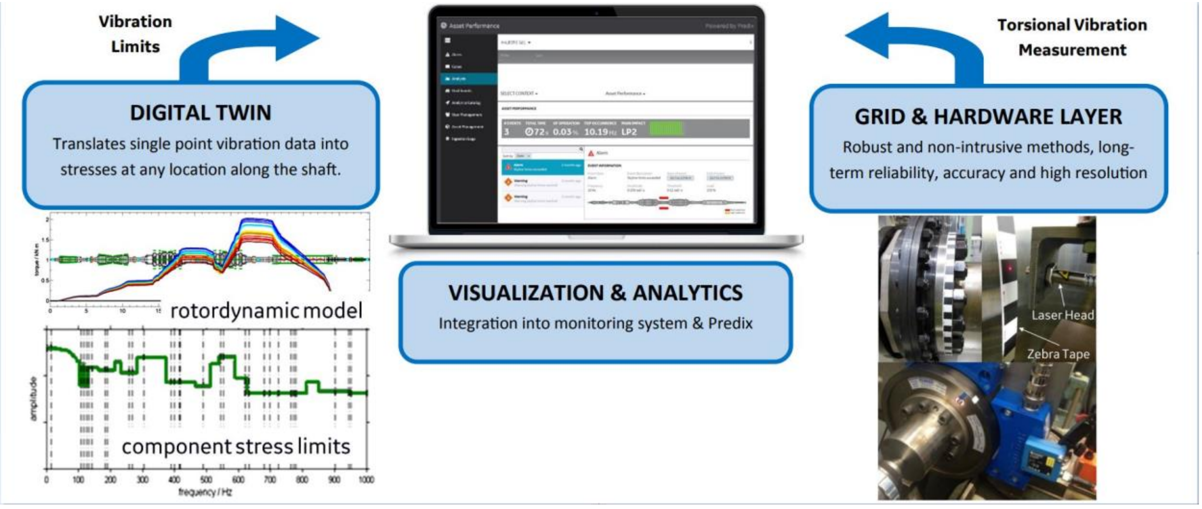
C. Mechanical model-based monitoring systems

One may refer to [12,13] for an example:

This example shows a more advanced and accurate solution to estimate torsional vibrations at different locations all along the shaft-line length consists in using model-based monitoring systems (also called '**digital twins**').

In such systems, the combination of the accurate measurement of angular vibrations at a suitably selected location on the shaft-line, with a detailed rotor-dynamic model embedded in the monitoring and protection cubicle, allows the reliable evaluation of the alternating torque levels in all machine sections along the shaft-line in real time, as shown in below pictures:





D. Combination of both electrical method (B) and model-based method (C)

Of course, combining the two precedent methods into one single common monitoring and protection system based on the measurements of both mechanical and electrical parameters results in the most optimal and robust protection of the saft-line.

Nevertheless, this may result in very onerous investment and maintenance costs that may not be justified.

E. Protective solutions integrated with the turbine controller

One may refer to [14] for an example:

In most of the cases where a basic but robust sub-synchronous shaft-line protection is sufficient, the plant designer may consider using protective solutions integrated with the turbine controller.

Such very cost-competitive protections, using for example the usual speed sensors already mounted in the shaft-line and connected in the turbine governor controller, together with advanced algorithms, are capable to generate an alert or trip signal when the amplitude of certain shaft-line torsional levels exceed predetermined thresholds.

This cheap but robust solution is currently being proposed on new nuclear turbine-generators being currently developed.

5. MITIGATION METHODS: IMPROVEMENT OF THE CONTROL OF THE GENERATOR EXCITATION CURRENTS TO REDUCE RISKS OF SSTI

In order to reduce the Sub-Synchronous Torsional Interactions (SSTI) between the shaft-line generators and the power electronic converters of the HVDC links or other large power converters such as wind farms, specific attention needs to be taken when designing the excitation system of the generator and its Power System Stabilizer (PSS) control function.

The torsional resonance oscillation frequencies of the shaft-line being well determined by mechanical analysis performed during the design of the plant, the control of the AVR can be optimized accordingly.

Different improvements of the excitation control system PSS can be evaluated and implemented to dampen the oscillations that could be generated by the excitation current of the generator.

This may include:
- Numerical notch filters on some of the resonance frequencies measured in the AVR in order to reduce the excitation source.
- Active strategies, known as ‘Supplementary Excitation Damping Control’ (SEDC), as explored in chapter 6 of this document.

It is worth noting, that these Sub-Synchronous Torsional Interactions (SSTI) may also be reduced in some cases by modifications implemented directly in the HVDC control system by means of Supplementary Sub-Synchronous Damping Control (SSDC). [15]

Some grid codes may already include requirements or guidance to reduce the risk of interactions between conventional generators and other plants. This may be found for example in chapter CC.A.6.2.5.5 and CC.A.6.2.6.1 of the UK’s national grid code [16] which recommend specific bandwidth for the output signals of excitation systems and PSS systems.

6. CASE STUDY: ASSESSMENT OF SEDC AVR CONTROL STRATEGY TO REDUCE SSTI BETWEEN A NUCLEAR SHAFT-LINE AND A HVDC CONVERSION STATION

The goal of this section is to highlight the performances of certain AVR control modifications on the net damping of torsional modes. Active strategy known as ‘Supplementary Excitation Damping Control’ (SEDC) was investigated.
For this purpose, an electro-Magnetic transient (EMT) model of a simplified test system was developed. The adopted test system is shown in Figure 1 and it consists of three branches: synchronous generator (SG) branch, HVDC-VSC link branch and a branch with an infinite source behind an equivalent impedance.

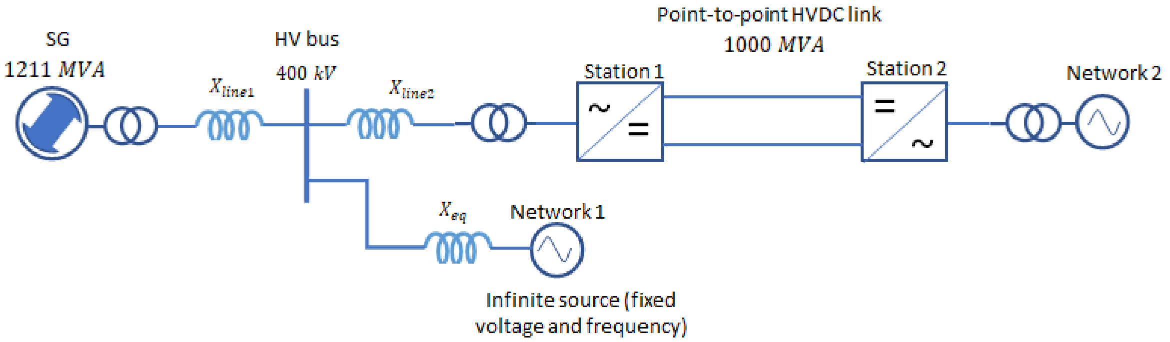


Figure 1: Simplified test power system

The equivalent reactance of the network branch (Network 1 in Figure 1) can be varied in order to represent strong or weak grids and different values of UIF (Unit Interaction Factor):

$$S_{cc\_nb}=\frac{\left(1-\sqrt{UIF\frac{MVA_{sg}}{MW_{hvdc}}}\right)S_{cc\_sgb}}{\sqrt{UIF\frac{MVA_{sg}}{MW_{hvdc}}}}$$

Where:

- Scc_nb is the short-circuit power of the network branch,
- Scc_sgb is the short-circuit power of the synchronous generator branch,
- UIF is the Unit Interaction Factor as defined in [17].

The EMT model includes detailed model of turbine-generator protection and HVDC converter control and it requires:

- Synchronous Generator (SG) electrical data,
- Data for the mechanical mass-spring-damper system,
- Details of generator controllers (AVR, PSS),
- Electric network topology and corresponding electrical data,
- Electric data for HVDC converter,
- Data and structure for the HVDC controllers.

In this power system it was considered a nuclear power plant with torsional frequencies given in the table below, and situated at the proximity of a HVDC-VSC link. Regarding the latter, a generic EMT model [18] was used, assuming the station is in rectifier operating mode.

Mode (i)	Frequency (fi) (Hz)	Modal inertia (H_i) (s)	Decrement factor (σ_i) (1/s)
1	6.28	2.62	0.071
2	11.98	3.21	0.262
3	15.96	1.49	0.437
4	17.32	62.55	0.324

Table 1: Torsional shaft system data

The values of the modal inertia (H_i) and decrement factor (σ_i) are obtained from the modal analysis performed on the mass-spring-damper system.

It was assumed that the SG is equipped with a typical static excitation system ST7B [19] and a power system stabilizer type PSS2B [19] tuned to enhance the damping of the electromechanical oscillations.

SEDC is an extension of the PSS concept used for torsional frequency oscillation damping [20], and it can be implemented for large synchronous generators. A damping reference based on external measurements such as rotational speed is added to the AVR (see Figure 2). The controller will produce an electrical torque component on the rotor which will be in phase with the speed variation to provide additional damping to the mechanical system.

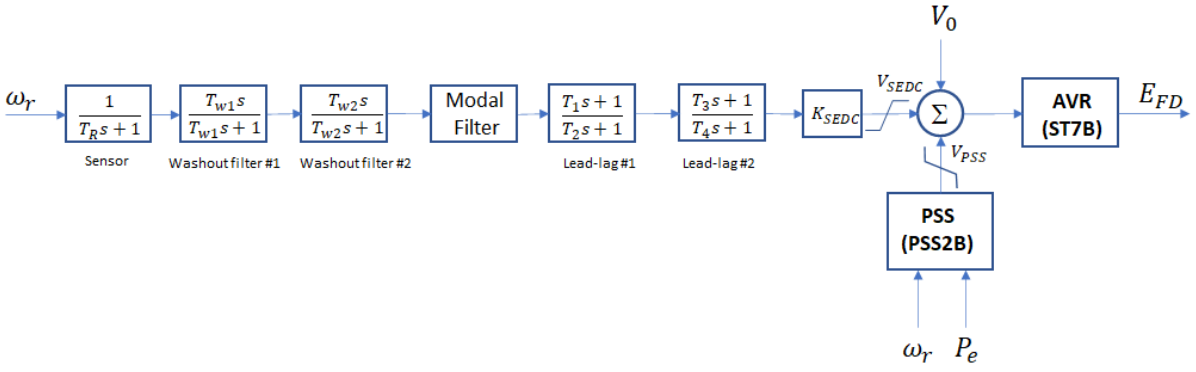


Figure 2: SEDC control structure

Each mode is isolated from the relevant speed signal using band pass filtering (modal filter in Figure 2). The necessary phase and gain compensation are applied to each torsional mode and the summed signal is used to control the excitation voltage.

In this example, the SEDC was designed to provide positive damping to the first torsional mode (6.28 Hz).

Firstly, the effectiveness of this SEDC loop has been verified by calculating the electrical damping and using the method of complex torque coefficients [21]. Simulations results are presented in Figure 3. It can be observed that, without SEDC loop, in weak grid conditions (UIF=0.3), inside the frequency range of the torsional modes, the electrical damping coefficient (D_e) is negative which means a reduction of the net damping (D_{net}) of these modes:

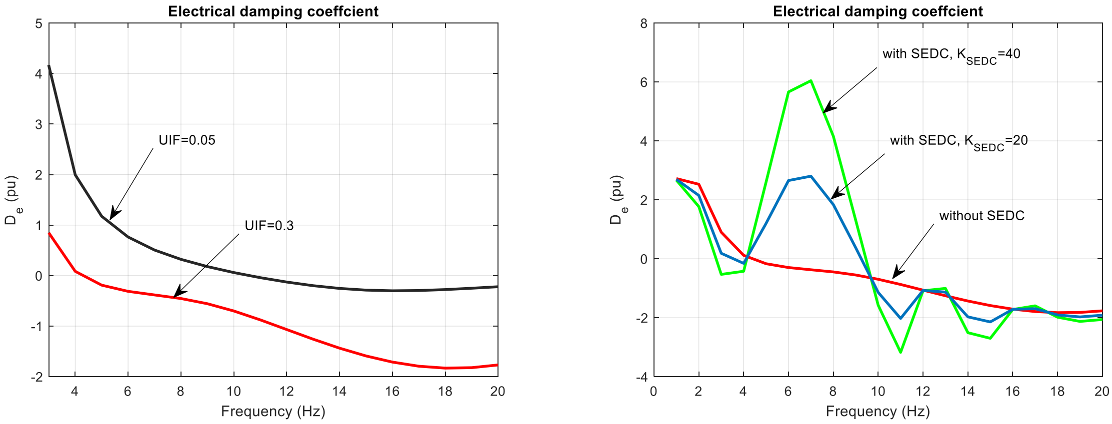
$$D_{net}(f_i) = D_e(f_i) + D_m(f_i)$$

where $D_e(f_i)$ and $D_m(f_i)$ respectively, are the electrical and mechanical damping for the *ith* mode.

In weak grid conditions, the first torsional mode (6.28 Hz) of the turbine-generator is poorly damped characterized by a low value of the net decrement factor σ_{net1}:

$$\sigma_{net1} = \frac{D_{net1}(f_1)}{4H_1}$$

As shown in Figure 3b, the SEDC loop allows introducing a positive electrical damping for the concerned torsional frequency (6.28 Hz) and the presence of this loop has an insignificant impact on the other modes of the turbine-generator, including the electrotechnical mode.



a) b)

Figure 3 Electrical damping: (a) without SEDC in weak and strong grid conditions, (b) damping effect of SEDC.

Based on the small-signal approach, the damping ratio ξ *(%)* of the first torsional mode was calculated for different values of UIF. Figure 4 shows that ξ decrease when UIF increase and the effect of the SEDC loop is to increase the damping ratio of this mode.

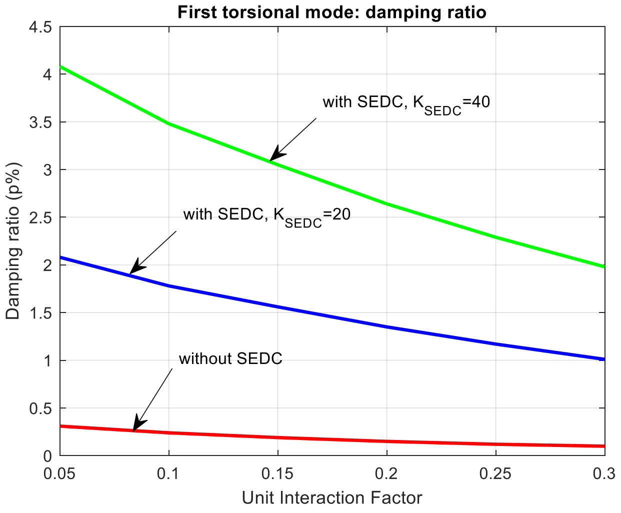
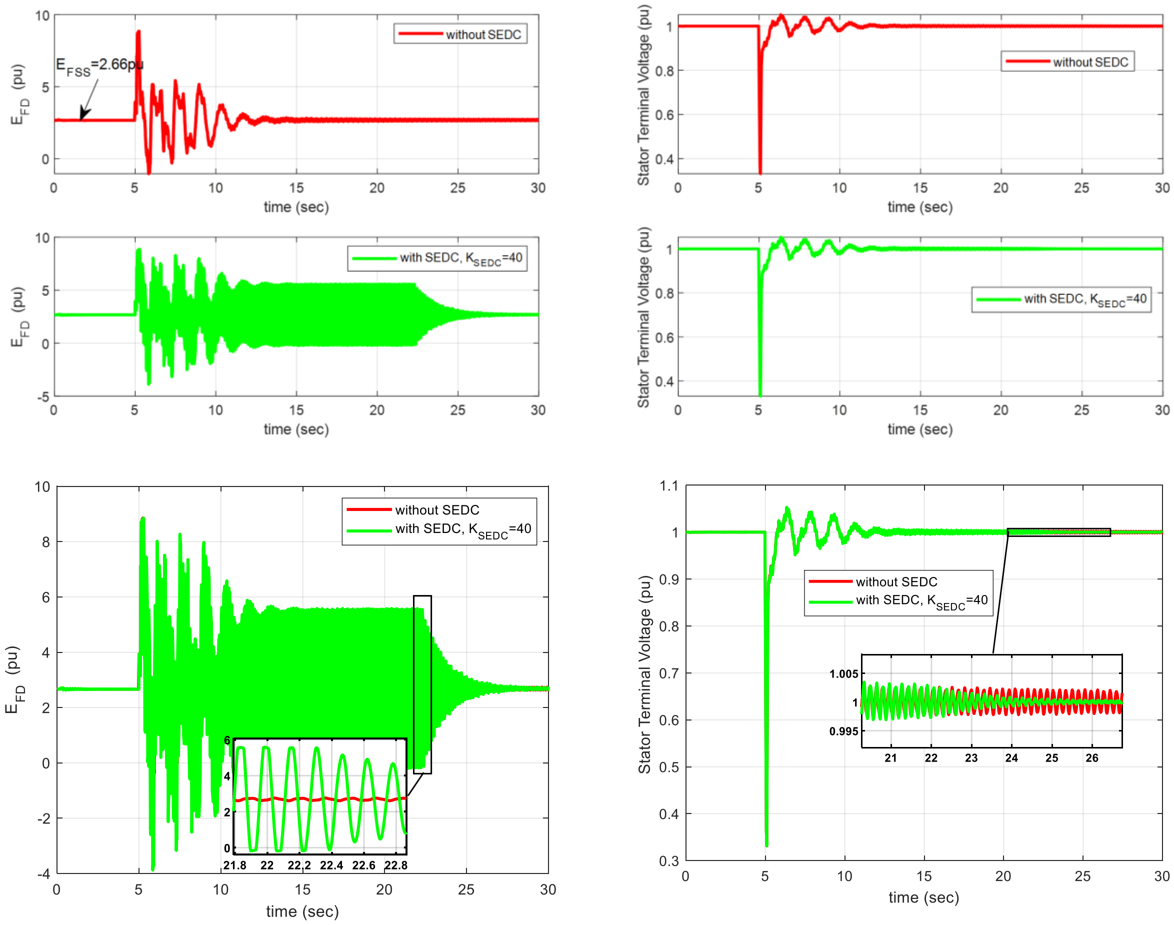


Figure 4 : Damping ratio (ξ) of the first torsional mode (6.28 Hz)

Secondly, the dynamic performances of the SG controllers (AVR, PSS, SEDC) were evaluated considering:

- large disturbances such as short-circuit fault at the point of common coupling of the turbine-generator,
- weak grid conditions, *UIF=0.3*.

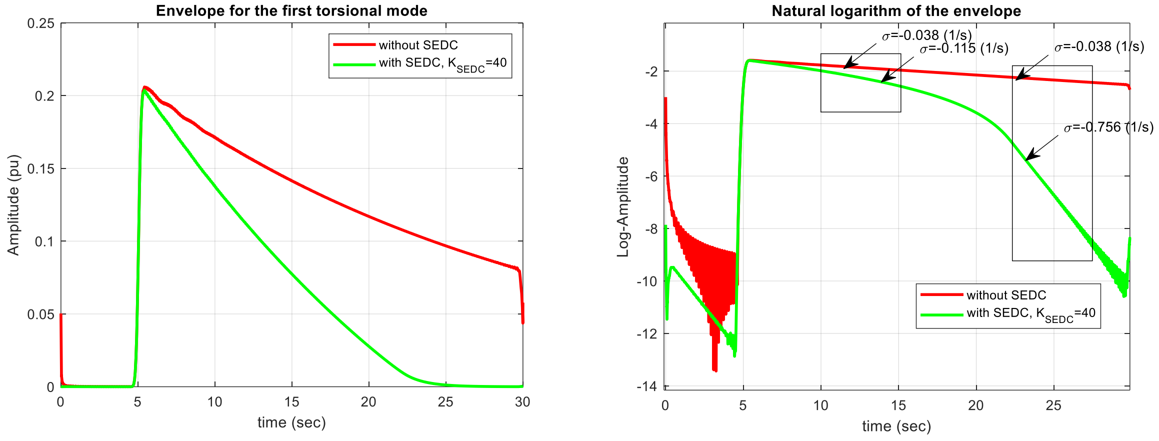
The simulation results are shown in Figure 5 when the fault occurs at 5s and supposing a fault clearing time of 85ms. It can be noted that the presence of the SEDC loop does not affect the stator voltage recovery after the fault clearing then, postfault response still satisfactory.
The SEDC in service, the output of the AVR reaches the limits in post-fault conditions.



a) b)

Figure 5 : AVR response: (a) Field Voltage (E_{FD}) (b) stator terminal voltage

The goal of these simulations was to evaluate if the SEDC can provide damping in large transient when the AVR output reaches the specified limits.
To achieve this, the response first torsional mode oscillation was analyzed. Knowing the mode frequency (6.28 Hz), the mode was extracted from the rotor speed signal using the continuous wavelet transform (CWT). The wavelet coefficient envelope of the mode frequency is found using the Hilbert transform. Taking the natural logarithm of the envelope plot, the net decrement factor (σ_{net1}) is obtained.
The results of this post-processing are presented in Figure 6. It can be observed that, even if the AVR output limits are reached, with the SEDC loop the decrement factor is improved. When the AVR output desaturates, the decrement factor changes (the slope of the natural logarithm changes around 22 s), and this calculated value corresponds to that found based on the small-signal approach.



a) b)

Figure 6 : First torsional mode oscillation (a) envelope plot (b) natural logarithm

Conclusion of this case study:

The simulation results presented in this chapter demonstrate the effectiveness of the SEDC loop in both small-signal domain and large disturbances: The improvement of the damping of the torsional oscillations is demonstrated, while no degradation of the performance of the AVR during grid perturbances (short-circuit at HV side of the PCC) are found.

In the present study, the SEDC was implemented to damp the resonances on only one torsional mode (6.28Hz). If necessary, such control could be applied to other torsional modes.

This study is the first step towards possible improvements of the control of PSS functions in generator AVRs in the future.

CONCLUSION

As explained in the present paper, risks of Sub-Synchronous Torsional Interactions (SSTI) between turbine-generators and the power electronic converters of HVDC links and large wind farms are re-emerging due to the increased penetration of these systems in electrical grids.

This paper explains the phenomena and the resulting risks for the safe operation of steam-turbine nuclear shaft-lines, which may consume lifetime of the shaft-line or could in the very worst-case lead to damages.

It provides explanations about the different design mitigation and protection methods that can be implemented by TSOs and utilities at the plant level to mitigate these risks. This includes specific shaft-line design rules, a review of different monitoring and protection systems, and appropriate design and setting of the excitation control system.

A possible improvement of the AVR control system in order to reduce torsional interactions between nuclear shaft-lines and the power-electronic converters of HVDC stations and windfarms is presented. Based on a typical study case, the effectiveness of a SEDC (Supplementary Excitation Damping Control) is demonstrated.

The interactions between the different production assets connected to a same electrical grid depend on the inherent characteristics of these production assets and of this grid. Therefore, the strong cooperation between experts from different field areas such as electrical grid designers, turbine-generator designers, power-electronic converter designers and controls engineers, is a key factor to study appropriately these risks of interactions, and define the best mitigation methods to ensure a safe operation of the power transmission systems worldwide.

BIBLIOGRAPHY

[1] https://bilan-electrique-2020.rte-france.com/reseau-de-transport-interconnexion/?lang=en

[2] D. Souque, D. Vielpeau “turbo-alternateur et réseau : une cohabitation parfois difficile” (Epure 1988)

[3] https://www.cigre.org/userfiles/files/News/2018/TOR-JWG%20C4_B4_52_Guidelines%20for%20Sub-synchronous%20Oscillation%20Studies%20in%20Power%20Electronics%20Dominated%20Power%20Systems.pdf

[4] “Steam Turbine-Generator Torsional Vibration interaction with the Electrical Network” (EPRI, December 2006)

[5] D. Bornard, D. Souque, D. Vielpeau “interactions torsionnelles entre les groupes de Gravelines et l’interconnexion France-Angleterre de 2000MW : protection des groupes turbo-alternateurs” (CIGRE 1988)

[6] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32016R1447&from=EN

[7] VDE/FNN: VDE-AR-N 4131 Technical Connection Rule for the connection of HVDC systems and generation plants connected via HVDC systems

[8] https://www.vgb.org/vgbmultimedia/VGB+WhP_SSTI+EN+FINAL_update08_2021-p-16566.pdf

[9] https://www.services-rte.com/en/learn-more-about-our-services/interaction-studies-survey-of-interests.html

[10] https://www.geenergyconsulting.com/content/dam/Energy_Consulting/global/en_US/pdfs/TsrApplications04d.pdf

[11] https://library.e.abb.com/public/ace00682ffe14daa9ba19c543160f996/1MRK502071-UEN_D_en_Application_manual__Generator_protection_REG670_version_2.2_IEC.pdf?x-sign=anDlowB0U8Of+r/cpwJ1q+PNyVc55Vf2b69zcONIYb+KlRMtbvqGf12PuTjfF3dv

[12] “Steam Turbine Digital Solutions - Turbine Torsional Vibration Advisor Package – fact sheet” (General Electric, document N°GEA33462, September 2017)

[13] Torsional Vibration Measurement and Model-based Monitoring in Todays Reality of Power Generation Business (SIRM 2019 – 13th International Conference on Dynamics of Rotating Machines, Copenhagen, Denmark, 13th – 15th February 2019)

[14] https://patentimages.storage.googleapis.com/14/d1/27/5e7925018523c1/US20160033321A1.pdf

[15] T. Rauhala and P. Järventausta, *On feasibility of SSDC to improve the effect of HVDC on subsynchronous damping on several lower range torsional oscillation modes*, *IEEE PES General Meeting*, Providence, RI, 2010, pp. 1-8, doi: 10.1109/PES.2010.5590190

[16] https://www.nationalgrid.com/sites/default/files/documents/8589935310-Complete%20Grid%20Code.pdf

[17] EPRI Report, EL-2708, « HVDC System Control for Damping Subsynchronous Oscillations », Final Report of Project RP1425-1, October 1982

[18] CIGRE WG B4.57. (2014). Guide for the Development of Models for HVDC Converters in a HVDC Grid (CIGRE - 604). Katalog BPS, XXXIII(2), 81–87. https://doi.org/10.1007/s13398-014-0173- 7.2

[19] IEEE Recommended Practice for Excitation System Models for Power System Stability Studies. IEEE Std 421.5-2016 (Revision of IEEE Std 421.5-2005), 2016, pp. 1–207, https://doi.org/10.1109/IEEESTD.2016.7553421

[20] K. R. Padiyar, *Analysis of Subsynchronous Resonance in Power Systems*, London, U.K: Kluwer, 1999

[21] Tabesh, A., Member, S., & Iravani, R. (2005). On the Application of the Complex Torque Coefficients Method to the Analysis of Torsional Dynamics, *20*(2), 268–275