Doc. no. E00010947/0050-NPRR562-01
Date 2013-08-22
From John P. Daniel
Phone +1 919 856 3306
E-mail john.daniel@us.abb.com
Fax +1 919 807 5060

Technical Memorandum

Comments on ERCOT NPRR562 and Other Informational tems - 2013-08-22

To	Paul Bell, Ken Donohoo - Oncor
Copy to	Willie Wong – ABB

Background

Oncor has asked ABB to comment on the draft ERCOT Nodal Protocol Revision Request number 562 (NPRR 562) posted August 12, 2013. ABB's observations of, comments on and questions about the NPRR are provided below.

In addition, Oncor asked ABB to help develop information in four specific items related to the issues addressed in the NPRR. These items are as follows:

- Determine what kind of damage can occur at a wind generation resource (WGR), conventional generator or transmission device due to subsynchronous resonance interactions or other harmful equipment-to-equipment interactions
- Determine what kind of damage can occur at a WGR due to other equipment-to-equipment interactions.
- Develop a complete list of devices that can cause harmful interactions with WGRs and conventional generators.
- Can similar interactions occur with photovoltaic or solar/steam generators? If yes, what are these interactions?

The comments regarding the NPRR are first, with general observations followed by point-wise observations. ABB's input on the additional items is after these point-wise observations.

NPRR 562 Observations, Comments and Questions

<u>*General Observations*</u>

Overall, it is ABB's opinion that the NPRR is striving to address multiple, distinct phenomena in a common overall document. While the phenomena are related in many ways, the differences among the phenomena are likely to be better addressed individually instead of as a single NPRR.

If it must be a single NPRR, one way to handle it would be to broaden the title to "Subsynchronous Issues" or "Subsynchronous Oscillations" with three major sections dealing with

1. SSR, meaning the torsional interactions between series capacitors and turbine-generators
2. SSTI, meaning the torsional interactions between turbine-generators and transmission-level active devices

3. Induction generator effects, meaning interactions involving the electrical network only between series capacitors and generation resources (synchronous and wind turbines – especially DFIG).

A preferable way to address this would be to have three different documents, each addressing one of the above separately. This will avoid the confusing and cumbersome nature of address all of them in a single document.

In discussing the phenomena and how study of the phenomena should be handled, ERCOT has defined several terms. The definitions provided reflect some usage that has been common in the discussions surrounding the study of the ERCOT CREZ system. At times these usages have been in conflict with terms and definitions established by IEEE in the mid-1980s, and at other times they are misnomers which attribute the cause of the phenomena to a secondary effect instead of the primary cause. As such, ABB recommends that a review of the IEEE document "Terms, Definitions and Symbols for Subsynchronous Oscillations," produced by the IEEE Subsynchronous Resonance Working Group [1] be made and the appropriate definitions used in order to maintain consistency in the industry. If it is found that a new phenomenon truly exists and warrants a new definition, it can be recommended in the NPRR and should probably be formally recommended through the IEEE. A similar appeal for clarity in terms was also made in [2].

In the comments below, ABB has tried to apply the definitions of [1] to the best of their understanding.

Point-wise Observations

Section / Statement	**Comment**
NPRR Title Subsynchronous Resonance	As mentioned previously, ABB believes that the multiple phenomena discussed in this NPRR are better treated as separate documents. However, if it is determined that they will treated in a common document a more accurate title – in keeping with [1], is "Subsynchronous Issues" or "Subsynchronous Oscillations"
Reason for Revision *"The ERCOT System has recently become more vulnerable to SSR because of the introduction of series capacitors for voltage support..."*	Voltage support is probably not the primary reason for application of series compensation. It is a secondary benefit that occurs arising from the reduced fundamental frequency impedance in the network due to the series capacitors. The reduced impedance provides smaller voltage angle differences between the bus voltages at either end of the series compensated line, improved power transfer capability, and often improved system stability with better voltage profiles across many buses. "Voltage support" is primarily provided by shunt compensation.

Section / Statement	**Comment**
Reason for Revision *"... although other transmission elements (including poorly tuned power electronic devices) and generator control systems can also create SSR."*	Here is one area where the different phenomena become incorrectly conflated. The interaction between power electronic devices and generators is not SSR because there is no system resonance involved. It is, instead a result of the action of the controls of active devices. This type of interaction best falls under the definition in [1] of Torsional Interaction (TI), although [1] discusses TI in terms of the electrical system natural frequency, so even this doesn't quite fit. As such, it has become common practice in the industry to call such interactions between transmission-level power electronic systems with torsional modes of nearby machines Subsynchronous Torsional Interactions (SSTI).
Reason for Revision *"Without proper mitigation, SSR can quickly destroy ..."*	If discussing SSR in the simple terms of a resonance occurring in the subsynchronous frequencies, it is not strictly necessary to mitigate all SSR. Not all resonances in the subsynchronous frame result in difficulties. Only those that create difficulties need mitigation. This sentence could properly be re-phrased to be "Detrimental subsynchronous oscillations, if not properly mitigated, may quickly destroy the Transmission Elements and/or Generation Resources involved. This can lead to cascading outages across the system.
2.1 Definitions *"Subsynchronous Resonance ...."*	ABB again recommends using a more general term of *Subsynchronous Oscillations* or *Subsynchronous Issues*. The SSR Working group in [1] specifically defines SSR as encompassing the "...oscillatory attributes of electrical and mechanical variables associated with turbine-generators when coupled to a series capacitor compensated transmission system where oscillatory energy interchange is lightly damped, undamped, or even negatively damped and growing." Since mechanical variables are involved, the issues often result in frequencies that are supersynchronous from the stator reference frame but subsynchronous on the rotor reference frame. In conjunction with this, it is noted that the classic papers from the 1970s-1990s tend to call the torsional interaction caused by resonances "SSR."
2.1(a) *"Subsynchronous torsional interaction"*	Based on the definition given, it would be best to simply state this as "Torsional Interaction" Although not strictly defined in [1], SSTI has a history in the industry of being related to the operation of active devices and turbine-generator shafts, whereas Torsional Interaction encompasses this meaning along with that associated with classical "SSR" studies that consider the possible destabilization of the mechanical torsion modes due to network resonances.

Section / Statement	**Comment**
2.1(a) (b) *"Subsynchronous torsional interaction… Induction generator effect"*	Please note that in [1], *Torsional Interaction* and *Induction Generator Effect* are identified as subcategories of *Self-Excitation*. Reference [1] provides a good summary of these issues. Therefore, it is suggested that the NPRR be limited to self-excitation phenomenon and a separate NPRR be issued for SSTI – meaning the torsional interaction between active transmission-level devices and generators.
2.1(b) *"Induction generator effect…"*	Note that the effect is not caused by a negative resistance "in the armature" of a synchronous resource. It is caused by a negative apparent resistance of the rotor as reflective to the armature due to slip relative to the speed of the subsynchronous frequency wave in the machine airgap – and it occurs in both synchronous and asynchronous machines. It tends to be more likely with asynchronous machines because of larger rotor resistances by design or because of the apparent rotor resistance due to the action of a converter connected to the rotor windings.
2.1(c) *"Subsynchronous control interaction"*	While this is becoming a common term, it is a misnomer. It suggests that the cause of the effect is the interaction of the controls with the series compensation. In reality, this phenomenon is simply the self-excitation of an asynchronous machine in which the converter controls of a doubly-fed induction machine exacerbate the apparent negative resistance of the rotor as reflected to the machine stator/armature. It is simply *Self-Excitation* – *Induction Generator Effect* and should be categorized as such. While adjustments to appropriate control gains may eliminate undamped and negatively damped self-excitation this is because reducing the gains reduces the apparent resistance of the rotor at selected operating points. In the actual event reported on the ERCOT system at Zorillo, while it is probable that the rotor-side converter's controls creating a large apparent resistance on the rotor – which becomes negative when reflected to the stator – was the primary cause of the initial event, the protection likely fired very quickly. If the crowbar consisted of large resistors switched in across the converter and the rotor windings, when it was switched in for protective purposes it would likely have sustained the event. Once the crowbar fired, no controls would be involved and the event is classical induction generator effect.

Section / Statement	**Comment**
<u>*3.21.1 (1)*</u> *"This evaluation shall include system-side frequency scans and any other appropriate measures and shall assess the risk of SSR..."*	How are the system-side frequency scans going to be used? What are the criteria to eliminate a bus from having a risk? What are the "other appropriate measures" and how will they be applied? Caution <u>must</u> be exercised here, especially since it is not defined how the system-side scans will be used to assess the risk (or lack of it) or what the "other appropriate measures" may entail. The system-side scans can help eliminate certain buses from the need to evaluate induction generator effects (self-excitation of the machine electrical system). For example, IGE can only occur if the total <u>*reactance*</u> of the system as seen from a point on the rotor is zero and is a problem only if the total <u>*resistance*</u> seen from that point is also zero or negative [3]. System-side scans ignoring the machines can then find conditions where IGE is impossible, because the system itself, even without the additional impedance of the machines, does not allow the necessary conditions to exist. Similarly, a bus could be eliminated from potential torsional interaction (TI) risk if it can be shown that the <u>*electrical damping*</u> of the system alone, which would be applied to a hypothetical generator at that bus, *never* produces a destabilizing influence at *any* subsynchronous frequency (rotor reference frame) for which a machine torsional mode may exist. If a bus cannot be shown to be free from IGE or TI risk, more complete evaluations are required. Further, even if no specific IGE or TI risk is found, it should be remembered that transient torques may still become large under some conditions simply because of the changes in network impedance that occurs around the resonance frequency, regardless of whether or not sustained oscillations will occur.
<u>*3.21.1 (1)*</u> *"If ERCOT's initial evaluation shows a risk of SSR in the case of five or fewer simultaneous Outages ... For the purposes of this Section, the Outage of a double-circuit transmission line shall be considered a single Outage."*	While there may be some argument for doing this from the standpoint of determining "how bad to things have to get before there is an SSR problem," it does not seem reasonable to require a Full Interconnection Study for conditions under which the transmission system has collapsed or is otherwise unstable. If there are 5 Outages, this may actually be ten (10) network elements out of service (per the ERCOT Outage definition) *in close proximity to the bus being evaluated.* Even if an SSR risk can be determined based on frequency scans, a secondary assessment should be made to determine if the system can survive in terms of voltage and transient stability under such conditions, while still allowing the bus being evaluated, near-by generation and the series compensation to all remain in service.

Section / Statement	Comment
<u>*3.21.1 (1)*</u> *"... until it has received written confirmation ... that the Generation Resource does not create a risk of SSR..."*	The generation resource will not "create" a risk of SSR. It may "have" a risk for SSR with its proximity to series compensation. It is still possible, however, that wind turbine and/or wind farm controls could create a risk of other issues such as SSTI in the sense of destabilization of the mechanical modes of other machines.
<u>*3.21.1 (1); 3.21.1 (2)*</u> *"... any other appropriate measures ..."*	As suggested before, such "other appropriate measures" should be defined so the stake holders can be assured that adequate and proper engineering principles are being applied.
<u>*3.21.1 (2)*</u> *"When required, the detailed study shall be performed by the TSP most affected by the SSR risk, as determined to ERCOT..."*	Since the development and construction of the CREZ system was ordered by the Texas Public Utility Commission, all existing facilities in the proximity of the CREZ system should have an interest and a stake in the nature and performance of the system. As such, shouldn't existing facilities be responsible, at least in part, for the study and, if necessary, the protection of their own equipment?
<u>*3.21.1 (4)*</u> *"The detailed SSR study shall comport with Good Utility Practice ..."*	While this is, generally, an acceptable statement, it is re-emphasized that not all phenomena seemingly covered by the NPRR are SSR.
<u>*3.21.1 (5)*</u> *"...data necessary to model the Generation Resource, Transmission Element, or network switching practice ... including ... manufacturing data, PSCAD/EMTDC simulation models, and field test results."*	Does this statement force wind plant developers and the WTG manufacturers to obtain PSCAD/EMTDC models, while ensuring that they are designed properly for use in such studies and while protecting their Intellectual Property? For example, making a Black-box model that has appropriate input and output handles available to everyone? The user written dynamic models for PSS/E are precedence for this type of model requirement.

Section / Statement	**Comment**
3.21.2 (3) *"If ERCOT identifies SSR risk in the case of three or fewer simultaneous Outages, each affected Resource Entity or TSP shall implement measures…"*	This approach of dealing with scenarios that have three or fewer Outages differently from those with four or five Outages, has merit. However, three Outages may still represent conditions with five or six elements out of service. It seem reasonably possible that this number of outages may still present a condition for which the system cannot continue to operate in a stable manner, and still allow the Resources in question – particularly Generation Resources – to continue operation. It is noted that due to the nature of the self-excitation with DFIG wind turbines, curtailment may be one option to address the issue for some wind plants.
3.21.2 (4) *"… the Entity introducing the new Generation Resource, Transmission Element, or switching practice shall be responsible for … any equipment installed as part of any …mitigation measure.*	Is this suggesting that the TSP must buy SSR relays for an existing plant if a new switching scheme results in an SSR risk that did not previously exist – assuming an SSR relay is determined to be part of the "mitigation" measure? Or are "protection" measures treated separately?
3.21.2 (4); 3.21.2 (5)	What are the distinctions between these two paragraphs? It appears that paragraph (4) is for the case of a new resource or scheme and its impact on equipment existing at the time of the study to implement it. Is paragraph (5) only associated with the initial studies by ERCOT to identify the SSR risks? Or is the distinction between ERCOT finding the SSR risk versus the TSP finding the SSR risk?

Input on Additional Issues

Determine what kind of damage can occur at a wind generation resource (WGR), conventional generator or transmission device due to subsynchronous resonance interactions or other harmful equipment-to-equipment interactions

WGR:

a) In one actual ERCOT event, self-excitation due to series compensation led to excessively high voltages (near 2 pu) at the wind turbine's crowbar circuit, damaging the electrical components in the wind turbine generators.

b) SSTI can conceivably occur as the controls of one wind turbine act to destabilize the torsional mod of other wind turbines at the same plant or ant near-by plants. This is particularly a concern for with turbine with a direct grid connection (Types 1-3).

Conventional Generation:

a) Subsynchronous resonance with series compensation leading to torsional interactions with the turbine-generator shaft can result in twisted or sheared shafts.

b) Subsynchronous resonance with series compensation leading to induction generator effect can result in excessively high currents in and/or high voltages at the machine. In most cases, normal overcurrent protection is expected to protect the machine.

c) Subsynchronous Torsional Interaction (SSTI) between active power electronic devices on the system and the turbine-generator shaft can result in twisted or sheared shafts

d) Control interactions between generator controls and nearby active power electronic devices may lead to hunting between voltage controllers of generation, SVCs, and wind generation if droops/slopes are not properly set, but this would typically be a relatively slow phenomenon (i.e. unlikely to interact with shaft torsionals).

e) Incorrect choice of Power System Stabilizer type and/or settings could lead to torsional oscillations within the same unit.

Transmission Devices:

a) If the current exchange with the series capacitor becomes excessive, there could be protective action by the MOV. The MOV may be destroyed if conditions persist.

b) Transformer could conceivably experience core saturation. The transformer core flux is directly proportional to the voltage and inversely proportional to the frequency. The measured V/Hz ratio is therefore an indication of excitation. When the allowable V/Hz ratio is exceeded, the magnetic core saturates. During saturation, excessive core flux increases the inter-lamination voltages, causing iron damage (burning, pitting). At this high level, the normal magnetic path cannot accommodate the increased flux, which flows in leakage paths not designed (not laminated) to carry it, causing heat damage.

Determine what kind of damage can occur at a WGR due to other equipment-to-equipment interactions.

Conceivably:

a) SSTI with active equipment on the transmission system could destabilize torsional modes on the wind turbine shaft leading to shaft fatigue, excessive gear wear or thrown blades

b) Control interactions between wind plants and thermal plants or between wind plants and active devices could cause hunting between the respective voltage controllers and/or high-frequency voltage interactions.

Develop a complete list of devices that can cause harmful interactions with WGRs and conventional generators.

a) Series compensation:

i. Fixed series capacitors present the highest potential risk

ii. Use of TCSC can eliminate most issues, but may still provide the potential for classical SSR for very low frequency (rotor frame) torsional modes of thermal generators or wind plants if not properly designed.

iii. Use of bypass filters can help lessen the likelihood of many issues, but have no control to adjust for potential changes in the system or detuning of the filter due to component tolerances or failures.

b) HVDC stations – particularly a potential concern for SSTI, but other interactions, such as high-frequency voltage interactions on Voltage Source Converter-type HVDC may be possible.

c) SVC or Statcom – particularly a potential concern for SSTI, but other control interactions, such as high-frequency voltage interactions or voltage-control hunting with nearby WGRs may be possible.

d) Other WGRs – may produce high-frequency voltage interactions with nearby WGRs, or local and interarea mode osciallations with conventional generators. There is also a potential for wear-down of turbine/boilers and their controls due to excessive penetration of WGRs.

Can similar interactions occur with photovoltaic or solar/steam generators? If yes, what are these interactions?

a) Only control interactions, mainly on the voltage-regulation side, have likelihood to occur with photovoltaics. This includes the SSTI and hunting issues mentioned previously.

b) Assuming that solar/steam means concentrated solar power used to create steam for driving a conventional steam-turbine generator, all of the same issues are possible as with any other machine and its shaft.

References

[1] "Terms, Definitions and Symbols for Subsynchronous Oscillations," IEEE Subsynchronous Resonance Working Group of the System Dynamic Performance Subcommittee Power System Engineering Committee. *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-104, No.6, June 1985, pp.1326-1334.

[2] "Subsynchronous Phenomena and Wind Turbine Generators," J.Daniel, W. Wong, G. Ingeström, J. Sjöberg, *Proceedings IEEE T&D Conference,* May 2012, Orlando, FL.

[3] "Self-Excitation of Induction Motors with Series Capacitors," Wagner, AIEE Transactions, Vol. 60, 1941, pp. 1241-1247.

[4] P. Pourbiek, R.J. Koessler, D.L. Dickmander and W. Wong, "Integration of Large Wind Farms into Utility Grids (Part 2 – Performance Issues)," in *Proceeding 2003 IEEE PES General Meeting,* vol. 3, July 2003.

TERMS, DEFINITIONS AND SYMBOLS FOR SUBSYNCHRONOUS OSCILLATIONS

IEEE Subsynchronous Resonance Working Group
of the System Dynamic Performance Subcommittee
Power System Engineering Committee

Abstract

This paper presents proposed terms, definitions and symbols in pursuit of electric utility industry uniformity and common understanding in the analysis of subsynchronous resonance. For the purpose of this paper, the discussion is limited to series compensated transmission systems. These definitions are recommended, where applicable, in other unique areas encompassing subsynchronous oscillations. The work presented is a product of the Subsynchronous Resonance Working Group as part of the activity of the IEEE System Dynamic Performance Subcommittee.

INTRODUCTION

The first proposed terms and definitions were presented in 1979 [1]. These were welcomed by the industry and applied by most authors of technical papers on subsynchronous oscillations. Through use, some deficiencies and needed clarification have been identified. In addition, the terms and definitions are expanded to cover other sources of subsynchronous oscillations. For these reasons, the Working Group has prepared this second set of terms and definitions. Words or terms being defined are underlined in this paper.

The definitions promoted in this paper pertain to the field of power system concern generally known as Subsynchronous Oscillations (SSO). These phenomena concern electromechanical interaction, either between a turbine-generator and passive system elements such as series capacitors, or between a turbine-generator and active system elements such as HVDC transmission equipment controls, and static VAR system controls.

The interactions are of concern to power system planners and operators due to the potential for elevated responses of power system variables either because of resonance or instability. In these instances equipment life may be threatened.

84 SM 568-2 A paper recommended and approved by the IEEE Power System Engineering Committee of the IEEE Power Engineering Society for presentation at the IEEE/PES 1984 Summer Meeting, Seattle, Washington, July 15 - 20, 1984. Manuscript submitted March 2, 1984; made available for printing May 22, 1984.

Turbine-generator electromechanical interaction with series capacitors has historically been known as the phenomena of "Subsynchronous Resonance" (SSR). The emergence of interactions between wide-bandwidth power controlling devices, such as HVDC converters, static var systems, and power system stabilizers, and turbine-generators has lead to a recognition of a broad range of turbine-generator torsional interactions that are grouped under the heading of subsynchronous oscillations. In the following, terms useful for communication of ideas in this field of concern will be defined, beginning with the physicist's definition of resonance. This definition provides a means to test the pertinence of the word resonance in connection with different causes of subsynchronous oscillations.

Resonance is defined, for physical systems in general, as the relatively large selective response of an object or system that vibrates in step (in phase) with an externally applied force [2]. Resonance for electrical systems is defined as the enhancement of the response of a physical system to a periodic excitation when the excitation frequency is equal to a natural frequency of the system [3]. Resonance, therefore, implies a periodic phenomena such as vibration, and two oscillators, one driven at or near its resonant frequency and the other driving as an externally applied force.

SUBSYNCHRONOUS RESONANCE

Subsynchronous oscillation is an electric power system condition where the electric network exchanges significant energy with a turbine-generator at one or more of the natural frequencies of the combined system below the synchronous frequency of the system following a disturbance from equilibrium. The above excludes the rigid body modes of the turbine-generator rotors.

Subsynchronous resonance (SSR), as defined here, encompasses the oscillatory attributes of electrical and mechanical variables associated with turbine-generators when coupled to a series capacitor compensated transmission system where the oscillatory energy interchange is lightly damped, undamped, or even negatively damped and growing. The electrical system frequency for a simple radial system (as shown in Figure 1) is calculated using Equation 1

$$f_{er} = f_o \sqrt{\frac{X_C}{X'' + X_g + X_T}} \qquad (1)$$

0018-9510/85/0006-1326$01.00©1985 IEEE

with reactances X defined at frequency f_o, the electrical frequency corresponding to the rotor average speed. The frequency f_o is equal to the synchronous frequency under ideal conditions.

Figure 1 is the simplest possible resonant circuit and yields a single natural frequency. Generally, the series compensated transmission system is more complex and will result in more than one natural frequency. The terms subsynchronous and supersynchronous are used to denote frequencies below and above the frequency corresponding to average rotor speed (f_o). Thus, f_{er} denotes the subsynchronous natural frequencies of the electrical system.

Currents of resonant frequency (f_{er}) in the electrical system give rise to rotor current of frequency f_r as indicated in Equation 2. A three-phase set of armature currents at frequency (f_{er}) produces positive and negative rotating magnetic fields in the synchronous machine. The time distribution of the phase currents together with the space distribution of the armature windings causes positive and negative rotation at an angular electrical velocity of $2\pi f_{er}$. The frequency of rotor body currents induced by these fields is governed by the relative velocity between the armature and the rotor. Positive sequence components of stator current produce rotor currents at subsynchronous frequency $f_r = f_o - f_{er}$. Negative sequence components of stator current produce rotor current at supersynchronous frequency $f_r = f_o + f_{er}$.

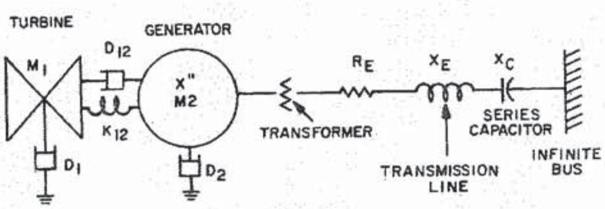

Figure 1. Turbine-Generator with Compensated Transmission

$$f_r = f_o \pm f_{er} \qquad (2)$$

The effect of such rotor currents on air gap flux are relatively small and for visualizing subsynchronous generator torques, dc rotor current can be assumed. As the constant rotor magnetic field overtakes the more slowly rotating subsynchronous mmf in the armature, a subsynchronous torque is produced having a frequency which is the difference between the frequency corresponding to rotor average velocity (f_o) and the electrical subsynchronous frequency (f_{er}). The subsynchronous electrical frequency and subsynchronous torque frequency are said to be complementary because when added the sum is equal to the synchronous frequency.

Self-Excitation

Electrical subsynchronous currents flowing in the armature produce subsynchronous rotor torques and induce subsynchronous rotor currents. These result in subsynchronous armature voltage components. These voltage components sustain or enhance the subsynchronous armature currents to produce the effect called self excitation. Self excitation, for the case of understanding and analysis, can be divided into two categories, one involving both the electrical system and mechanical system (turbine-generator) dynamics and the other involving electrical system dynamics only.

Torsional Interaction

Torsional Interaction involves both the electrical and mechanical system dynamics. Generator rotor oscillations at a torsional mode frequency (f_n) induce armature voltage components of subsynchronous frequency ($f_{en} = f_o - f_n$) and supersynchronous frequency ($f_{en} = f_o + f_n$). When the frequency of the subsynchronous component of armature voltage (f_{en}) is close to an electrical system natural frequency (f_{er}), the resultant subsynchronous current will produce a rotor torque which is phased to sustain the rotor oscillations. If the component of subsynchronous torque in phase with rotor velocity deviation equals or exceeds the inherent damping torque of the rotating system, the system will become self-excited. This interplay between the electrical and mechanical system is called torsional interaction. The above discussion, which neglects induced rotor current effects on air gap flux is permissible for the purposes of 1) understanding torsional interaction and 2) some quantitative analysis [4].

Induction Generator Effect

Induction generator effect involves only electric system dynamics. Generator armature currents at subsynchronous frequency (f_{er}) produce a component of rotating mmf in the armature air gap of angular velocity $2\pi f_{er}$. This mmf interacts with the main field air gap mmf to produce torques at subsynchronous frequency ($f_o - f_{er}$) and at supersynchronous frequency ($f_o + f_{er}$). If the generator rotor torsional mode frequency f_n is different from the subsynchronous torque frequency ($f_o - f_{er}$), then relatively little torsional interaction takes place. However, because the rotor circuits are turning more rapidly than the rotating mmf, the resistance to the subsynchronous current viewed from the armature terminal is negative due to the commonly understood induction machine theory. When this negative resistance exceeds the sum of the armature and network resistance at the resonant frequency (f_{er}), the armature currents can be sustained or grow. This phenomena is called induction generator effect.

Combined Effect of Torsional Interaction and Induction Generator Effect

It is important to recognize that induction generator effect and torsional interaction are not mutually exclusive and will co-exist, but are often separated for ease of analysis. Torsional interaction generally dominates when the subsynchronous torque frequency ($f_o - f_{er}$) is close to one of the torsional modes (f_n). Induction generator effect generally dominates when the subsynchronous torque frequency ($f_o - f_{er}$) is separated from the torsional frequency (f_n). There is no clear cut criteria to indicate which type of self-excitation dominates and, in fact, both effects may be significant.

Shaft Torque Amplification

In a series capacitor compensated transmission system, the complement of the electrical network natural frequency may align closely with one of the torsional natural frequencies. If this be the case, torques may be induced in the shafts following a system disturbance which are much larger than those developed as a result of a three-phase fault in an uncompensated system. This is due to the resonance effect and the fact that the torsional mode damping in a turbine-generator rotor system is extremely low. This effect is referred to as shaft torque amplification.

Most often, the shaft response is not sinusoidal with a single frequency component, but contains contributions from all the torsional modes. In general, for the same peak torque level, the torsional fatigue life consumption will be significantly lower for a multi-modal response in comparison to a single mode response.

Device Dependent Subsynchronous Oscillation (SSO)

Device Dependent Subsynchronous Oscillation is an emerging category of interaction between turbine generator torsional systems and power system components. Such interaction has been observed on DC Converter controls, and power system stabilizers, and may occur for any wide bandwidth power control device located near a turbine generator.

DC Converter Control Interaction

DC converter control interaction is a torsional system destabilizing phenomena caused by inherent feedback and tight coupling between the turbine-generator speed voltage component and the firing angle control of a DC Converter. The term subsynchronous oscillation applies rather than subsynchronous resonance.

This form of control interaction is a natural consequence of DC Converter controls trying to maintain constant current or power, and the natural feedback established between generator speed voltage and the rectifier firing control synchronized to the DC Converter bus.

Power System Stabilizer SSO Control Interaction

Power System Stabilizer (PSS) SSO control interaction is another form of torsional interaction. In this case, the action is produced by feedback from Stabilizer input through to exciter and generator power by generator field voltage modulation. Destabilization occurs when the generator and exciter torque have a significant component in phase with generator speed. Again, this phenomena is not due to resonance, as there is only a single oscillator involved, namely, the turbine generator. The name SSO Interaction exemplifies this fact.

TORSIONAL MECHANICS

Torsional Natural Frequencies and Mode Shapes

Following a disturbance, the turbine-generator rotor masses will oscillate relative to one another at one or more of the turbine mechanical natural frequencies called torsional mode frequencies dependent on the nature of the disturbance. When the mechanical system oscillates under such steady-state conditions at one of the natural frequencies, the relative amplitude and phase of the individual turbine-generator rotor elements are fixed and are called the mode shapes of torsional motion, Figure 2. The notion of mode shape in this context is defined for the mechanical system acting alone and in the absence of damping. This mode shape, often displayed graphically, is an eigenvector of rotational displacement or rotational velocity of the rotor inertial elements when the system is represented mathematically.

The torsional modes involving shaft twist are commonly numbered sequentially according to mode frequency and number of phase reversals in the mode shape. Thus, Mode 1 has the lowest mode frequency and only one phase reversal in the mode shape. More generally, Mode n has the nth lowest frequency and a mode shape with "n" phase reversals. The total number of modes including the rigid body mode is equal to the number of inertial elements in the spring-mass model.

Damping and Decrement Factor

Torsional mode damping quantifies the rate of decay of torsional oscillations at a torsional mode frequency and can be expressed in several ways. The most easily measured quantity is the ratio of successive peaks of oscillation; the natural logarithm of this ratio is known as the logarithmic decrement or log-dec(δ). For slow decay, the log-dec is approximately equal to the fraction of decay per cycle. A more accurate measure is the time in seconds for the envelope of decay to decrease to the fraction 1/e of its value from an earlier point in time. This measure is the time constant of decay. The inverse of the time constant is defined as the decrement factor (σ_n) and is equal to the mode frequency in hertz multiplied by the log-dec.

Damping measured by test includes the combined effects of both the mechanical and electrical system damping. In the course of system studies, mechanical and electrical system damping are normally represented separately. Care must be exercised in translating test data to studies so that electrical torsional damping effects are not included twice.

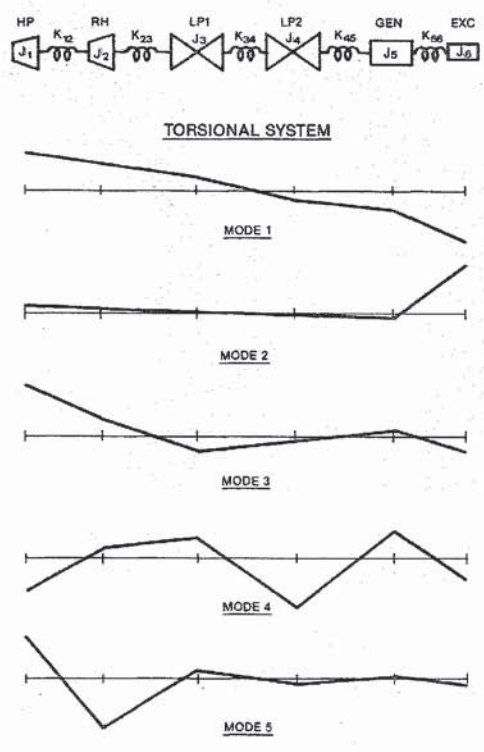

Figure 2. Typical Mode Shapes of Torsional Mechanics

Several factors affect the apparent damping of the torsional modes of vibration. These factors can be conveniently grouped based on their origin being either mechanical or electrical. The dampings of mechanical origin are associated with the dissipative force of windage, bearing friction, and hysteresis loss. The damping due to steam forces on the turbine blades is suspected to be the dominant influence that causes increased damping with load. These components of damping are small and are generally load and vibration amplitude dependent. The collective damping effects of mechanical origin can be represented by σ_{mn}, the decrement factor of the n-th mode, when the mechanical system is acting alone.

The damping contributions of electrical origin are associated with incremental I^2R losses per unit of generator velocity, produced in the transmission lines, synchronous machine armature windings, field winding, and rotor body surface. These loss components are particularly frequency sensitive and to some extent amplitude sensitive due to magnetic hysteresis and saturation. The collective damping elements of electrical origin are represented by σ_{en}, the decrement factor of the n-th torsional mechanical mode in the absence of mechanical damping. The electrical damping σ_{en} is load and system dependent and also depends upon generator electrical behavior. For small amplitudes of oscillation, the net modal damping (σ_n) is given by Equation 4. In the presence of series capacitor compensation σ_{en} and, hence, σ_n may be negative due to self-excitation.

$$\sigma_n = \sigma_{mn} + \sigma_{en} \tag{4}$$

Mathematical Models

An analysis of self-excitation or transient shaft torques caused by disturbances in the electrical system requires mathematical modeling of the torsional mechanical system. A complete representation would require the solution of the elastic behavior of the whole turbine-generator. A frequently used mechanical representation called a spring-mass model, Figure 2, allows computation of rotor motion with torques applied to individual masses as inputs.

As a computational aid, it has been found desirable to construct a separate model for each torsional mode to represent the generator rotor displacement only, Figure 3. This model, called the modal spring-mass model, consists of a single mass and spring tuned to the modal frequency. This model has the same energy storage as the real turbine-generator rotor, at the modal frequency, for the same generator rotor displacement. The modal spring-mass model is described in terms of its modal inertia, modal damping, modal spring constant, modal frequency, modal energy, etc.

The terms of Figure 3 are reduced to mathematical notation by Equations 5 and 6.

$$\omega_n = \sqrt{\frac{2\pi f_o \bar{K}_n}{\bar{J}_n}} \tag{5}$$

$$\sigma_n = \frac{1}{t} \ln \frac{A(o)}{A(t)} \tag{6}$$

where

A(o) is the initial amplitude of oscillations.
A(t) is the nth cycle amplitude of oscillations.
t is time between amplitude crests A(o) and A(t).

The modal spring-mass model is a mathematical representation of the complete spring-mass model of Figure 2 for oscillations in mode n. Its derivation follows from the eigenvectors and frequencies of the spring-mass model in the absence of damping. The equations of motion of the spring-mass model, given by Equation 7, are seen to be N second order differential equations of motion for an N mass model and coupled to one another by the spring elements.

Diagonalization of the stiffness term while preserving the equality implied by Equation 7 would yield N uncoupled equations called the modal spring-mass models. This diagonalization can be accomplished by coordinate transformation from a reference frame in the rotors to a reference frame of the eigenvectors.

The transformation that will perform this diagonalization is given by Equation 8

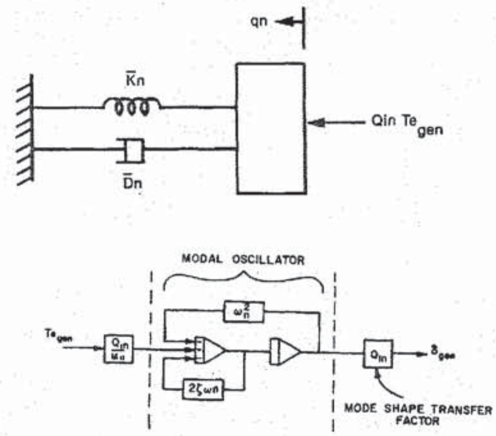

Figure 3. Mode Spring-Mass Model

$$\begin{vmatrix} J_1 & & & & \\ & J_2 & & & \\ & & \cdot & & \\ & & & \cdot & \\ & & & & J_N \end{vmatrix} \begin{vmatrix} \ddot{\theta}_1 \\ \ddot{r}_2 \\ \cdot \\ \cdot \\ \ddot{\theta}_N \end{vmatrix} + \begin{vmatrix} K_{12} & -K_{12} & & & \\ -K_{12} & K_{12}+K_{23} & -K_{23} & & \\ & -K_{23} & \cdot & \cdot & -K_{NI,N} \\ & & \cdot & \cdot & \\ & & & -K_{NI,N} & K_{NI,N} \end{vmatrix} \begin{vmatrix} \theta_1 \\ \theta_2 \\ \cdot \\ \cdot \\ \theta_N \end{vmatrix} = \begin{vmatrix} T_1 \\ T_2 \\ \cdot \\ \cdot \\ T_N \end{vmatrix} \tag{7}$$

$$\begin{vmatrix} \theta_1 \\ \theta_2 \\ \cdot \\ \cdot \\ \theta_N \end{vmatrix} = \begin{vmatrix} Q_{11} & Q_{12} & \cdot & \cdot & Q_{1N} \\ Q_{21} & Q_{22} & \cdot & \cdot & Q_{2N} \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ Q_{N1} & Q_{N2} & \cdot & \cdot & Q_{NN} \end{vmatrix} \begin{vmatrix} q_1 \\ q_2 \\ \cdot \\ \cdot \\ q_N \end{vmatrix} \tag{8}$$

where q_i are the new coordinates and $[Q_{1i}, Q_{2i}, Q_{Ni}]^T$ is the i-th eigenvector of displacements of the N masses.

The result of the diagonalization of (7) by (8) defines the modal spring-mass model data. This data is not unique since the eigenvectors (mode shapes) defined by Equation 8 may be normalized in any arbitrary manner. There are several common ways of performing normalization for subsynchronous resonance analysis. One method assigns the value unity to the generator mass location. Another assigns values such that one or more value is unity and all others are less than unity.

This substitution (8) into (7) yields the mode data and the reallocation of rotor input torque given by (9).

The symbols $\bar{J}_n$ and $\bar{K}_n$ of Equation 9 are the normalized constants and their values will depend on the manner used for normalization.

$$\begin{vmatrix} \bar{J}_1 & & & & \\ & \bar{J}_2 & & & \\ & & \cdot & & \\ & & & \cdot & \\ & & & & \bar{J}_N \end{vmatrix} \begin{vmatrix} \ddot{q}_1 \\ \ddot{q}_2 \\ \cdot \\ \cdot \\ \ddot{q}_N \end{vmatrix} + \begin{vmatrix} \bar{K}_1 & & & & \\ & \bar{K}_2 & & & \\ & & \cdot & & \\ & & & \cdot & \\ & & & & \bar{K}_N \end{vmatrix} \begin{vmatrix} q_1 \\ q_2 \\ \cdot \\ \cdot \\ q_N \end{vmatrix} = \begin{vmatrix} Q_{11} & Q_{21} & \cdot & \cdot & Q_{N1} \\ Q_{12} & Q_{22} & \cdot & \cdot & Q_{N2} \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ Q_{1N} & Q_{2N} & \cdot & \cdot & Q_{NN} \end{vmatrix} \begin{vmatrix} T_1 \\ T_2 \\ \cdot \\ \cdot \\ T_N \end{vmatrix} \qquad (9)$$

The uncoupled equations represented by Equation 9 may be related to N physical, single degree of freedom, models of motion, one of which is shown in Figure 3a. Alternatively, they may be represented by N second order servomechanisms defined by Figure 3b.

In general, the mechanical response to a torque on the generator involves all modes of vibration of the mechanical system. The solution of the mechanical response is a linear combination of the model responses. These modal responses are obtained by application of some proportion of the exciting torque to each of the modal spring-mass models. This proportion or multiplier is called the Modal Transfer Factor (Q_{ij}). The use of the mode shape vectors as weighting functions to linearly combine the modal responses allows the calculation of the actual response such as rotor displacement and speed.

FATIGUE DAMAGE

Fatigue is defined as the process of progressive localized permanent structural change occurring in a material subjected to conditions which produce fluctuating stresses and strains at some point or points and which may culminate in cracks or complete fracture after a sufficient number of fluctuations.

Transient disturbances that might occur on either an uncompensated or series capacitor compensated transmission network can result in fatigue of turbine-generator shafts. In applications where the complete fracture or separation of a component would result in serious secondary damage, it is common to define 100% fatigue life expenditure as the initiation of a crack, rather than gross failure. Clearly, the integrity of turbine-generator shaft systems falls into the category where serious secondary damage is a natural consequence of shaft separation.

Fatigue is a cumulative process. It is not until all the fatigue life is used up that an observable defect such as a crack will be obtained. Hence, for example, if a shaft system is inspected and no cracks are identified following a severe torsional disturbance, there is little assurance of low fatigue life expenditure, as most of the shaft fatigue life may have been consumed. A few relatively minor incidents in the future may then initiate a crack and possible subsequent gross failure.

Estimation of torsional fatigue life expenditure is a complex subject. Care must be taken to suitably derate torsional fatigue data obtained from a small smooth specimen to make it applicable to actual machine shafts. For example, effects such as stress concentrations, processing, periodic overstrain and increased size, considerably reduce the fatigue capability of a machine shaft relative to small smooth unnotched test specimen.

High cycle fatigue, damage due to a large number of low amplitude fluctuations, is characterized by elastic deformation. Low cycle fatigue, damage due to a small number of large amplitude fluctuations, involves local plastic deformation in regions such as keyways, fillets, etc. For elastic deformations, the structure will return to its initial dimensions when the loading is removed. Conversely, deformations which contain plastic components will not return to zero upon removal of the load.

The fatigue life N of a component as defined by the ASTM is the number of stress-strain cycles of a specified character or magnitude that can be withstood before failure of a specified nature occurs.

The S-N Diagram is a plot of cyclic stress amplitude against the number of cycles to failure.

The fatigue limit, sometimes called the endurance limit, is the maximum stress which results in negligible fatigue life expenditure as the number of cycles (N) becomes very large.

For additional fatigue definitions, refer to the following ASTM specifications:

E6-76	Method of Mechanical Testing
E8-77a	Tension Testing of Materials
E206-72	Fatigue Testing and Statistical Analysis of Fatigue Data
E380-76	Metric Guide Practice
E468-76	Standard Recommended Practice for Presentation of Constant Amplitude Fatigue Test Results for Metallic Materials
E513-74	Constant-Amplitude, Low Cycle Fatigue Testing

E606-77T Tentative Recommended Practice for Constant-Amplitude Low Cycle Fatigue Testing

SAE-6 Fatigue Under Complex Loading; Analysis and Experiments

PREFERRED SYMBOLS AND DIMENSIONS

In the pursuit of uniformity and common understanding, the following symbols, definitions and dimensions, MLT and FLT for mass length, time, and force length time, respectively, are proposed:

Symbol	Definition	Dimensions (MLT)	Dimensions (FLT)
f_{er}	Electrical system subsynchronous natural frequency	T^{-1}	T^{-1}
ω_n, f_n	nth torsional mode undamped frequency	T^{-1}	T^{-1}
f_{en}	Electrical subsynchronous frequency produced by f_n	T^{-1}	T^{-1}
f_o	Frequency corresponding to average rotor speed	T^{-1}	T^{-1}
f_r	Rotor current frequency	T^{-1}	T^{-1}
J_i	Inertia of ith turbine-generator rotor element	ML^2	FLT^2
K_{ij}	Stiffness of shaft between rotors i and j	ML^2T^{-2}	FL
D_{ij}	Viscous damping between rotors i and j	ML^2T^{-1}	FLT
D_i	Viscous damping of rotor i	ML^2T^{-1}	FLT
H_i	Rotor i inertia constant	ML^2	FLT^2
T	Applied turbine or generator torque	ML^2T^{-2}	FL
σ_n	nth mode net decrement factor including torsional interaction	T^{-1}	T^{-1}
σ_{mn}	Decrement factor, mechanical component	T^{-1}	T^{-1}
σ_{en}	Decrement factor, electrical component	T^{-1}	T^{-1}
$\bar{J}_n$	Inertia ($2\bar{H}_n$) of nth modal oscillator	ML^2	FLT^2
$\bar{K}_n$	Stiffness of nth modal oscillator	ML^2T^{-2}	FL
$\bar{D}_n$	Viscous damping of nth modal oscillator	ML^2T^{-1}	FLT
S	Power	ML^2T^{-3}	FLT^{-1}
Q_{ij}	Mode Transfer Factor element of torsional mode eigenvector matrix where i is the mode number and j is the generator mass location	–	–
N	Average speed of rotation RPM	T^{-1}	T^{-1}
N	Number of masses	–	–
N	Cycles in S-N data	–	–
X"	Average subtransient reactance of both axes	–	–
δ	Logarithmic decrement	–	–
J_u	Per Unit Inertia	–	–
K_u	Per Unit Stiffness	–	–
D_u	Per Unit Damping	–	–
ω_u	Per Unit Angular Velocity	–	–
α_u	Per Unit Angular Acceleration	–	–

MECHANICAL NORMALIZATION EXAMPLE FOR TORSIONAL SYSTEM

To perform calculations concerning SSR stability and torque amplification, it is necessary to obtain electrical and mechanical system data on a common base. While the power engineer is familiar with unit manipulation for the electrical system and a single inertia mechanical system, difficulties are often encountered in the transfer of spring-mass model data in engineering units to a common base. These difficulties occur when data relates to machines with more than two poles and where gear driven exciters are used. First, to avoid data ambiguity, it is preferred that data be obtained in engineering units, rather than in per unit on some base, together with an indication of rated speed of each inertia or spring element. Second, the engineering units should clearly indicate which dimension system is in use, either Force units (FLT) or Mass units (MLT) and for each data element if both systems are in use.

Per unit systems applied for SSR data preparation and studies is centered on the following dynamic mechanical system equation:

$$J\,\alpha + D\,\omega + K\,\theta = T \tag{10}$$

where the elements of the equation can be either single parameters and variables or can be in matrix form.

It is often convenient to apply a per unit system of the same term:

$$J_u\alpha_u + D_u\omega_u + K_u\theta_u = T_u \tag{11}$$

where $J_u = J/J_b$, etc.

One common per unit system provides for T_u and all other per unit quantities to be dimensionless. This system results in $J_u = 2H\omega_b$.

Starting with S_b as the machine rated MVA and ω_b as the rated angular velocity of the specific inertia or spring element, $T_b = S_b/\omega_b$. On this basis, Equation 11 can then be written.

$$\frac{J}{\frac{S_b}{\omega_b^3}} \frac{\alpha}{[\omega_b^2]} + \frac{D}{\frac{S_b}{\omega_b^2}} \frac{\omega}{[\omega_b]} + \frac{K}{\frac{S_b}{\omega_b}} \frac{\theta}{[\theta_b]} = \frac{T}{\frac{S_b}{\omega_b}} \qquad (12)$$

Where the quantities in brackets are the base quantities. The consistency of the base quantities can be shown:

Angular Velocity Base: ω_b = rated mechanical angular speed in rad/sec.
$= \frac{N2\pi}{60}$, where N is rated speed in RPM

Time Base : $t_b = \frac{1}{\omega_b}$ sec.

Angle Base : $\theta_b = \omega_b \cdot t_b = 1$ rad.

Angular Acceleration Base : $\alpha_b = \frac{\omega_b}{t_b} = \omega_b^2$ rad/sec^2

Power Base : S_b MVA

Inertia Base : $J_b = \frac{S_b}{\omega_b^3}$ MVA - sec^3

Damping Base : $D_b = \frac{S_b}{\omega_b^2}$ MVA - sec^2

Stiffness Base : $K_b = \frac{S_b}{\omega_b}$ MVA-sec

Torque Base : $T_b = \frac{S_b}{\omega_b}$ MVA

The validity of the per unit system can be verified by a simple test to show that the following relations for a second order system are satisfied by the per unit system as well as physical units:

$$\omega_n = \frac{K}{J}^{1/2} \qquad t_c = 2\,\frac{J}{D} \qquad (13)$$

From Equation 11 and the definitions of ω_b and t_b it can be written

$$\bar{\omega}_n = \left[\frac{\bar{K}}{\bar{J}}\right]^{1/2} = \left[\frac{\frac{K}{S_b/\omega_b}}{\frac{J}{\frac{S_b}{\omega_b^2}}}\right]^{1/2} = \frac{1}{\omega_b}\left[\frac{K}{J}\right]^{1/2}$$

$$\omega_n = \bar{\omega}_n\,\omega_b = \left[\frac{K}{J}\right]^{1/2} \qquad (14)$$

$$\bar{t}_c = 2\,\frac{\bar{J}}{\bar{D}} = 2\left[\frac{\frac{J}{\frac{S_b}{\omega_b^3}}}{\frac{D}{\frac{S_b}{\omega_b^2}}}\right] = 2\,\omega_b\,\frac{J}{D}$$

$$t_c = \bar{t}_c\,t_b = 2\,\frac{J}{D} \qquad (15)$$

It is shown that Equations 14 and 15 satisfy Equation 13, thereby validating the per unit system. Other per unit systems could be developed and tested in the same manner.

To establish the base quantities from the physical quantities usually provided, the following method is applied.

Inertia - J

J is usually provided in English units of lbm-ft^2 or lbf-ft-sec^2, or in metric units of Kg-m^2. To establish the base inertia in the appropriate units, the inertia base must be transformed from MVA-sec^3.

$$J_b = \left|MVA_b\right| \left|.737 \times 10^6 \frac{\text{ft-lbf}}{\text{MVA-sec}}\right| \left|32.2\,\frac{\text{lbm-ft}}{\text{lbf-sec}^2}\right| \left|\frac{\text{sec}^3}{(\frac{2\Pi N}{60})^3}\right|$$

$$= 20.7 \times 10^9\,\frac{MVA_b}{N^3} \qquad \text{lbm-ft}^2$$

$$= 0.642 \times 10^9\,\frac{MVA_b}{N^3} \qquad \text{lbf-ft-sec}^2$$

$$= 0.871 \times 10^9\,\frac{MVA}{N^3} \qquad \text{kg-m}^2$$

Stiffness - K

K is usually provided in English units of lbf-ft or metric units of N-m. To establish the base stiffness in the appropriate units, the stiffness base must be transformed from MVA-sec.

$$K_b = \frac{S_b}{\omega_b} = \left|MVA_b\right| \left|.737 \times 10^6 \frac{\text{ft-lbf}}{\text{MVA-sec}}\right| \left|\frac{\text{sec}}{\frac{2\Pi N}{60}}\right|$$

$$= 7.04 \times 10^6\,\frac{MVA_b}{N} \qquad \text{lbf-ft}$$

$$= 9.55 \times 10^6\,\frac{MVA_b}{N} \qquad \text{N-m}$$

Damping - D

D is usually provided in English units of lbf-ft-sec or metric units of N-m-sec. To establish the base damping in the appropriate units, the damping base must be transformed from MVA-sec^2.

$$D_b = \frac{S_b}{\omega_b^2} = \left|MVA_b\right| \left|\frac{.737 \times 10^6 \text{ ft-lbf}}{\text{MVA-sec}}\right| \left|\frac{\text{sec}^2}{(\frac{2\Pi N}{60})^2}\right|$$

$$= 67.2 \times 10^6 \frac{MVA_b}{N^2} \quad \text{lbf-ft-sec}$$

$$= 91.1 \times 10^6 \frac{MVA_b}{N^2} \quad \text{N-m-sec}$$

Torque - T

T is usually in English units of lbf-ft or metric units of N-m. To establish the base torque in the appropriate units, the torque base must be transformed from MVA-sec.

$$T_b = \frac{S_b}{\omega_b} = \left|MVA_b\right| \left|\frac{.737 \times 10^6 \text{ ft-lbf}}{\text{MVA-sec}}\right| \left|\frac{\text{sec}}{\frac{2\Pi N}{60}}\right|$$

$$= 7.04 \times 10^6 \frac{MVA_b}{N} \quad \text{lbf-ft}$$

$$= 9.55 \times 10^6 \frac{MVA_b}{N} \quad \text{N-m}$$

CONCLUSIONS

The use of common definitions and units is a goal worth striving for as a means to promote understanding. The analysis of subsynchronous resonance requires higher levels of equipment modeling in areas not previously considered important for the safe and reliable operation of power systems. The terms and data requirements for adequate analysis are new and in an early evolutionary state.

The problems of SSR will be solved only with a complete understanding on the part of utility planners and equipment manufacturers.

CHAIRMAN'S NOTE

The Chairman wishes to acknowledge the contribution of Colin Bowler who provided the impetus and coordination for the very difficult task of preparing these Terms and Definitions.

Members of the IEEE Subsynchronous Resonance Working Group Chaired by R.G. Farmer, B.L. Agrawal, D.H. Baker, C.E.J. Bowler, C.V. Childers, C. Concordia, J.W. Dorney, A.E. Hammad, M.S. Hamman, R.G. Harley, R.A. Hedin, F. Iliceto, E. Katz, L.A. Kilgore, J.F. Luini, A.J. Perez, D.G. Ramey, A.J. Smith, J. Spiegl, J.F. Tang, E.R. Taylor, H.L. Thanawala, J.M. Undrill, D.N. Walker

References

1. "Proposed Terms and Definitions for Subsynchronous Oscillations," IEEE Subsynchronous Resonance Working Group, IEEE Transactions on Power Apparatus and Systems, Vol. PAS-99, No. 2, March/April 1980.

2. Encyclopedia Brittanica.

3. IEEE Standard Dictionary of Electrical and Electronics Terms. Second Edition 1977.

4. L.A. Kilgore, D.G. Ramey, M.C. Hall, "Simplified Transmission and Generation System Analysis Procedures for Subsynchronous Resonance Problems," 1976 Symposium, "Analysis and Control of SSR," IEEE PES publication #76CH1066-0-PWR.

Discussion

R.A. Achilles (Hidronor S.A., Cipolletti-Rfo Negro, Argentina): As this paper expands the phenomena spectrum defined previously [1] with other generator self-excitation forms (mainly SSO-related) I wonder whether, for the sake of generalization, similar kinds of interaction but affecting nontorsional components of the prime mover system should be included in this set of definitions.

This would be the case of Electrohydraulic Resonance, basically a near-resonant coupling of the electrical network - through the inertial mode of the torsional system - with the hydraulic system associated to a hydroelectric generator, from which incidents in the U.S. are reported as far back a 1912 [2]. The hydraulic resonance frequencies interacting are the penstock and draft-tube surge natural frequencies functions of, respectively, penstock length and machine mechanical speed and load. These frequencies are, in modern design practices, detuned mutually and from the machine accelerating power loop frequency at early functional specification stages. The tendency up to now, in matter of Countermeasures, has been the application of dividing walls, splitters and compressed air injection in the draft-tube low-pressure zone regarded as the main source of perturbations. The advent of Power System Stabilizers could introduce in the near future not only and additional perturbation source but an electric counteraction means to the phenomenum.

REFERENCES

1. Reference [1] of the Paper
2. W.J. Rheingans, "Power Swings in Hydroelectric Power Plants," ASME Transaction 62(1940) 3 pp. 171-184, April 1940.

Manuscript received August 10, 1984.

B.T. Doi and **G. Joos** (McGill University, Montreal, Canada): The IEEE Subsynchronous Resonance Working Group in particular and the Power Engineering community at large are to be congratulated for their commendable restraint from confecting unnecessary neologisms. For this reason, we are hesitant to point out that a few new labels may be necessary to avoid a lot of confusion in the literature. We refer to the over-worked terms: *subsynchronous frequency* and *supersychronous frequency* which as shown in Table I are required to take on three specific meanings.

Meaning	Context	Supersynchronous Frequency	Subsynchronous Frequency
1	everyday English	$f > f_0$	$f < f_0$
2	Torsional Interaction	$f_{en} = f_0 + f_n$	$f_{en} = \mid f_0 - f_n \mid$
3	Induction Generation	$f_r = f_0 + f_{er}$	$f_r = \mid f_0 - f_{er} \mid$

Meaning No. 1 is the way we understand the terms in everyday usage. Meaning No. 2 and Meaning No. 3 are specific definitions and would have been better served by some technical jargon. The fact that the technical jargon has been avoided is really a disservice, because it is at the expense of expropriating Meaning No. 1 from the English language.

Besides being over-worked, the term *subsychronous frequency* in Meaning No. 2 and 3 is latent with self-contradiction. This is because for any f_n or f_{er} which are greater than 2 f_0, f_{en} and f_r will be greater in magnitude than f_0. A subsynchronous frequency should not be supersynchronous at the same time!

Without inventing new terms, it is proposed that in torsional interaction the terms, *upper sideband frequency* and *lower sideband frequency*, be used for $f_{en} = /f_0 + f_n/$ and $f_{en} = /f_0 - f_n/$ respectively. These are ready-made terms borrowed from the "phase modulation theory" of the communication engineers, which forms the mathematical basis for Reference [4] of the text. The terms "sideband frequencies" have already been used in [A,B,C,].

REFERENCES

[A]. B.T. Ooi, "Phase modulation theory of electromechanical damping in synchronous generators." *IEEE Trans. Power App. Sys.* Vol PAS-100, No.5 pp. 2211-2218, May 1981.

[B] B.T. Ooi and G. Joos, "The interaction of torsional resonances with network resonances in sychronous generators." IEEE/PES 1984 Summer Meeting, Seattle 84 SM 589-8.

[C] B.T. Ooi and G. Joos "The nature of torsional interaction in sychronous generators." Proceedings, International Conference on Electric Machines September 1984 Lausanne Switzerland.

Manuscript received August 6, 1984.

Subsynchronous Resonance Working Group R.G. Farmer, Chairman: We appreciate the comments by Ooi, et al., concerning the use of definitions for sub and super sychronous frequency. Their comments are well taken for the general case of f_{er} and f_n of arbitrary value. We must point out, however, that the terms and definitions are generally for the case of series compensated systems, which for the most part will never create electrical resonances higher than synchronous frequency in the ac system reference frame. Notwithstanding this, we feel the terms are useful as is, because when we communicate between ourselves as engineers, it is clear that the terminology, subsynchronous frequency, and supersynchronous frequency are always given in context with the subject matter; either everyday English, or concerning torsional interaction, or induction generator effect.

We also appreciate that definitions are never static and get changed by usage to fit other phenomena. The proposed use of the terminology, UPPER and LOWER side band is in common use with those concerned with SSR, as well as those concerned with supersynchronous frequency interactions. This usage will probably become a standard in the more general case of both sub and super sychronous ac network interaction with turbine-generators. Responding to Mr. Achilles, we would say that the hydraulic interaction he describes is within the general province of turbine-generator torsional interaction. For the present, the terms and definitions have been concerned with interaction between the turbine-generator and the power system only. It is possible that for definitions outside of this arena, there are other places to look for standardization. At the present time, the SSR working group is not concerned with other forms of interaction, but will respond where there is a clear need.

Manuscript received December 21, 1984.