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Use of FACTS Devices in Mitigating Sub Synchronous Resonance

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Abstract. *This study evaluates the use of Flexible Alternating Current Transmission System (FACTS) devices in mitigating Subsynchronous Resonance (SSR). SSR is defined as a condition wherein an electrical network exchanges energy with a turbine generator at one or more of the natural frequencies of the combined systems below its synchronous frequency. The presence of SSR in a system can lead to catastrophic outcomes, and the application of FACTS devices has been found to be one of the most effective approaches to reduce SSR. The study investigates the core concepts associated with FACTS devices and SSR. The concepts underlying SSR interactions, including self-excitation and transient torques, are examined in this study. The study also focuses on the use of FACTS devices in mitigating or eliminating SSR from the system or network of interest. The results of simulations conducted by using eigenvalue analysis and the IEEE second benchmark model are also presented and discussed.*

Keywords

Eigenvalue analysis, FACTS devices, self-excitation, SSR, SSSC, STATCOM, UPFC.

1. Introduction

This study investigates the use of Flexible Alternating Current Transmission System (FACTS) devices in mitigating Subsynchronous Resonance (SSR), whose presence in electrical systems can lead to catastrophic system breakdown. Several studies [1] have reported on the use of FACTS devices for the dynamic control of the phase angle, impedance, and voltage of high-voltage AC lines [2]. FACTS devices offer a wide range of strategic benefits for improved and high-quality transmission system management. Some benefits include environmental benefits, enhanced quality of power supply for industries (for instance, production of computer chips), transient grid stability, increased dynamic and enhanced transmission system availability and reliability, and improved utilization of existing transmission assets [3]. Previous study [4] have indicated that it takes approximately 12 to 18 months to manufacture flawless FACTS device. In addition to all their other benefits, FACTS devices also play an indispensable role in mitigating SSR [5] and [6].

SSR can be considered as an electrical system condition wherein the electrical network exchanges energy with a turbine generator at one or more natural frequencies of combined system [2] and [7]. The SSR operates at a frequency below the synchronous frequency of the system. On the other hand, SSR can also be understood as any condition of the system that offers an opportunity for exchange of energy at subsynchronous frequencies [1]. In addition, this frequency can also be considered as one of the natural modes of oscillation or fluctuations arising due to the inherent characteristics of the system [3].

SSRs can occur due to forced-mode oscillations. It is noteworthy that these forced modes are usually driven by a specific control system or a particular device. According to a previous study [4], a subsynchronous oscillation natural mode is most commonly observed in networks with series-capacitor-compensated transmission lines. These transmission lines, along with their series combinations (LC combinations), possess natural frequencies (ωn) as well as the particular conditions for the occurrence of SSR [8] and [9].

It has been contended that SSR may lead to the inclusion of an additional or extra resonance in the system, hence affecting the system performance and efficacy [3]. The presence of SSR in a system can even lead to shaft failure. Thus, it is essential to mitigate SSR by using appropriate techniques or tools. In this regard, the utilization of FACTS devices has been found to be most effective. As per previous studies [8] and [9], newly developed and advanced FACTS controllers can play a significant role in minimizing or reducing the SSR problem. These controllers are usually based on Voltage Source Converters (VSCs) such as Static Synchronous Series Converters (SSSCs) and Static Synchronous Compensators (STATCOMs) [1], [10] and [11]. A method of remedying the subsynchronous resonance effect is with the use of a fuzzy logic-damping controller, the output of which was used as the input for a 3-phase damping resistive. This contribution is theoretically and practically relevant because the proposed method was shown to successfully damp torsional interactions among system components, and constrain the rotor speed within steady limits [12].

The primary purpose of these devices is to control and regulate the power and voltage flow, thus reducing or eliminating the SSR problem [3]. This study mainly focuses on the analysis of FACT devices in mitigating or diminishing SSR and its effects. In this regard, the study provides a brief yet in-depth assessment of the core concept underlying FACTS devices. Furthermore, the study also attempts to summarize the evaluation of SSR. Subsequently, we examine different methods and FACTS devices that can aid in controlling or eliminating SSR from the system.

2. Methods of Analyzing Sub Synchronous Resonance

Previous analyses [8] have demonstrated that self-excitation in systems or networks is one of the primary manifestations of SSR. The problem of self-excitation causes considerable instability in the systems, making them vulnerable to breakdown. In this regard, it has been reported that the stability or instability of the system can be easily analyzed by utilizing different techniques applied in linearized models [3]. Some of the most prominent techniques utilize damping and synchronizing torques as well as frequency scanning. In this context, eigenvalue analysis [8] can be considered as a highly suitable method to examine power systems subject to SSR. Moreover, the frequency domain method can also be adopted as it is computationally feasible. To analyze the torsional interaction (angular vibration of the shaft due to subsynchronous torque), the technique of eigenvalue can also be utilized. This study uses eigenvalue analysis to compute and evaluate the SSR. Importantly, our simulation is conducted on the IEEE second benchmark model. We remark here that eigenvalue technique is extensively being used for the evaluation of system transients.

2.1. Eigenvalue Analysis

Eigenvalue analysis is considered as one of the most effective tools to calculate the states of specific operating points of any system or model [4]. In this approach, the stability of a power system can be examined by the calculation of the system's eigenvalues [13] and [14]. From the eigenvalues, we can determine the state of the system. In the approach, the following dynamic Eq. (1) and Eq. (2) of the system are solved empirically.

$$\frac{d\delta_i}{dt} = w_i - w_0, \tag{1}$$

$$2 \cdot \frac{H_i}{w_0} \cdot \frac{dw_i}{dt} = T_{mi} - T_e - K_i \cdot (\delta_i - \delta_{(i+1)}). \tag{2}$$

Here, δ_i, $\delta_{(i+1)}$ = twist angle of the i^{th} mass with respect to the $(i+1)^{th}$ mass between the generator and High Pressure (HP) masses, w_i = angular frequency of the i^{th} mass between the generator and HP masses, w_o = bass angular frequency (60 Hz), H_i = inertia constant of the i^{th} mass between generator and the HP masses, K_i = stiffness constant of the shaft of the i^{th} mass between the generator and HP masses, T_{mi} = magnetic torque of the i^{th} mass between generator and HP masses, and T_e = electrical torque of the i^{th} mass between generator and HP masses.

Equation (1) and Eq. (2) yield the set of torsional modes of the turbine generator mechanical system in the state-space form (expressed below), where A denotes the state coefficient matrix and $\vec{u}$ the forcing torque vector.

$$\dot{\mathbf{X}} = \begin{bmatrix} \delta_i \\ w_i \\ \delta_{(i+1)} \\ w_{(i+1)} \\ \vdots \\ \delta^n_{w_n} \end{bmatrix} = [A]\mathbf{X} + [B]\vec{u}. \tag{3}$$

In the study presented in this paper, Simulink linear analysis tool has been used to calculate the states of specific operating points of the model. These states are transferred to the workspace where the model is linearized using 'Linearize' command at that operating point, followed by determining the eigen values. In addition, the controller that was utilized was the one used in [7]. In order to dampen subsynchronous oscillations thoroughly and assiduously, this controller utilizes rotor speed deviation and its derivatives as inputs. The fundamental variation in the suggested method is an optimized procedure for damping control favoring it over usual conventional methods, inefficacious fuzzy designs. The proffered method is markedly efficient and effective due to the fact that it is involved with remarkably less fuzzy variables.

3. Turbine Generator Network

Previous study [1] has shown that the turbine generator network can be categorized as a spring-mass system comprising different masses. The most common masses include the HP and Low Pressure (LP) turbines running in tandem on a single shaft, as shown in Fig. 1.

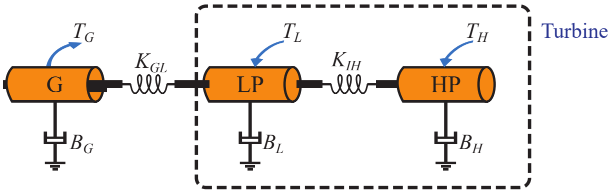

Fig. 1: Turbine generator network.

Figure 1 depicts the entire structure related to the turbine. In this regard, it has been assessed that under normal operating conditions, i.e., when the shaft is rotating at its synchronous speed, these masses undergo torsional oscillations. According to [4], the torsional oscillations can be understood as vibrations occurring at the angle of rotation at which a rotor is rotating. The masses connected to the shaft undergo torsional oscillations because of the difference in their masses, i.e., inertia. These torsional oscillations can be easily diminished with the passage of time under normal conditions [5].

Meanwhile, series compensation, which means reducing or eliminating the reactance of the transmission line by the incorporation of capacitors or any other passive elements, within the transmission network is found to be most effective in terms of controlling the network [8]. Network "control" may include increasing the power transfer capability and the power factor. On the other hand, the series compensation of transmission lines also poses the risk of affecting the system functionality via the occurrence of SSR [2]. We next discuss the SSR phenomenon in detail.

Sub Synchronous Resonance

According to [1], SSR can be understood as the phenomenon that occurs in power systems when the turbine generator (mechanical system) exchanges or transfers energy with the electrical network. We note here that the system exchanges energy at one or more natural frequencies of other interconnected systems. The presence of SSR can lead to several problems. Two major effects of SSR include self-excitation and transient torques. These two problems can be further classified into induction generator effects and torsional interactions [2]. We next briefly examine the various aspects of the SSR problem.

3.1. Self-Excitation

The phenomenon of self-excitation takes place when a current with subsynchronous frequency flows into the terminals of the generator [5], producing subsynchronous-frequency terminal-voltage components. These voltage components can maintain the flow of the current, and this phenomenon is called self-excitation. There are two common categories of self-excitation, one involving both the rotor's mechanical and electrical dynamics and the other involving only the rotor electrical dynamics. The first type of self-excitation is known as torsional interaction [4], while the second one is referred to as the induction generator effect.

1) Torsional Interaction

Torsional interaction often takes place when the induced subsynchronous torque within the generator is close to one of the natural torsional modes of the turbine-generator shaft [8]. Torsional interaction leads to rotor oscillations of the generator, resulting in the stimulation of armature voltage components. This armature voltage is induced at both supersynchronous and subsynchronous frequencies. Furthermore, the induced subsynchronous frequency voltage is phased in order to maintain the subsynchronous torque. In this situation, when this torque exceeds or equals the intrinsic mechanical damping of the oscillating system, self-excitation occurs. This phenomenon is commonly referred to as torsional interaction [3]. The rotor oscillations of the generator rotor, at frequency f_m (torsional mode frequency) stimulate the voltage components of the armature at frequency f_{em}. The corresponding frequency relationship can be expressed as:

$$f_{em} = f_o \pm f_m. \tag{4}$$

According to a previous study [8], torsional interaction can also be understood as the incorporation of negative resistance into the armature of the generator, thereby damaging the shaft of the generator.

2) Induction Generator Effect

The induction generator effect often occurs due to self-excitation of the electrical system. According to [5], the rotor's resistance to subsynchronous current is usually negative. Simultaneously, the network plays a vital role in resisting these same currents, which are positive in nature. On the other hand, if the generator's negative resistance is greater than the magnitude of the positive resistance, there is a constant flow of subsynchronous currents. This entire phenomenon is usually referred to as the induction generator effect [3].

3.2. Transient Torques

Transient torques can be understood as the forces that are produced from disturbances occurring within the system. Such system disturbances [1] can lead to swift and unexpected changes in the network, which may result in variations in the natural frequencies of the network, thus affecting the functionality of the system. System disturbances in transmission systems that do not have series capacitors take the form of only dc transients. On the other hand, transmission networks with series capacitors usually contain one or more oscillatory frequencies [3]. These frequencies depend on the total capacitance, resistance, and inductance of the network. The transient electrical torque comprises a wide range of components including oscillatory torques and unidirectional exponentially decaying torques [2] and [8]. These torques correspond to subsynchronous frequencies as well as multiples of network frequencies.

4. FACTS Devices

FACTS devices are found to be most effective in providing dynamic control of different network parameters. Parameters of interest may include the phase angle, impendence, and voltage of high-voltage AC transmission lines [3]. We discuss some prominent and widely used FACTS devices in the following section.

4.1. Static Series Synchronous Compensator

SSSCs or series compensators are FACTS devices that are considered as an extension of the conventional series of the capacitors. These devices are primarily constructed by adding or incorporating thyristor-controlled reactors along with the conventional series capacitor. As reported previously [8], a controlled reactor positioned in parallel with a series capacitor yields a continually variable and instantaneous variable series compensation system. Some advantages of SSSCs include control of line power flow, dampening of SSR, dampening of power oscillations, and increased energy transfer [4].

4.2. Static Synchronous Compensator

STATCOMs can be considered as Gate Turn Off (GTO)-type thyristor-based Static VAR Compensators (SVCs) [1]. In contrast to traditional SVCs, STATCOMs do not need to have large capacitive and inductive components to provide capacitive and inductive reactive power to high-voltage transmission systems. One of the most significant advantages of STATCOMs is the significantly higher reactive output obtained at low system voltages. The characteristics of STATCOMs are comparable with those of the synchronous condenser [2]. STATCOMs find a wide range of applications including transient stability enhancement, power oscillation damping in power transmission systems, and dynamic voltage control in distribution and transmission systems.

4.3. Unified Power Flow Controller

The Unified Power Flow Controller (UPFC) is the most versatile of FACTS controller capable of control of three system parameters: voltage, power angle, and transfer impedance. UPFC consists of a shunt connected voltage source converter and a series connected voltage source converter. Series voltage converter injects a series voltage while Shunt voltage source converter is controlled to inject reactive current. The series and shunt branches of UPFC can generate/absorb reactive power independently and the two branches can exchange active power. The injection of series reactive voltage provides active series compensation while the injection of the shunt reactive current can be controlled to regulate the voltage at the bus where shunt voltage source converter is connected. The injection of series real voltage (in-phase with the line current) can be controlled to regulate the reactive power in the line or the voltage at the output port of the UPFC [11].

4.4. Use of FACTS Devices in Mitigating SSR

FACTS devices can be understood as a source of the voltage behind a reactance. FACTS devices offer absorptive and reactive power generation through electronic processing of current and voltage waveforms in a VSC, thereby resulting in more stable operation while eliminating SSR [1].

SSRs are usually evaluated with the use of the IEEE second benchmark model. This model is also used to evaluate the torque amplification after the occurrence of a fault; such faults usually occur in series-compensated power systems. The single-line diagram of the IEEE benchmark model is shown in Fig. 2.

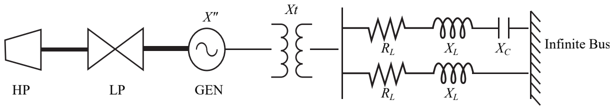

Fig. 2: Single-line diagram of IEEE second benchmark model.

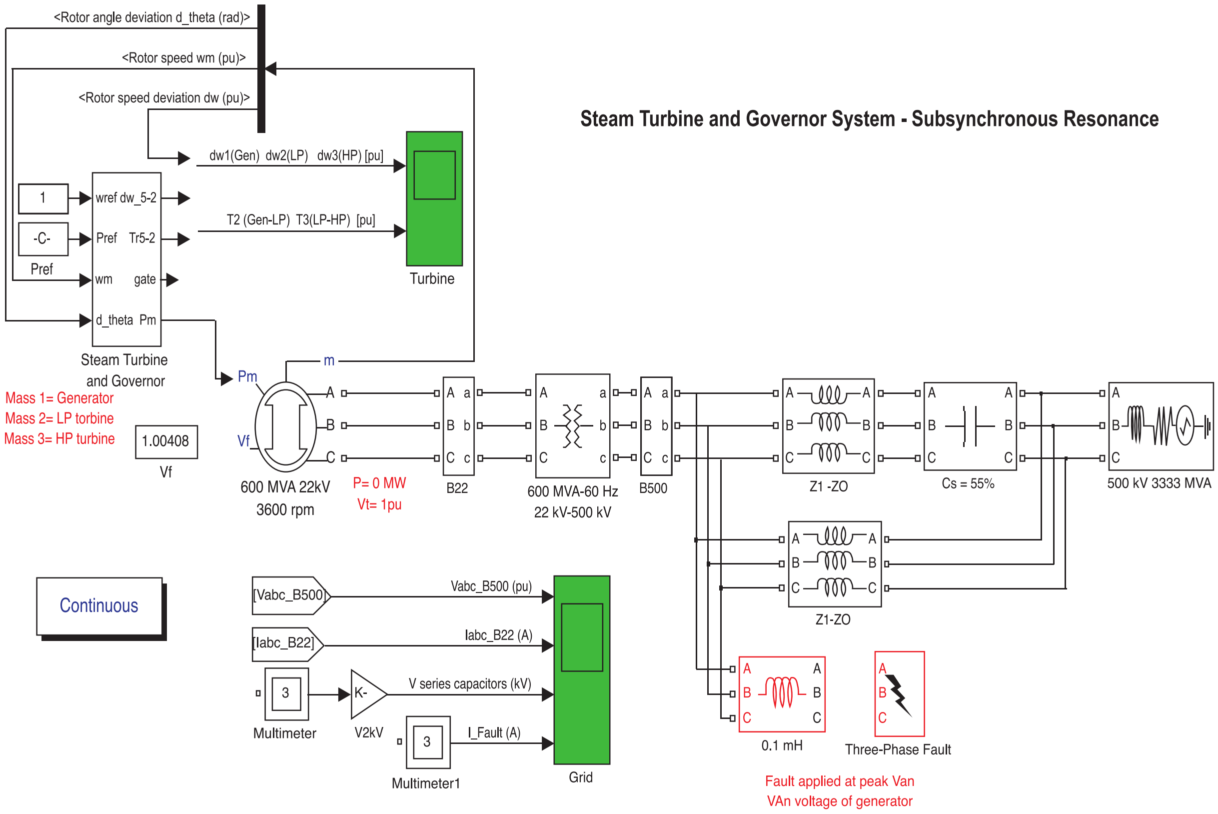

Fig. 3: IEEE second benchmark model.

The overview of this model was incorporated in MATLAB/Simulink in this study, as shown in Fig. 3.

To mitigate SSR using FACTS devices, the entire system or network is connected to an infinite bus. The voltage magnitude is maintained at 1 pu with power at 0 MW. In the simulation, the fault occurs at 0.0169 s, and it is cleared at 0.022 s. Subsequently, the FACTS device is coupled to the middle of the transmission line. The voltage at the terminal of the FACTS devices regulates the absorption and injection of the reactive power from the system in the process of SSR mitigation. However, the threshold voltage is considered as the reference. It has been observed that if the terminal voltage is less than the reference voltage, reactive power is extracted from the system, and when the terminal voltage is greater than the reference voltage, reactive power flows into the system. Table 1 lists the ratings of the STATCOM device used for SSR mitigation. Here, we remark that in our simulation, the reference voltage was assumed as 1 (pu).

Tab. 1: Rating of statcom.

Power	100 MVA
Voltage	500 kV
Frequency	60 Hz

5. Simulation Results

In the simulations, STATCOM, SSSC, and UPFC devices are separately introduced into the transmission network, and the torsional oscillation of the shaft of the turbine generator network is evaluated. From Fig. 4, Fig. 5, Fig. 6, Fig. 7, Fig. 8, and Fig. 9, we note that all three devices (SSSC, STATCOM, and UPFC in that order) are effective in damping the torsional oscillation. For the SSSC, this can be verified by examining the real component of the eigenvalues; positive real-component values indicate a positive damping factor (Tab. 2), which means that SSR can undergo damping. In the light of comparing the efficiencies of the FACTS devices in SSR mitigation, Tab. 5 lists the peak-to-peak values obtained with the three devices. We note that the UPFC offers better damping of the torsional oscillation than the other two FACTS devices. Furthermore, the UPFC damping factor (i.e., the real component) of the eigenvalue is more than those of the other devices, which also signifies that the torsional oscillations are damped more effectively by the UPFC.

From Tab. 5, we note that the UPFC is most efficient in damping torsional oscillations. The damping achieved by the UPFC is decent when compared with the system under fault disturbance.

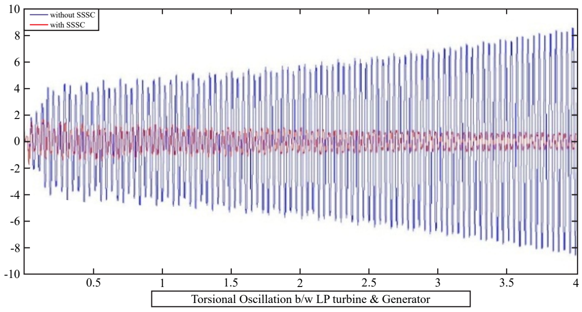

Fig. 4: Variation in torque between LP turbine and generator with use of SSSC.

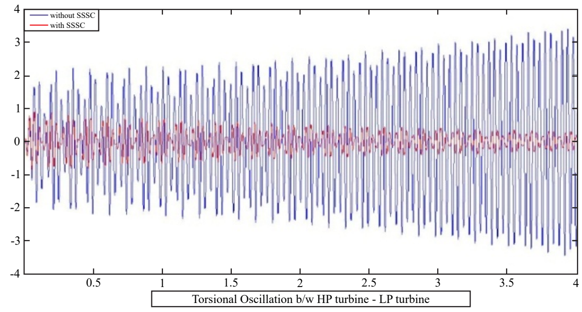

Fig. 5: Variation in torque between HP-LP turbine with application of SSSC.

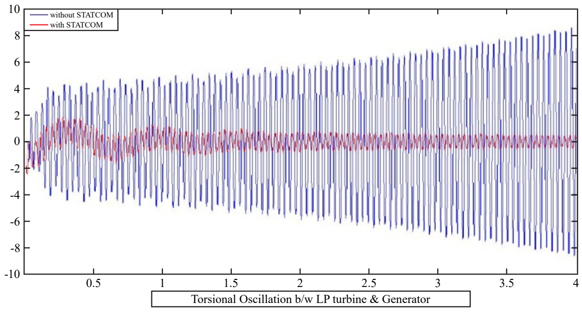

Fig. 6: Variation in torque between ip turbine and generator with application of static synchronous compensator.

Tab. 2: Eigenvalues obtained with static series synchronous compensator.

Eigenvalues	Comments
$-0.045 \pm 7.85j$	Low-frequency mode
$-0.51 \pm 163.28j$	Subsynchronous mode
$-0.43 \pm 207.24j$	Subsynchronous mode

Tab. 3: Eigenvalues obtained with use of static synchronous compensator.

Eigenvalues	Comments
$-0.046 \pm 3.92j$	Low-frequency mode
$-0.521 \pm 155.13j$	Subsynchronous mode
$-0.681 \pm 202.92j$	Subsynchronous mode

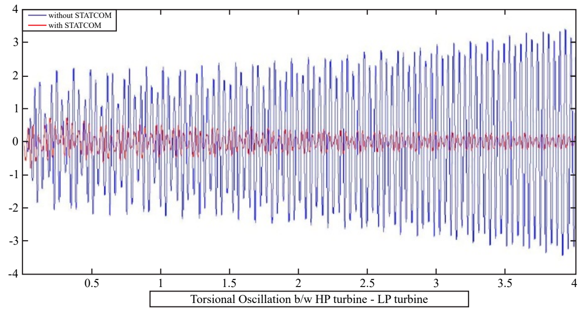

Fig. 7: Variation in torque between HP-LP turbine with use of static synchronous compensator.

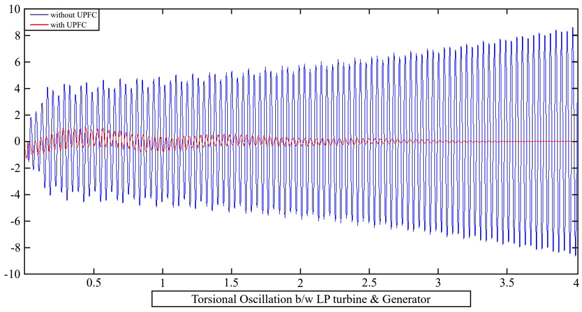

Fig. 8: Variation in torque between LP turbine and generator with UPFC.

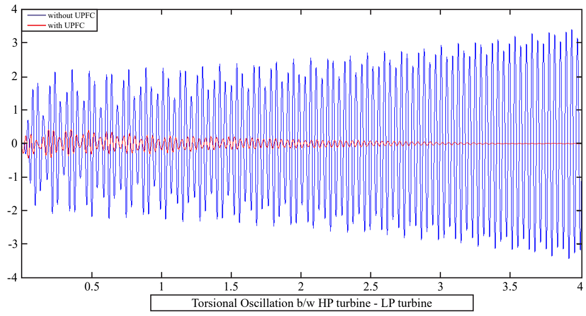

Fig. 9: Variation in torque between HP-LP turbine with UPFC.

Tab. 4: Eigenvalues obtained with unified power flow controller.

Eigenvalues	Comments
$-0.057 \pm 4.46j$	Low-frequency mode
$-0.532 \pm 156.043j$	Subsynchronous mode
$-0.761 \pm 204.84j$	Subsynchronous mode

In the above simulation, the subsynchronous modes of the torsional fluctuations between the networks of turbine-generator were damped, which is evident from Tab. 2, Tab. 3 and Tab. 4 that list the damping factors of the eigenvalues. It is significant that these values are negative. The simulation results indicate that the modes are damped over time. Further, we note that the torque between the generator mass and LP section is considerably low. In addition, the total mechanical stress is also fairly low in this particular region.

Tab. 5: Comparison of peak-to-peak values obtained with the three devices.

	Peak-to-peak torque at 3 s (pu)				
Section	**W/o FACT devices**	**STATCOM**	**SSSC**	**UPFC**	**Dynamic resistance**
HP-LP	5.612	1.207	0.211	0.0856	0.3746
Gen-LP	12.945	2.403	0.221	0.124	0.5695

Our comparison of the damping provided by the three FACTS devices and dynamic resistance can aid in the choice of the FACTS device required to mitigate SSR. Our time-domain and eigenvalue analyses show that the UPFC is the most efficient in damping subsynchronous oscillations. Future studies on dynamic resistance techniques need to focus on the use of inductors, through which energy can be absorbed and used in other processes, thereby increasing the efficiency of the system.

6. Conclusion

Our study on FACTS devices clearly demonstrates their efficacy in mitigating SSR. The presence of SSR has a negative impact in a high-voltage electrical system because it affects the functionality and operation of the system. This study first provides a brief overview of important aspects related to SSR. Next, it briefly introduces three FACTS devices: SSSC, STATCOM, and UPFC. The performances of the three FACTS devices in mitigating SSR are compared via MATLAB simulations. The UPFC is found to be most efficient in damping torsional oscillations. Finally, we draw attention to the use of eigenvalue analysis and the IEEE second benchmark model in studying and mitigating SSR.

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