Reciprocal Impacts of PSS and Line Compensation on Shaft Torsional Modes

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***Abstract*— In this paper, the effects of Power System Stabilizer (PSS) along with an uncompensated or series compensated transmission line on turbine-generator shaft torsional oscillations are investigated. Time domain simulations and eigenvalue analysis are carried out in MATLAB and SIMULINK to study the interaction between PSS and torsional modes. A six-mass shaft is employed to accurately study the torsional oscillations between the masses. The results show that under certain conditions, serious problems may occur between Low Pressure (LP) turbine and generator masses. Also, for a series compensated line, torsional oscillations are likely to occur between Intermediate Pressure (IP) and LP turbines on the shaft at certain levels of compensation. As opposed to electromechanical mode, the PSS not only cannot make any damping improvements to torsional oscillations, but also may even make the situation worse.**

Keywords- Torsional oscillations; series compensated transmission lines; PSS

I. Introduction

Within the last couple of decades, the electricity demand growth has happened so rapidly that the pace of establishing new power plants and corresponding transmission lines (TLs) has been unable to meet the needs. Due to the biological and environmental issues associated with introducing new TLs [1], the utilities have tried to increase the efficiency of the existing transmission systems by means of adding PSS to more number of units, Flexible AC Transmission Systems (FACTS) and phase-shifter transformers [2]. Although these devices have a significant impact on enhancing the utilization factor of the existing systems, they may create interference in the dynamic behavior of other power system equipments. For instance, Sub-Synchronous Resonance (SSR) may occur in series compensated lines with a constant capacitor leading to Turbo-Generator Shaft Oscillation (TGSO) which is among the most dangerous phenomena for power generators. It has been recognized to be so difficult to predict and prevent this group of SSR.

Also, during a transient state (e.g. a single phase to ground fault), currents and voltages may vary in a wide range of frequencies, thus leading to ferroresonance, which is a threat for power system stability and security [3].

Previous studies were conducted on analyzing the impact of FACTS on TGSO and how to control them for damping these oscillations [4-6]. Fault occurrence and reclosing policies have also been investigated and methods for preventing TGSO have been introduced [7], [8]. Most studies have made simplifying assumptions in modeling the shaft stages; for instance, the IEEE second benchmark model [16] proposes two stages to consider the Low Pressure (LP) and High Pressure (HP) stages of a turbine. In this paper, however, a more detailed model with six stages is used, namely: HP, Intermediate Pressure (IP), LBA, LPB, generator and exciter that are all mounted on the shaft [12].

The proposed model in [9] is employed to simulate the electrical and mechanical characteristics of synchronous generator and PSS in MATLAB.

The series capacitors are simple but are not controllable within the time window of power system transients. Therefore, as an alternative, the TCSC is used to enhance the power system stability [10]. However, due to its capacitive nature and the intrinsic limitations of power electronic devices, its impact on SSR cannot be removed completely. Many TCSC control strategies have been proposed for damping SSR [11] that make significant improvement in dynamic behaviors of power systems.

Most of previous researches done on SSR are focused on cases where the interaction of compensated lines and SSR are studied. However, in uncompensated lines, the PSS may have an adverse impact on torsional modes, thus leading to shaft fatigue. Therefore, the interaction of PSS and uncompensated lines are carefully examined and studied in this paper. Besides time domain simulation, results are also confirmed by means of eigenvalue analysis.

In Section II, the modeling procedure is described for each part of the test system. Section III presents simulation results for both time domain and eigenvalue analysis methods. Section IV concludes the main findings of this paper.

II. Modeling Procedure

A single-machine-infinite-bus (SMIB) model is used in this paper as displayed in Fig. 2. Three different sections of the whole system modeled and explained in the following sections.

A. Shaft Model

Mechanical parts of the system include steam turbine and its subsections. Generally, each turbo-generator system has six

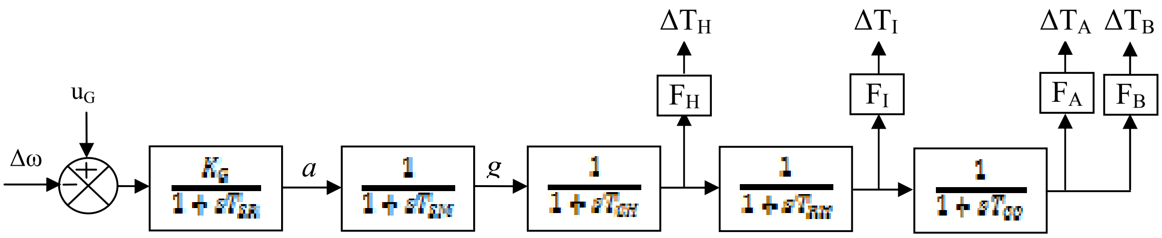

Figure 1. Governor and steam turbine model. u_G is an optional auxiliary signal for enhancing the governor stability.

recognizable parts. The shaft system as displayed in Fig. 3 consists of a turbo-generator, HP, IP, a low-pressure turbine including LPA and LPB, the generator rotor (GE) and a rotating exciter (EX). Mechanical data for this model is taken from the IEEE first benchmark model established for SSR studies and are reported in appendix [12]. There is also a reduced order model proposed in the IEEE second benchmark model [16] which has been previously used for SSR studies, e.g. [13]. Although the 2nd model is much simpler in terms of computation procedure, it does not have enough accuracy for modeling the relation between all torsional modes.

A lumped-mass scheme for turbo-generator mechanical system is shown in Fig. 4 [14] with each major rotating element being modeled as a lumped mass. Also each shaft segment is considered as a massless rotational spring with its spring constant representing the shaft stiffness. D_i denotes mechanical damping; T_{Mi} represents the i^{th} mechanical torque imposed to each mass and $K_{i,i+1}$ is the stiffness factor between neighboring masses.

General differential equation describing this system (in per unit) is:

$$M_i \Delta\dot{\omega}_i = \Delta T_{Mi} - D_i \Delta\dot{\theta}_i + K_{i-1,i}(\Delta\theta_{i-1} - \Delta\theta_i) - K_{i,i+1}(\Delta\theta_i - \Delta\theta_{i+1}),\ 1 \le i \le 6$$
$$\Delta\dot{\theta}_i = \omega_b \Delta\omega \qquad (1)$$

where θ is the rotational angle; ω is the rotational speed and ω_b is the fundamental frequency of network.

Consider that for the first and last mass $K_{i-1,i} = 0$, $K_{i,i+1} = 0$ respectively. Note that for generator mass $\Delta T_{Mi} = \Delta T_E$ and is negative.

Each turbine subsection has a fraction in the whole generated torque which is represented by F_i coefficients. A simplified transfer function for steam turbine and governor is depicted in Fig. 1. In this figure, *a* denotes the speed relay position, *g* the governor opening, *CH* is the chamber before HP turbine, *RH* is the reheater between the HP and IP turbines, and *CO* is the crossover connection between IP and LP turbines. The sum of output torques $(\Delta T_H, \Delta T_I, \Delta T_A, \Delta T_B)$ generates the whole mechanical torque presenting to the generator shaft.

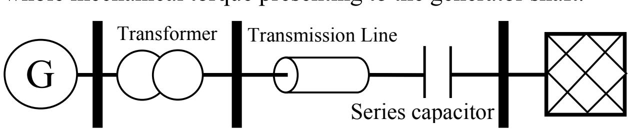

Figure 2. SMIB model with series compensation

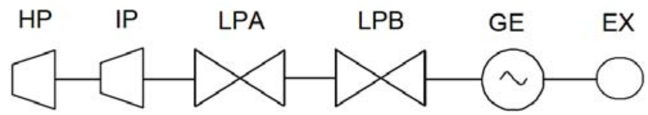

Figure 3. Six part of turbo-generator shaft model according to the IEEE First Benchmark Model

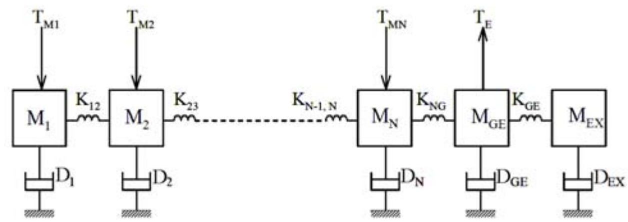

Figure 4. Lumped-mass model for turbo-generator shaft

Figure 5. Block diagram of a typical power system stabilizer (PSS)

B. *Electrical Model of Generator*

There are various models for simulating a synchronous generator. For more accuracy, we have chosen an 8th order model which is fully described in [9]. The state-space equations are reported in the Appendix. The state variables are chosen to be i_d and i_q (stator currents), i_D and i_Q (first damper winding current on rotor), i_S (second damper winding current on q-axis), i_F (field current), V_R (output voltage of AVR), and E_{FD} (field voltage). The PSS contains two parts as shown in Fig. 5: a washout filter and a lead-lag block. Input signal for PSS is decided to be the rotational speed (ω) of generator. Series compensated line is also modeled using method suggested in [9]. After applying Park Transformation to the 3-phase voltages, the following two-dimensional equations are obtained for the capacitor voltage:

$$\begin{pmatrix}\Delta\dot{e}_{cd} \\ \Delta\dot{e}_{cq}\end{pmatrix} = \omega_b \begin{pmatrix}0 & 1 \\ -1 & 0\end{pmatrix}\begin{pmatrix}\Delta e_{cd} \\ \Delta e_{cq}\end{pmatrix} + \omega_b X_c \begin{pmatrix}\Delta i_d \\ \Delta i_q\end{pmatrix} \qquad (2)$$

Voltages across the capacitor (e_{cd} and e_{cq}) are among the state space variables (X_C is the reactance of the fixed capacitance).

III. SIMULATION RESULTS

A. Uncompensated System

In this section, SMIB model with PSS is simulated. The state-space equations are

$$E\dot{X} = A_c X$$
$$\text{or } \dot{X} = (E^{-1} A_c) X \ , \ E \in \mathbb{R}^{27\times 27}, \ A_c \in \mathbb{R}^{27\times 27} \quad (3)$$

Our purpose here is to show that in an uncompensated system, torsional oscillations are possible due to the presence of PSS. Both time domain and eigenvalue analyses are done. Table I shows the eigenvalues of system with and without PSS assuming output power of the generator is set to *0.95p.u.* As it can be seen from Table I, the generator electromechanical mode (GE) is marginally unstable when the PSS is disabled.

PSS parameters are tuned based on the method suggested in [9] which successfully stabilizes the mentioned mode. The presence of PSS adds two new eigenvalues to the system as highlighted in the Table I. Although the PSS has a favorable impact on electromechanical modes, it makes the eigenvalues associated with IP, LPA, EX, LPB and damper current on d-axis less stable. With PSS gain Kc = 40, the LPB mode would become unstable. It means that a torsional oscillation will occur between LPB and GE. This is the main point of this study and should attract more analytical modeling for finding a solution. Figure 7 depicts the difference between the rotational angles of LPB, LPA and GE.

B. Series Compensated System

In this part, a series fixed capacitor is added to the previous model. Therefore, a 29th order system is to be analyzed. The generator operates with 110% of its nominal power and due to the presence of capacitor the electromechanical modes are still stable.

TABLE I EIGENVALUES OF UNCOMPENSATED SYSTEM WITH AND WITHOUT PSS FOR K_C=20 AND K_C=40

State Variable	Without PSS	With PSS, K_C=20	With PSS, K_C=40
HP	-0.18 ± 298.18i	-0.18 ± 298.18i	-0.18 ± 298.18i
IP	-0.24 ± 202.99i	-0.23 ± 202.98i	-0.20 ± 202.96i
LPA	-0.27 ± 160.61i	-0.25 ± 160.60i	-0.22 ± 160.58i
EX	-0.68 ± 127.02i	-0.67 ± 127.01i	-0.66 ± 127.01i
LPB	-0.37 ± 99.05i	-0.24 ± 99.04i	**0.03 ± 99.02i**
GE	**0.04 ± 7.60i**	-2.26 ± 9.80i	-2.31 ± 16.00i
Stator Currents	-12.94 ± 376.73i	-12.94 ± 376.73i	-12.94 ± 376.73i
Damper d-axis	-2.04	-1.93	-1.56
Damper1 q-axis	-24.74	-24.75	-24.75
Damper2 q-axis	-30.67	-38.84	-47.44
Field	-8.54	**-8.52 + 1.96i**	-7.63
AVR	-101.90	-101.09	-99.31
Exciter	-499.98	-499.97	-4.9994
CH	-2.76	-2.73	-2.69
RH	-0.14	-0.14	-0.14
CO	-4.70	-4.73	-4.78
Governor	-4.76 ± 0.87i	-4.75 ± 1.32i	-3.59 ± 1.51i
PSS	Non	**-8.52 - 1.96i**,-0.35	-5.88, -0.38

TABLE II EIGENVALUES ASSOCIATED WITH THE %50-COMPENSATED SYSTEM WITH AND WITHOUT PSS FOR K_C=20

State Variable	Without PSS	With PSS, K_C=20
HP	-0.18 ± 298.18i	-0.18 ± 298.18i
IP	0.35 + 202.73i	0.33 + 202.71i
LPA	-6.54 + 160.81i	-6.90 + 160.97i
EX	-0.73 + 127.09i	-0.71 + 127.09i
LPB	-0.70 + 99.52i	-0.44 + 99.58i
GE	**-0.35 + 9.81i**	-2.07 + 13.59i
Stator Currents	-6.92 + 590.89i	-6.88 + 590.88i
Damper d-axis	-2.04	-1.83
Damper1 q-axis	-24.80	-24.79
Damper2 q-axis	-32.77	-39.74
Field	-7.69	**-7.32**
AVR	-101.51	-101.96
Exciter	-499.98	-500.23
CH	-3.33	-3.31
RH	-0.14	-0.14
CO	-4.00	-4.58
Governor	-4.84 + 0.30i	-4.47 + 0.55i
Capacitor	0.90 + 162.31i	0.92 + 162.08i
PSS	None	**-0.35**

However, IP and capacitor modes are unstable as shown in Table II. Note that in this case only critical modes are reported. It is obvious that PSS does not make significant improvement in mechanical modes of the system even though its impact on electromechanical modes is remarkable. Note that changing the PSS gain (K_C) further cannot make any differences in the situation.

Figure 6 depicts the real part (α) variation of eigenvalues associated with IP versus line compensation factor (*CF*). It can be understood that at 35% of compensation, the maximum instability for the IP mode will occur. Also, there is no big difference between the case with and without PSS.

Figure 8 displays the time variation of $\theta_{IP} - \theta_{LPA}$ and $\theta_{LPA} - \theta_{LPB}$. Comparing these two graphs, the torsional oscillation between LPA and IP is more critical.

As it is reported in [15], with series compensated line, both power and speed feedbacks may contribute negative damping in the frequency range of torsional oscillations of the turbo-generators under certain operating conditions. However, it is underlined that the negative or positive damping introduced by PSS depends on the compensation level and may change under different operating conditions.

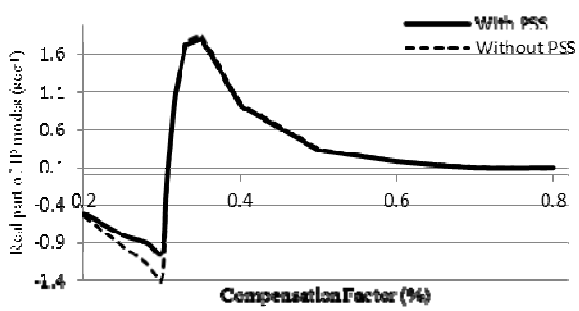

Figure 6. Real part variation of IP eigenvalues versus compensation level with and without PSS

Applying a Linear Optimized Controller (LOC) can fix this problem. However, this controller requires many communicational signals and thus is not reliable in power systems.

In order to perturb the system, a disturbance in delivering power from the generator to the network is applied. This can also be achieved by means of a single-phase fault, operation of a circuit breaker or even changing a tap in power transformer.

IV. Conclusion

The impacts of PSS in both uncompensated and series compensated transmission lines on torsional oscillations of turbo-generator shaft are studied. The results show that torsional oscillations are likely to occur between IP and LPA in series compensated line and between LPB and generator in uncompensated line. Both eigenvalues and time domain simulations were performed and results are reported. It is shown that PSS basically unable to provide damping for mechanical modes of turbo-generator shaft and hence alternative solutions have to be provided including FACTS devices such as TCSC and SVC.

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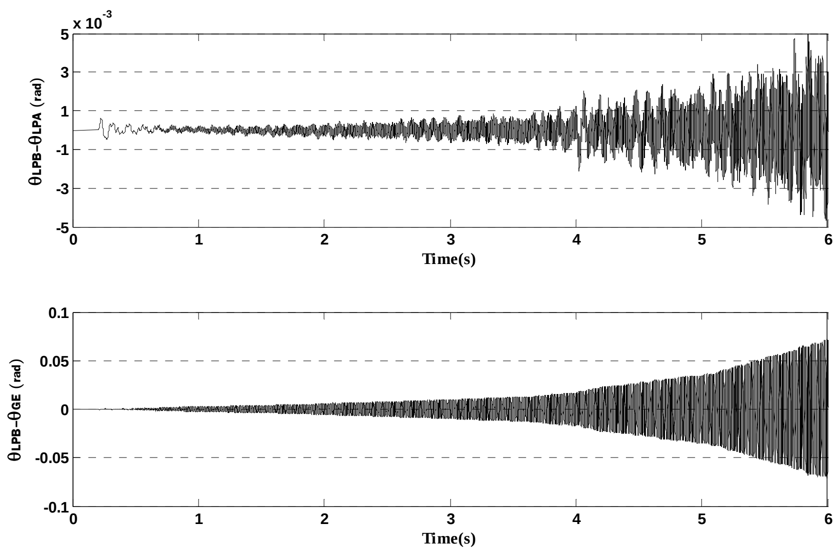


Figure 7. Difference between rotational angles of LPB-LPA and LPB-GE (PSS gain =40, uncompensated system)

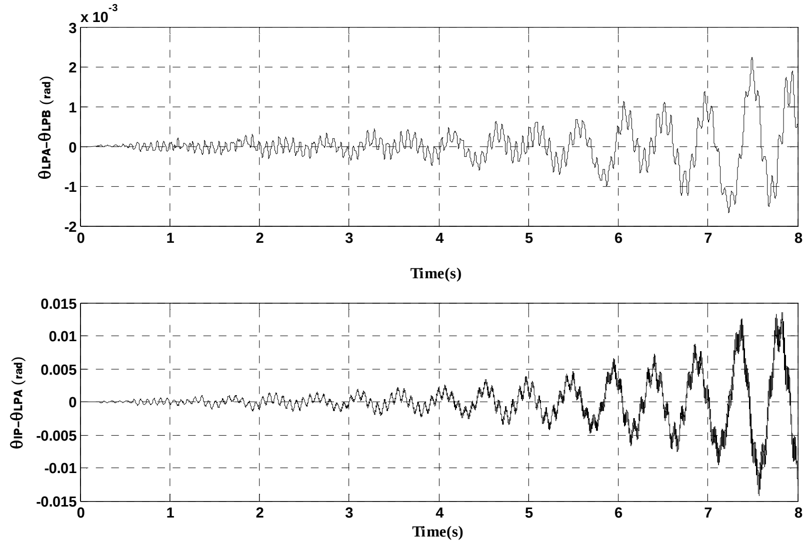


Figure 8. Difference between rotational angles of LPA-LPB and IP-LPA (%35 compensated system)

APPENDIX

GENERATOR PARAMETERS (PU)

x_d=1.79	x'_d=0.169	x''_d=0.135	T'_{do}=4.3	T''_{do}=0.032	x_L=0.13	x_{md}=1.66	x_F=1.7	x_D=1.666
x_q=1.71	x'_q=0.228	x'_q=0.200	T'_{qo}=0.85	T''_{qo}=0.050	R_L=0	x_{mq}=1.58	x_Q=1.695	x_S=1.825
r_F=0.001	r_D=0.0037	r_Q=0.0053	r_S=0.0182	r_a=0.0015	K_A=50	T_A=0.01	T_E=0.002	K_E=1

MECHANICAL PARAMETERS

Mass	Inertia H(sec)	Shaft	Spring Stiffness K(pu)	Torque fraction F	Damping (p.u./rad/s)
HP	0.092897	HP-IP	19.303	0.3	0.1
IP	0.155589	IP-LPA	34.929	0.26	0.1
LPA	0.858670	LPA-LPB	52.038	0.22	0.1
LPB	0.884215	LPB-GE	70.858	0.22	0.1
GE	0.868495	GE-EX	2.822	-	0.1
EX	0.034216				0.1

OTHER PARAMETERS

Governor	K_G = 25	T_{SR} = 0.2	T_{SM} = 0.3	-
Steam Turbine	T_{CH} = 0.3	T_{RH} = 7.0	T_{CO} = 0.2	-
Transmission System	R_T = 0.01	X_T = 0.14	R_{Line} = 0.02	X_{Line} =0.56
PSS	K_C =20	T_1 =0.125	T_2 =0.05	T =3.0
Initial State	Pe_0 =0.9	Vt_0 =1.05	Power Factor =0.9 (lag)	-

GENERATOR ELECTRICAL MODEL EQUATIONS:

$$\frac{1}{\omega_b}\left(-x_d\Delta i'_d + x_{md}\Delta i'_F + x_{md}\Delta i'_D\right) = -x_q\Delta i_q + x_{mq}\Delta i_Q + x_{mq}\Delta i_S + \psi_{q0}\Delta\omega + r_a\Delta i_d + \Delta v_d$$

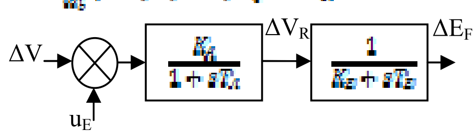
$$\frac{1}{\omega_b}\left(-x_q\Delta i'_q + x_{mq}\Delta i'_Q + x_{mq}\Delta i'_S\right) = x_d\Delta i_d - x_{md}\Delta i_D - x_{md}\Delta i_F - \psi_{d0}\Delta\omega + r_a\Delta i_q + \Delta v_q$$

$$\frac{1}{\omega_b}\left(-x_{md}\Delta i'_d + x_F\Delta i'_F + x_{md}\Delta i'_D\right) = -r_F\Delta i_F + \frac{r_F}{x_{md}}\Delta E_{FD}$$

$$\frac{1}{\omega_b}\left(-x_{md}\Delta i'_d + x_{md}\Delta i'_F + x_D\Delta i'_D\right) = -r_D\Delta i_D$$

$$\frac{1}{\omega_b}\left(-x_{mq}\Delta i'_q + x_Q\Delta i'_Q + x_{mq}\Delta i'_S\right) = -r_Q\Delta i_Q$$

$$\frac{1}{\omega_b}\left(-x_{mq}\Delta i'_q + x_{mq}\Delta i'_Q + x_S\Delta i'_S\right) = -r_S\Delta i_S$$



Excitation System