Performance of Power System Stabilizers in A Fixed Series Capacitor Compensated System

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***Abstract*—In this paper, the performance of two IEEE-type power system stabilizers (PSS), i.e., a slip-signal PSS and a Delta-P-Omega PSS are studied in a fixed series capacitor compensated system employing the IEEE first benchmark system. An eigenvalue analysis of the well-known slip-signal-torsional interaction showed that the slip-signal-interactions occur only when the degree of line compensation is above a certain level depending on the loading condition. The time-domain verifications of the eigen-predictions are carried out through modal speed plots instead of a confusing participation factor-based method. Further, the swing-mode damping performances of PSS are analyzed for different levels of series compensation. This study not only validated the poor swing-mode damping performances of a slip-signal PSS, but also demonstrated that a Delta-P-Omega PSS does not worsen the damping of swing-mode even at higher levels of series compensation which permits a straight forward PSS design.**

***Index Terms*—Eigenvalue analysis, Modal speeds, Power system stabilizers, Subsynchronous resonance.**

I. INTRODUCTION

Series capacitive compensation of long transmission lines is an economical solution to the problem of enhancing power transfer and improving system stability [1]. However, series-compensated transmission lines connected to turbogenerators can result in subsynchronous resonance (SSR) due to the negative damping introduced by the electrical network [2]-[4]. From the literature [5]-[14], it is clear that there has been a continued effort to analyze the SSR phenomenon employing various techniques such as eigenvalue analysis, frequency scanning and time-domain techniques to investigate different countermeasures for mitigating the SSR effects. The analysis of SSR is not straight forward as it requires detailed modeling of network transients in addition to other components and controllers. With the development of FACTS -based systems [15]-[20] to provide an effective solution to the SSR problems, the analysis has become much more complex even for a simple system configuration [18], [20].

Before a full-fledged SSR analysis is taken up with FACTS controllers, it is essential to understand some of the basic characteristics and controller interactions with fixed series capacitor (FSC) compensated cases as there is a widespread usage of FSC in many power systems. For example, in Indian power systems, there exists FSC installations at Raipur-Rourkela, Gorakhpur-Muzaffarpur, Muzaffarpur-Purnea and at Kanpur-Ballabhgarh, to name a few. At some of these installations TCSC controllers have also been implemented. SSR analysis with FSC, generally involves parametric analysis with regard to controller/network parameters and model details of various components. For example in [21] a well known slip-signal-torsional interaction is discussed demonstrating the effect of torsional filters. In this connection, it is shown that power-type PSS perform superior to slip-signal PSS. Where as in [4] the effect of model details employed for generator on SSR is presented. In [22], the effect of different type of exciters in association with slip-signal PSS on SSR damping is illustrated through damping-torque analysis.

Though a parametric kind of analysis has been well documented, in this paper a detailed SSR analysis has been carried out with various IEEE-type controllers for a FSC compensated scheme. The results obtained for the IEEE first benchmark model [23] shows that the Delta-P-Omega PSS performs superiorly not only with regard to the torsional interactions, but also with respect to the swing-mode damping performance in series capacitor compensated systems when compared to slip-signal PSS. The inferences made here are found to be very relevant even when FACTS controllers such as TCSC is used since it is generally used as a top-up with respect to a FSC compensation. The paper is organized as follows. Section II describes the SSR study model and also presents the observations made with regard to the slip-signal-torsional interaction and the swing-mode damping performances of PSS.

II. SSR ANALYSIS- CASE STUDIES

Fig. 1 shows the IEEE first benchmark model (FBM) used in the SSR analysis [23]. In this study mechanical damping is considered as specified in [4] for ease of comparison of results.

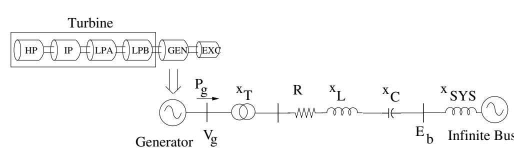

Fig. 1. IEEE first benchmark model.

In the following sections the slip-signal-torsional interaction related observations and the swing-mode damping performances of PSS are discussed.

A. Slip-signal-torsional Interactions

To illustrate the dependency of the well known slip-signal-torsional interaction on the loading level, the level of network compensation and the PSS gain, the following scenario is chosen. The network is tuned to torsional mode-3 choosing

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a single time-constant static exciter and a slip-signal PSS without the torsional filter. Two different loading levels such as P_g= 0.5 and P_g= 1.0 are considered.

1) Effect of Loading Level and PSS Gain: The PSS gain is varied to note its effect on the critical torsional modes (i.e., mode-1 and mode-3) and the results are depicted in Fig. 2. From the study the following observations are made:

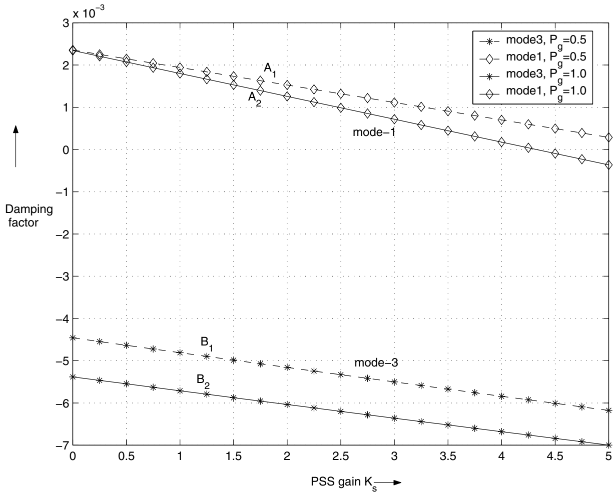

Fig. 2. Critical torsional modes in the presence of slip-signal PSS without torsional filter.

- The damping of torsional mode-1 decreases with an increase in the loading level -see the plots A_1 (for $P_g = 0.5$) and A_2 (for $P_g = 1.0$) in Fig. 2.
- For any loading level, the effect of increased PSS gain is to decrease the damping of mode-1. For a loading level of P_g =1.0 (-see plot A_2), when the PSS gain is increased beyond 4.25 then only the mode-1 becomes unstable.
- The figure also shows that mode-3 continues to be negatively damped at both the loading levels and is more prominent at full load than at 50% loading.

It is observed that when a torsional filter is used in the PSS, the mode-1 becomes stable and mode-3 remains unstable irrespective of the PSS gain. This clearly shows that the mode-1 destabilization is mainly due to the torsional interaction of the unfiltered slip-signal used for the PSS and mode-3 destabilization is caused by the torsional interaction with the network.

NOTE: The above studies are repeated with a Delta-P-Omega PSS instead of a slip-signal PSS. The following are noted:

- Mode-1 remains stable over the entire range of PSS gain demonstrating no torsional interaction unlike the slip-signal PSS.
- Higher loading level slightly worsens the damping of mode-3, but has very little effect on mode-1.
- The above observations are found be true even with the IEEE-type exciters such as AC4A and DC1A exciters.

2) Effect of Series Compensation Level: The effect of series compensation level on slip-signal-torsional interaction is studied for two loading levels, P_g= 0.5 and P_g= 1.0. A single time-constant static exciter and a slip-signal PSS *without* the torsional filter are considered with PSS gain set to K_s=4.5. The following observations are made (see Fig. 3).

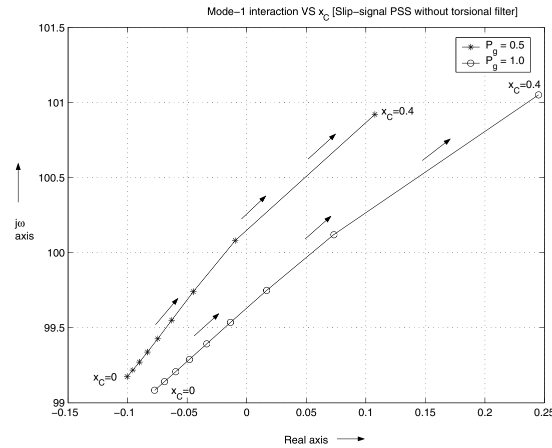

Fig. 3. Effect series compensation level on slip-signal-torsional interaction wrt mode-1.

- At a lower loading level (i.e., P_g= 0.5), mode-1 becomes unstable only when the series compensation is above 70%.
- At full load, mode-1 become unstable when the series compensation is just above 50%.

This task clearly shows that the slip-signal-torsional interactions generally occur depending on the *loading level* and the *magnitude of the network compensation*.

NOTE: In this study a series compensation level above x_C=0.4 is not considered as there is every possibility that mode-1 become unstable due to torsional interaction (TI).

3) Usage of Modal Speeds to Analyze SSR: Having carried out the eigenvalue analysis many a times it is required to verify the predictions by a detailed time-domain simulation. With regard to this, the following difficulties are generally faced:

- The stability inferences made out of the eigenvalue analysis about any particular mode is very difficult to infer from the time-domain simulation as a time-domain response is generally made up of many modes associated with the system.
- As an extension to the determination of eigenvalues, the participation factor -based analysis provides an information about a dominant state variable wrt a mode and observing which in the time-domain simulation, the stability information of that particular mode can be inferred. However, such an analysis is found to be effective in the power swing (i.e., mode-0) oscillation studies and they fail in the analysis of the stiff systems such as SSR studies especially when multiple modes are unstable.

The mode identification using modal speed calculation is found to be very effective in time-domain simulations. Further, the modal speed deviation can also be used as a control

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signal for the supplementary controllers to damp the torsional oscillations [25], [26].

To demonstrate the usage of modal speeds to verify the eigenvalue predictions, a case study with x_C=0.39, P_g=1.0 and a static exciter with a slip-signal PSS (without torsional filter) have been considered. The corresponding eigenvalues are listed in column-1 of Table I. Here, two modes (i.e., mode-1 and mode-2) are seen to be unstable. From the participation factor -based mode verification, the dominant states participating in mode-1 are found to be ω_G and δ_G (G-generator). While in mode-2 they are ω_E and δ_E (E-exciter). However, on observation of the time-domain response of these state variables, it is found to be difficult to verify the eigen-inferences.

TABLE I
EIGENVALUES: SLIP-PSS WITHOUT TORSIONAL FILTER

$x_C = 0.39$	$x_C = 0.15$	Comments
-4.7143± j629.98	-4.6242± j533.85	Supersync. Mode
-2.3736± j123.99	-3.7542± j219.53	Subsync. Mode
-1.8504± j298.17	-1.8504± j298.17	Torsional Mode 5
-0.3457± j202.82	-0.1947± j203.06	Torsional Mode 4
-0.6354± j160.38	-0.6044± j160.68	Torsional Mode 3
0.3659± j126.35	-0.0617± j127.04	Torsional Mode 2
0.1851± j100.77	-0.04809± j99.291	Torsional Mode 1
-2.5355± j12.269	-1.0127± j9.3564	Swing Mode (Mode 0)

In an effort to calculate the modal speed in the simulation responses, the modal speed deviation $\Delta\omega_{Ml}$ corresponding to the mode l is approximately obtained as follows:

$$\Delta\omega_{Ml} = q_l^T[\Delta\omega_{HP}, \Delta\omega_{IP}, \cdots \Delta\omega_{EXC}]^T$$

where, q_l^T is a vector containing the left eigenvector components corresponding to individual angular speed deviations of the rotor masses of the turbine-generator system $(\Delta\omega_{HP}, \Delta\omega_{IP}, \cdots \Delta\omega_{EXC})$.

For the case in hand, the time-domain simulations are carried out in MATLAB/SIMULINK and the modal speed deviations are calculated. These deviations in modal speeds are as shown in Fig. 4. In the figure, the growing oscillations in modal speeds clearly indicate the instability of mode-1 and mode-2. Rest of the modes are seen to be stable as predicted by the eigen-analysis (refer Table I).

A similar case study has been considered with $x_C = 0.15$ and the eigenvalues of which are shown in column-2 of Table I. The modal speed deviation plots are shown in Fig. 5. All modes are seen to be stable as predicted by the eigenvalue analysis.

B. Swing-mode Damping Performance of PSS with FSC Compensation

In this section, the level of FSC compensation in association with the type of PSS on the swing-mode damping performance of a system is analyzed. Here, slip-signal PSS and Delta-P-Omega PSS are compared through a detailed eigenvalue analysis.

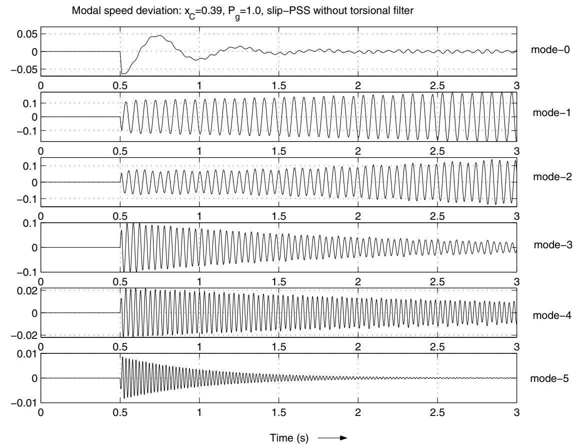

Fig. 4. Modal speed deviations: $x_C = 0.39$ and slip-signal PSS without torsional filter.

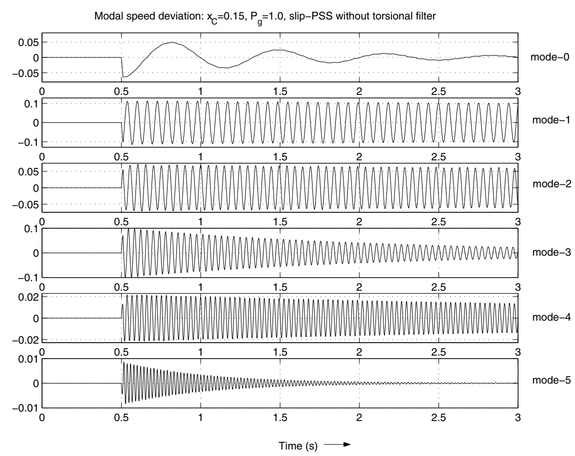

Fig. 5. Modal speed deviations: $x_C = 0.15$ and slip-signal PSS without torsional filter.

1) Swing-mode Damping Performance Without PSS: To start with, a well established swing-mode damping behaviour of a FSC compensated system is studied for two different loading levels, P_g=0.5 and P_g=1.0 without PSS for the first benchmark system. The root-locus plot of the swing-mode is as shown in Fig. 6 when a single-time-constant static exciter is used with $K_A = 200$ and T_A=0.025 s. It can be seen from the figure that as FSC compensation level increases the frequency and damping of the swing-mode increases at both the loading levels. Further, at higher loading levels (i.e., $P_g = 1.0$) negative damping of the swing-mode is observed due to the presence of the high gain, fast- acting exciter, as expected.

2) Swing-mode Damping Performance With PSS:
With slip-signal PSS:

A slip-signal PSS is designed for the system when the series compensation, x_C is 0.3 and the loading level, P_g is 1.0. A phase lead circuit (with center frequency f_m=2.37 Hz and angle lead ϕ_m=22.29^o) and a torsional filter (with ζ=0.6 and

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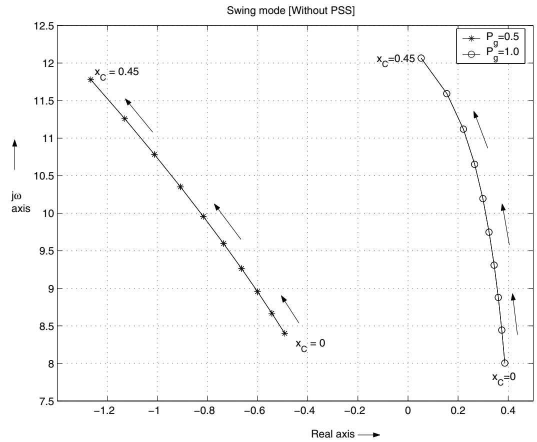

Fig. 6. Root locus of swing-mode in the absence of PSS.

ω_n=22 rad/s) are chosen so that the swing-mode damping factor is about 5% with K_s=4.5 [4]. With this configuration when the FSC compensation is varied from x_C=0 (i.e., no compensation) to x_C=0.45 (i.e., 90% compensation) in suitable steps, the following observations are made (see Fig. 7):

1) At both the loading levels, the damping for the swing-mode improves with the series compensation up to a certain level of compensation, (i.e., x_C=0.35 at P_g=0.5 and x_C=0.2 at P_g=1.0), beyond which an increase in the compensation worsens the damping unlike in a case where the PSS is absent.
2) With full load, an increase in the compensation beyond x_C=0.4 results in an unstable swing-mode.

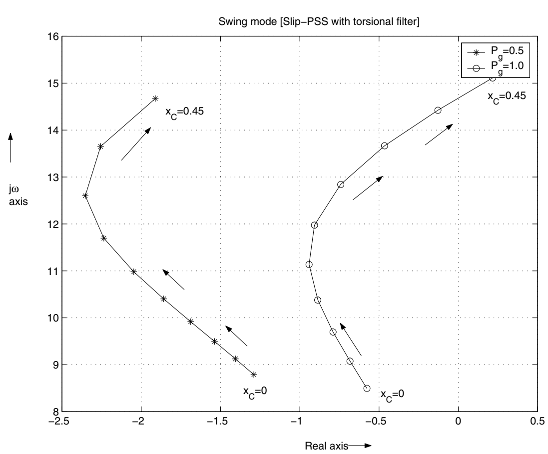

Fig. 7. Root locus of swing-mode with slip-signal PSS and torsional filter.

With Delta-P-Omega PSS :

The above study has been repeated with a Delta-P-Omega PSS. Here, the parameters of the PSS are chosen to be the same as that with the slip-signal PSS. The root-locus plot of the swing-mode is depicted in Fig. 8. From the figure it can be concluded that

- As FSC compensation increases the damping of the swing-mode continues to increase unlike that with the slip-signal PSS. Thus, it can be said that a Delta-P-Omega PSS aides the damping performance of a series compensated system, where as a slip-signal PSS may tend to nullify the inherent swing-mode damping of the system (without a PSS).
- Even at higher compensation levels, a Delta-P-Omega PSS continues to offer positive damping for swing-mode at full load.

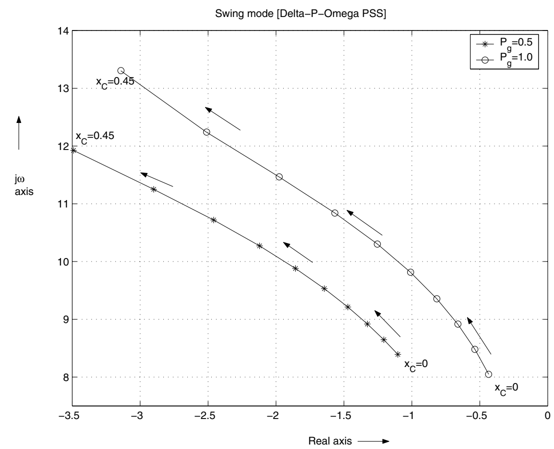

Fig. 8. Root locus of swing-mode with Delta-P-Omega PSS.

An example with FSC compensation $x_C = 0.35$ with PSS:
For this case, the eigenvalues are listed in Table II for two types of PSS, a slip-signal PSS (with torsional filter) and a Delta-P-Omega PSS, for P_g =1.0.

TABLE II
EIGENVALUES: FSC COMPENSATION OF $x_C = 0.35$.

slip-signal PSS	Delta-P-Omega PSS	Comments
-4.7059± j616.65	-4.7053± j616.56	Supersync. Mode
-2.243± j137.18	-2.2852± j137.11	Subsync. Mode
-1.8504± j298.17	-1.8504± j298.17	Torsional Mode 5
-0.3634± j202.82	-0.3632± j202.82	Torsional Mode 4
-0.6291± j160.31	-0.6289± j160.31	Torsional Mode 3
-0.0422± j127.22	-0.0388± j127.23	Torsional Mode 2
-0.2401± j99.767	-0.2246± j99.793	Torsional Mode 1
-0.4649± j13.66	-1.9778± j11.465	Swing Mode (Mode 0)

From the table it can be seen that the swing-mode damping with the slip-signal PSS is relatively low compared to that with the Delta-P-Omega PSS. These observations are verified by a SIMULINK run for both the PSS -see Fig. 9. It is also found that when $x_C = 0.42$, (see Fig. 7) the swing-mode becomes unstable with the slip-signal PSS. This has been validated even using the augmented GEP(s) phase angle [27] study. The increased phase angle with FSC compensation showed the need for re-designing a slip-signal PSS for the highest possible series compensation and the loading level. These design requirements may have the following implications:

- The lead compensator needs to be designed for a large phase angle effecting the noise performance of the PSS.
- The PSS performance may be influenced prominently when dynamic series compensators are used.

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The above difficulties/constraints need not be dealt with a Delta-P-Omega PSS.

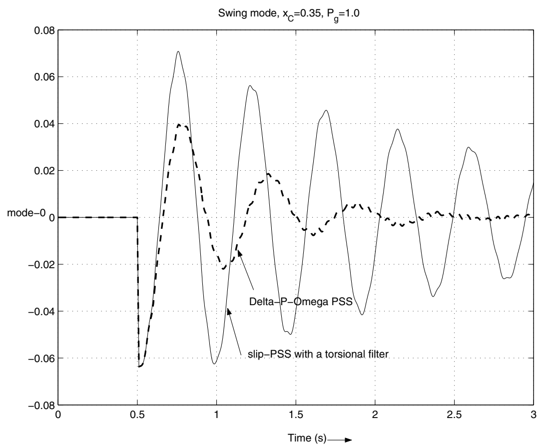

Fig. 9. Swing-mode: $x_C = 0.35$, P_g=1.0.

III. CONCLUSIONS

This paper discusses the behaviour of two types of PSS, a slip-signal PSS and a Delta-P-Omega PSS with regard to the well known slip-signal-torsional interaction and swing-mode damping performance of PSS when a system is FSC compensated. The following inferences are made:

1) A slip-signal PSS suffer from the problem of torsional interactions depending on the level of series compensation. At a low compensation level such an interaction may not occur.
2) A slip-signal PSS is generally designed for a strong system to take into account the destabilization effect due to the increased phase angle lag. Such a requirement may effect the overall damping performance of the system when dynamic compensators are used.
3) Delta-P-Omega PSS performs superiorly not only with regard to the torsional interactions, but also with respect to the swing-mode damping performance in series capacitor compensated systems when compared to slip-signal PSS. Thus, design of a Delta-P-Omega PSS for series compensated systems is very straight forward and can be tuned for an uncompensated system unlike a slip-signal PSS.

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