Some Aspects of Power System Stabilizer Performance in Subsynchronous Resonance Study

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***Abstract*—In this paper, behavioural aspects of two types of 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 for SSR study. The well-known slip-signal-torsional interaction is studied to understand its dependency on the magnitude of network compensation. From such a study it is noted that the slip-signal-interaction is prominent only at higher degree of line compensation. It is also shown that Delta-P-Omega PSS is immune to such torsional interactions. Further, using the eigenvalue-based study, the swing-mode damping performance of slip-signal PSS and Delta-P-Omega PSS are studied when a system is series compensated. This study not only demonstrated the superiority of Delta-P-Omega PSS, but also validated the poor performance of slip-signal PSS. All these observations are verified by carrying out simulations on PSCAD/EMTDC. To enhance the understanding about the SSR phenomenon, some fundamental observations made in the study are also listed.**

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

I. Introduction

Subsynchronous resonance (SSR) has been the subject of concern for utilities and researchers when long transmission lines are compensated with fixed series capacitors (FSC) and are connected to turbo-generators [1]-[13]. The SSR is mainly due to the negative damping introduced by the electrical network in the form of torsional interaction (TI) and/or induction generator effect (IGE). The reduction of damping at torsional frequencies tends to magnify shaft torque oscillations when a transient disturbance occurs. From the literature, 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 SSR analysis 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 [14]-[19] to provide an effective solution to the SSR problems, the analysis has become much more complex even for a simple system configuration [17], [19].

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 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. SSR analysis with FSC, generally involves parametric analysis with regard to controller/network parameters and model details of various components. For example in [20] a well known slip-signal PSS-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 [12] the effect of model details employed for generator on SSR are presented. In [21], 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 FSC compensated scheme

- To illustrate some of the fundamental issues with SSR which are of academic interest.
- To demonstrate the dependency of the well known slip-signal-torsional interaction on the magnitude of network compensation. The eigenvalue-value based prediction has been validated by performing time-domain simulations on PSCAD/EMTDC [22] by calculating the modal-speeds for the system.
- To show the effect of the level of FSC compensation (i.e., the strength of the system) in association with the type of PSS on the swing-mode damping performance of a system. Here, slip-signal PSS and a dual-input PSS, Delta-P-Omega PSS [23], are compared through a detailed eigenvalue/time-domain/modal speed analysis.

The results obtained for the IEEE first benchmark model [24] 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 some of the fundamental observations made related to the SSR. The slip-signal PSS-torsional interaction related observations and the swing-mode damping performance of PSS are discussed in Section III.

II. SSR Analysis- Some Fundamental Observations

Fig. 1 shows the IEEE first benchmark model (FBM) used in the SSR analysis [24]. The circuit is composed of a 892.4 MVA synchronous generator connected to an infinite

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bus via a FSC compensated 500 kV transmission line. The mechanical system consists of a four-stage steam turbine, the generator and a rotating exciter.

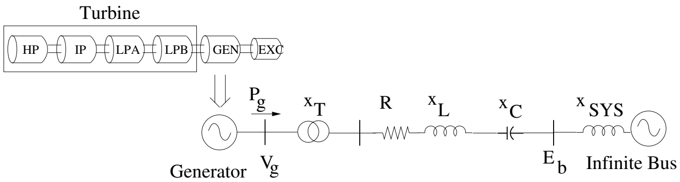

Fig. 1. IEEE first benchmark model.

The mechanical system is modeled by a multi-mass spring-dashpot system, with six lumped masses coupled by shaft sections of known torsional elasticity. The system data are provided in [24]. Mechanical damping is considered as specified in [12] for ease of comparison of results.

Some of the fundamental observations related to the SSR analysis of the IEEE FBM have been listed below for ready reference as they enhance the understanding about the SSR phenomenon.

1) Induction generator effects (IGE) and torsional interactions (TI) are not mutually exclusive and will co-exist, but are often separated for ease of analysis. For example, considering only the rotor electrical circuit transients without mechanical system dynamics, the SSR is only due to IGE, however, when classical model (where there is no rotor electrical circuit dynamics) is employed with mechanical system dynamics, the SSR is only due to TI. Such kinds of analysis are purely of academic interest.
2) Effect of generator model: When detailed (2.2) model or any reduced (1.1) model is employed for the generator, TI inferences are almost similar with a little difference in the damping and frequencies of the modes. However, detailed generator model has to be employed for accurate IGE studies. Further, q-axis rotor circuit has a strong influence on IGE than the d-axis rotor circuits.
3) Network resistance plays an important role in IGE. At lower compensation levels, a lower value of network resistance is sufficient to trigger IGE.
4) IGE is found to be independent of the loading level. However in TI studies, an increase in the loading level will result in an increase in the negative damping for the critical torsional mode.
5) Turbine model has a little effect on TI except for a small decrease in the swing-mode damping.
6) Each of the torsional modes has its largest SSR interaction at a certain value of the series capacitor compensation level x_C. Table I presents the frequency and the level of series compensation associated with the maximum torsional interactions. These compensation levels are found to be less effected by the type of PSS/exciter employed. From the table, it can be seen that torsional mode-2 becomes unstable at x_C = 0.38 (i.e., 76% compensation). However, it is found that the mode-2 becomes stable at x_C = 0.41 (i.e., 82% compensation). This means that TI is a discrete event. Therefore any compensation level can be used unless the network subsynchronous mode frequency does not coincide or in the close proximity with any of the torsional mode frequency.

TABLE I
FREQUENCY OF OSCILLATION AND CAPACITIVE REACTANCE FOR THE MAXIMUM TI

Mode	Frequency (Hz)	x_C
Torsional mode-4	32.368	0.18
Torsional mode-3	25.472	0.29
Torsional mode-2	20.221	0.38
Torsional mode-1	15.62	0.44

7) At very low compensation level, say at $x_C = 0.038$, even though the frequency of subsynchronous mode coincides with that of the torsional mode-5, the mode damping remains unaltered due to its high value of modal inertia. This shows that mode-5 cannot be controlled by any means.

III. CASE STUDIES

In this section slip-signal-torsional interaction related observations and the swing-mode damping performance of PSS are discussed.

A. Slip-signal-torsional Interactions

In this section, dependency of slip-signal-torsional interaction on the level of series compensation in association with the type of PSS is illustrated. The loading level of P_g=1.0 is assumed.

1) With Slip-signal PSS: In order to illustrate slip-signal-torsional interaction, two different compensation levels i.e., x_C=0.38 and x_C=0.25 are considered. A single time-constant static exciter and a slip-signal PSS without the torsional filter is considered with PSS gain set to K_s=4.5.
The eigenvalues corresponding to x_C=0.38 are listed in column-1 of Table II. Here, two modes (i.e., mode-1 and mode-2) are seen to be unstable. Mode-1 destabilization is due to the torsional interaction of the unfiltered slip-signal used for the PSS and mode-2 destabilization is caused by the torsional interaction with the network. The mode identification using modal speed calculation is found to be very effective in time-domain simulations.

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 PSCAD/EMTDC and the modal speed deviations are calculated. These deviations in modal speeds are as shown

TABLE II
EIGENVALUES: SLIP-PSS WITHOUT TORSIONAL FILTER

$x_C = 0.38$	$x_C = 0.25$	Comments
-4.7118± j626.71	-4.6715± j579.53	Supersync. Mode
-3.021± j126.91	-3.2074± j174.06	Subsync. Mode
-1.8504± j298.17	-1.8504± j298.17	Torsional Mode 5
-0.34602± j202.82	-0.34136± j202.63	Torsional Mode 4
-0.63562± j160.35	-0.46444± j161.08	Torsional Mode 3
0.93444± j126.90	-0.05678± j127.07	Torsional Mode 2
0.14439± j100.55	-0.013581± j99.537	Torsional Mode 1
-2.4337± j12.10	-1.4638± j10.382	Swing Mode (Mode 0)

in Fig. 2. 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 II).

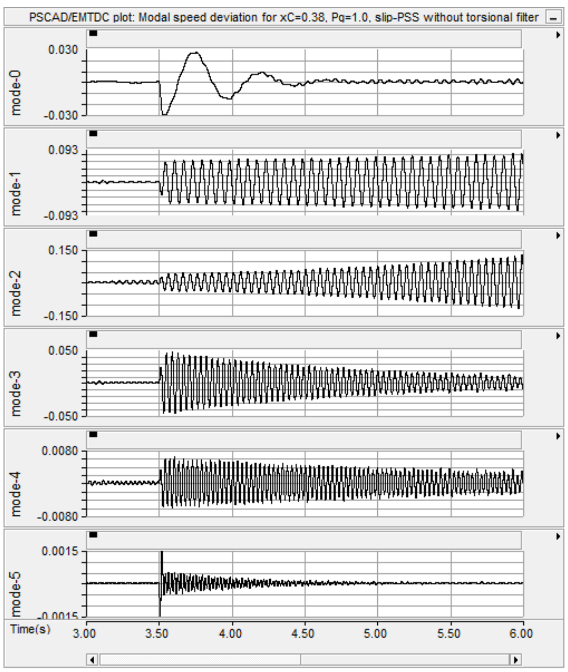

Fig. 2. Modal speed deviation: $x_C = 0.38$ and slip-signal PSS without torsional filter.

The eigenvalues corresponding to $x_C = 0.25$ are shown in column-2 of Table II. The modal speed deviation plots are shown in Fig. 3. All modes are seen to be stable as predicted by the eigenvalue analysis.

The above case studies illustrated that the slip-signal-torsional interaction is more prominent at higher series compensation levels when a slip-signal PSS is used.

2) With Delta-P-Omega PSS: In order to study the slip-signal-torsional interaction in the presence of Delta-P-Omega PSS, the compensation level of x_C=0.38 is considered. The corresponding eigenvalues are listed in Table III. From the table mode-1 is seen to be stable unlike in the case of slip-signal PSS without torsional filter. Where as mode-2 remain unstable as it is due to network interactions. These eigen

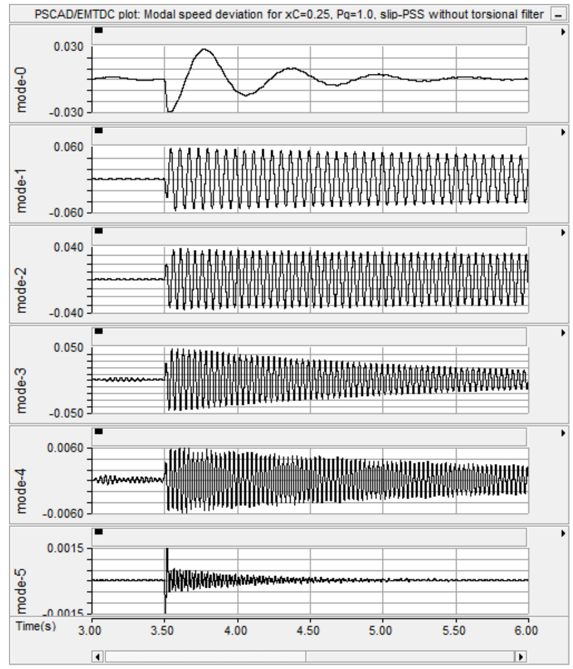

Fig. 3. Modal speed deviation: $x_C = 0.25$ and slip-signal PSS without torsional filter.

predictions are further justified from the modal speed deviation plots -see Fig. 4. This case study demonstrated the immunity of a Delta-P-Omega PSS to torsional interaction.

TABLE III
EIGENVALUES: $x_C = 0.38$ AND DELTA-P-OMEGA PSS

Eigenvalues	Comments
-4.7133± j626.71	Supersync. Mode
-2.7651± j126.91	Subsync. Mode
-1.8504± j298.17	Torsional Mode 5
-0.36406± j202.84	Torsional Mode 4
-0.63964± j160.40	Torsional Mode 3
0.76716± j127.03	Torsional Mode 2
-0.21619± j100.10	Torsional Mode 1
-2.2825± j11.904	Swing Mode (Mode 0)

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 for two different loading levels, P_g=0.5 and P_g=1.0. Here, slip-signal PSS and Delta-P-Omega PSS are compared through a detailed eigenvalue analysis involving the plot of well-known GEP transfer function [25],[26].

1) 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 ω_n=22 rad/s) are chosen so that

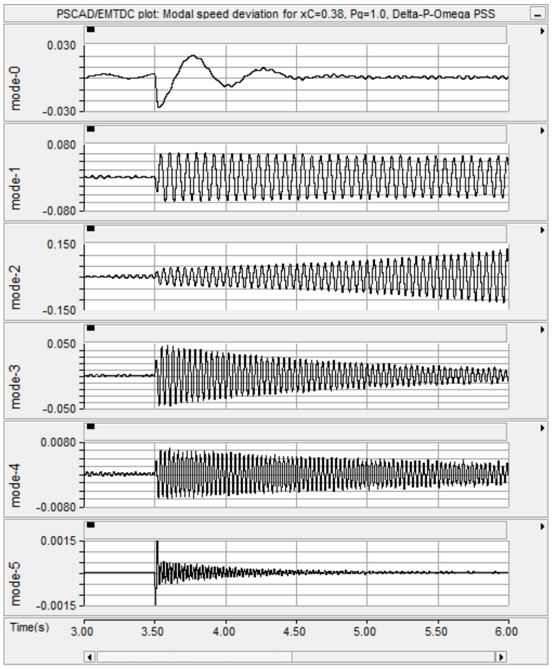

Fig. 4. Modal speed deviation: $x_C = 0.38$ and Delta-P-Omega PSS.

the swing-mode damping factor is about 5% with K_s=4.5 [12]. 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. 5):

1) At both the loading levels, 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.
2) With full load, an increase in the compensation beyond x_C=0.4 results in an unstable swing-mode.

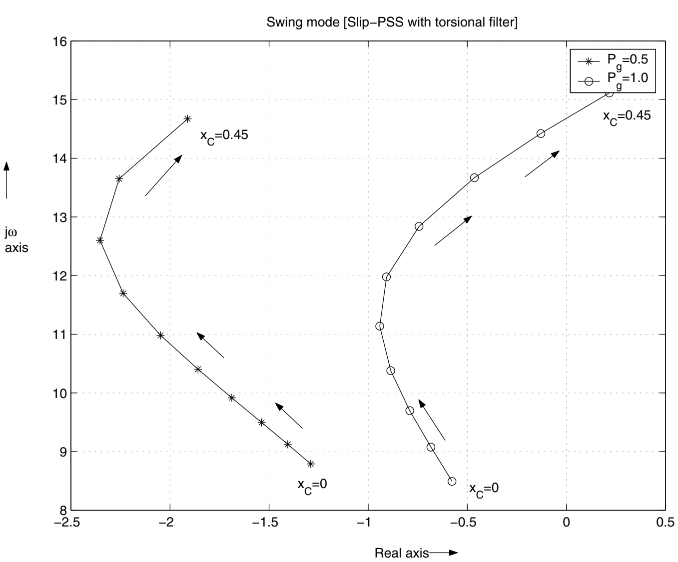

Fig. 5. Swing-mode in the presence of slip-signal PSS with torsional filter.

2) *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 same as that with the slip-signal PSS. The root-locus plot of the swing-mode is depicted in Fig. 6. 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.

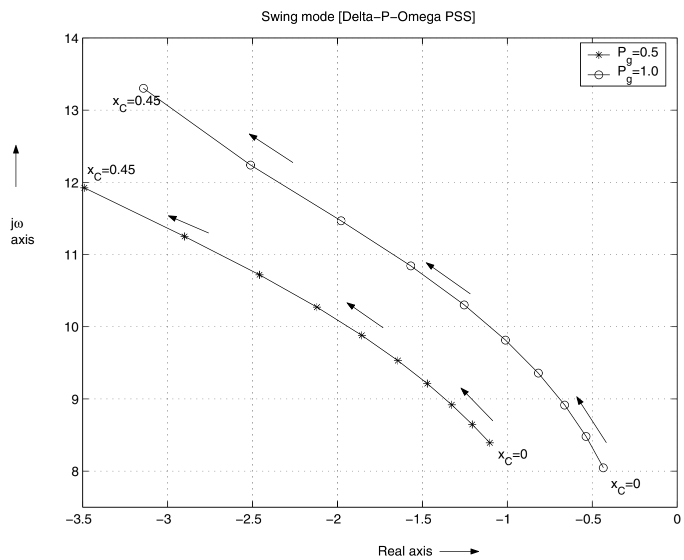

Fig. 6. Swing-mode in the presence of Delta-P-Omega PSS.

3) *GEP Transfer Function- based Analysis:* The above inferences about the change in the swing-mode damping with a variation in the FSC compensation in the presence of PSS can be better explained with the help of a GEP transfer function, i.e., $GEP(s) = \frac{\Delta T_e(s)}{\Delta V_{ref}(s)}$ -based analysis. The phase angle response of the augmented $GEP(s)$ which is the combined phase response of the $GEP(s)$ and the PSS-transfer function, provides better insight into the behaviour. Fig. 7 shows the phase response of the augmented $GEP(s)$ (denoted as the phase angle lag ϕ_a) for two different compensations levels, x_C=0 and x_C=0.35 at full load. From the figure it can be said that

1) The phase angle lag 'ϕ_a' increases with an increase in the series compensation.
2) In the case of Delta-P-Omega PSS, for the compensation level of x_C=0.35, ϕ_a is around 26^o at 2.5 Hz and it is found to be less than 50^o in the swing-mode frequency range even at 90% series compensation. This has assured enough positive damping torque at swing-mode frequencies. Hence the swing-mode remains stable even at increased compensation.

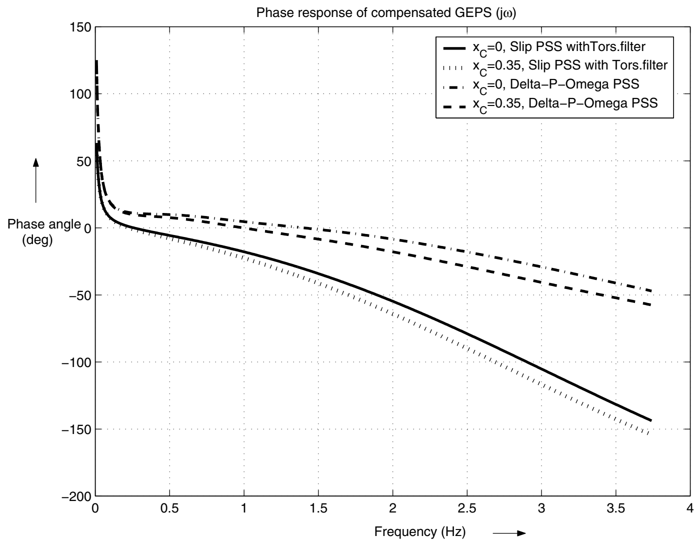

Fig. 7. Phase response of the augmented $GEP(s)$.

3) In the case of slip-signal PSS (with torsional filter), for the compensation level of x_C=0.35, the phase angle lag ϕ_a is nearly 90^o at 2.5 Hz. Also, for a series compensation of x_C=0.4 and above, ϕ_a is found to be more than 90^o resulting in a negative damping torque causing the swing-mode destabilization. This is mainly due to the fact that the torsional filter offers a significant phase lag due to which ϕ_a becomes excessively large at the increased compensation level.

The above case studies are further verified by performing time-domain simulations on PSCAD/EMTDC. Fig. 8 shows the swing-mode damping performance of the slip-signal PSS for both the compensation levels, i.e., x_C=0 (thick line plot) and x_C=0.35 (thin line plot). The increase in the swing mode frequency and reduction in the damping at x_C=0.35 can be seen in the figure as predicted in Fig. 5.

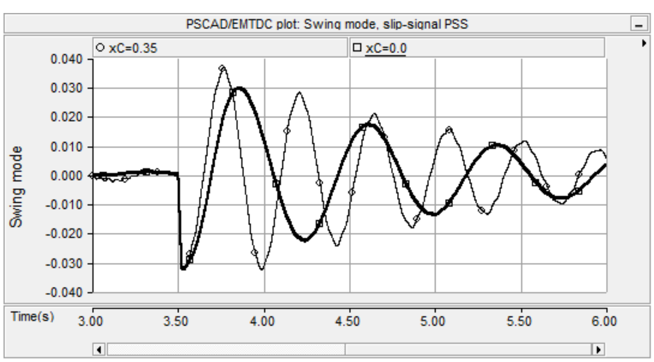

Fig. 8. Swing-mode in the presence of slip-signal PSS with torsional filter.

Fig. 9 shows the swing-mode damping performance of the Delta-P-Omega PSS for x_C=0 and x_C=0.35. The increase in the swing-mode frequency and the improvement in the damping are evident in the figure.

The above study clarifies the need for designing a slip-signal PSS for the highest possible series compensation and the

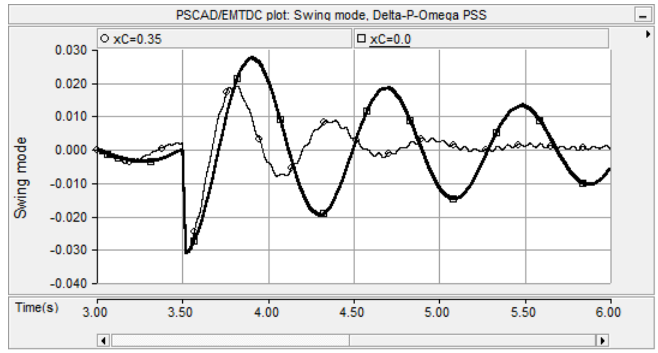

Fig. 9. Swing-mode in the presence of Delta-P-Omega PSS.

loading level. This design requirement may have the following implications:

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

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

IV. Conclusions

This paper presents some of the basic know-how about the SSR analysis when FSC compensation is employed. In addition, it discusses the behaviour of two types of PSS, a slip-signal PSS and a Delta-P-Omega PSS with regard to the 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. However there is no such problems with Delta-P-Omega PSS.
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 is not there with a Delta-P-Omega PSS as it can be tuned for an uncompensated system.

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