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DAMPING OF ELECTROMECHANICAL MODES USING POWER SYSTEM STABILIZERS (PSS) CASE: ELECTRICAL YEMENI NETWORK

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The aim of this paper is to examine the effect of inclusion of a power system stabilizer (PSS) in improving the dynamic stability of different power systems. A nonlinear dynamic model of PSS is applied here to study two electrical network configurations in order to show the influence of PSS controller to damp unstable interarea electromechanical modes. Such modes appeared during a previous study conducted to investigate the dynamic stability of the Yemeni electrical network. Nonlinear simulation using Matlab/Simulink is applied on a single machine infinite bus system to show the effect of using PSS in enhancement of power system dynamics. Also, small signal stability analysis is used in this paper to prove the improvement of voltage stability of the Yemeni network when PSSs are included in system representation.

Keywords: power system dynamics, power system stabilizers, voltage stability, small signal stability

1 INTRODUCTION

Supplementary excitation control, commonly referred to as power system stabilizer (PSS) has become an important means to enhance the damping of low frequency oscillations, *ie* dynamic or steady-state stability [1–4, 6]. The coordination of power system stabilizers for improved dynamic performance of multi-machine power systems, and in particular methods for determination of PSS parameters [5], have drawn much attention. In a previous paper the investigation of the dynamic stability of the Yemeni electrical power network [7] has shown the existence of interarea oscillatory electromechanical mode. The sources of such an interarea mode have been determined using sensitivity analysis. To overcome the unwanted effect of this mode a PSS is used. A dynamical model of PSS is included to investigate the effect in providing positive damping to overcome the undamped electromechanical modes. In some cases PSSs are used as an additional control feature so that that excitation system with a high response may be used without compromising the small signal instability of the generators. A practical stabilizer has as input either a generator speed, terminal voltage frequency or electrical power. Its output is normally a signal applied to the reference input of the automatic voltage regulator. Here, the generator speed is used as an input. The design of PSS is not the subject of this paper and it can be found in different references [8–10]. This paper is organized as follows. Section 2 presents the dynamic voltage stability model of different electrical components used. Two study cases are in Section 3. A single machine against infinite bus model is studied using Matlab/Simulink first in Section 3 with and without PSS. Then a larger system of the Yemeni network has been studied with PSS provided at some generator sites. The study details and simulation results are presented in this section.

2 THE DYNAMIC VOLTAGE STABILITY MODEL

The dynamic voltage stability model includes the following components: the nonlinear machine model with a 2-axis representation of the generator, the IEEE Type 1 excitation system, the power system stabilizer.

In this model the direct axis internal transient voltage E'_d is very small compared to the quadrature axis internal transient voltage E'_q. Thus, the effect of this can be neglected for the simplicity of analysis [11]. However, in this paper the model is taken as a whole, *ie* with E'_d. The nomenclature of different symbols is given in Appendix 1. The dynamic voltage stability model of the generator, excitation and PSS using operational calculus (s - is the differential operator), is expressed as follows

Generator Model and Type 1 IEEE Excitation:

$$T'_{do}sE'_{qi} = -E'_{qi} - (X_{di} - X'_{di}) + E_{fdi} \tag{1}$$

$$T'_{qo}sE'_{di} = -E'_{di} + (X_{qi} - X'_{qi}) \tag{2}$$

$$P\delta_i = \omega_0(v_i - 1) \tag{3}$$

$$2H_i s v_i = E'_{qi} - D_i(v_i - 1) + T_{mi} \tag{4}$$

$$T_{Fi}sR_{Fi} = -R_{Fi} + \frac{K_{Fi}}{T_{Fi}}E_{fdi} \tag{5}$$

$$T_{Ei}sE_{fdi} = -(K_{Ei} + S_{Ei})E_{fdi} + V_{Ri} \tag{6}$$

$$T_{Ai}sV_{Ri} = K_{Ai}\big(R_{Fi} - V_{ti} + V_{refi} - \frac{K_{Fi}}{T_{Fi}}E_{fdi}\big) - V_{Ri} + K_{Ai}U_{Ei}\,. \tag{7}$$

PSS model:

$$sX_{pssi} = -\frac{1}{T_{ri}}X_{pssi} + \frac{1}{\omega_s}sv_i \tag{8}$$

$$sU_{E2i} = -\frac{1}{T_{2i}}U_{E2i} + \frac{k_{Ci}}{T_{2i}}X_{pssi} + \frac{T_{1i}K_{Ci}}{T_{2i}}sX_{pssi} \tag{9}$$

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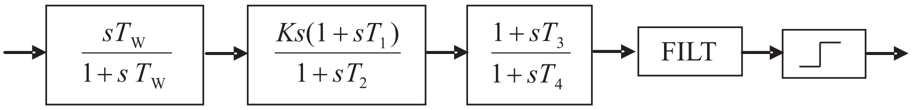

Fig. 1. Block diagram of PSS

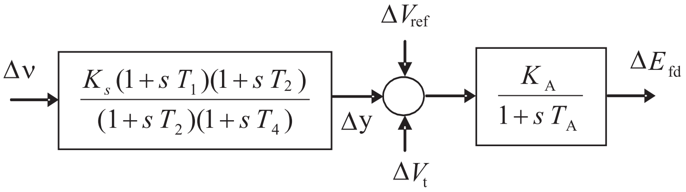

Fig. 2. Exciter with PSS.

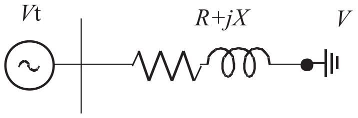

Fig. 3. System under study.

$$sU_{Ei} = -\frac{1}{T_{2i}}U_{Ei} + \frac{1}{T_{2i}}U_{E2i} + \frac{T_{1i}}{T_{2i}}sU_{E2i}\,, \qquad i = 1,\ldots,m \tag{10}$$

$$I_{di} = \sum_{j=1}^{n} Y_{ij}\left(E'_{dj}\cos(\delta_{ji}) - E'_{qj}\sin(\delta_{ji})\right) \tag{11}$$

$$I_{qi} = \sum_{j=1}^{n} Y_{ij}\left(E'_{qj}\cos(\delta_{ji}) - E'_{dj}\sin(\delta_{ji})\right). \tag{12}$$

In all above equations V_t and I_i are not state variables and therefore need to be eliminated.

These variables can be written in terms of the state variables as above. The system model equations are then linearized. The linearized model may be put into the form of a set of linear, first order differential equations with constant coefficients in the form of:

$$\Delta\dot{X} = A\Delta X + B\Delta U \tag{13}$$

$$\Delta Y = C\Delta_X + D\Delta U. \tag{14}$$

Here X constitutes the system state variable. U and Y represent the input and output variables respectively.

3 POWER SYSTEM STABILIZER DESIGN

The power system stabilizer is a control device used to damp out low frequency oscillations. Such modes are known as interarea or local modes. The parameters of the PSS are tuned on-line to suppress these modes. The design of the PSS is still made on the basis of a single machine infinite bus system (SMIB) system even though a considerable research is being done in designing PSS for a multimachine system with no significant results as several rotor oscillation frequencies have to be considered. The block diagram of the PSS used in real life is shown in Fig. 1.

The stabilizer signal input can be derived from the machine speed (taken as normalized speed in this paper), terminal frequency, or power.

The second block is the Washout circuit. It eliminates the steady-state bias in the output of PSS which will modify the generator terminal voltage. The PSS is expected to respond only to transient changes in the rotor speed rather than to any dc offsets signal. The selection of the Washout time constant T_w value depends upon the type of modes under study. For example in this paper it is taken as a low value in the range of 1 to 2 as we are interested in damping local modes of the system.

The dynamic compensation in Fig. 1 is made up of two lead-lag stages. Its transfer function is $T(s) = \frac{K_s(1+sT_1)(1+sT_3)}{(1+sT_2)(1+sT_4)}$ where K_s is the gain of the PSS and T_1, T_2, T_3 and T_4 are time constants selected to provide a phase lead for the input signal in the range of frequencies of interest.

A filter section may be added to suppress frequency components in the input signal of the PSS that could excite undesirable interactions. The criteria for designing the torsional filter are of two folds. One is the minimized phase lag of the filter in the low frequency range (1 to 3 Hz). The second is that the maximum change in damping of any torsional mode is less than some fraction of the evolved torsional damping [13].

A block of a limiter is shown in Fig. 1. Limits are included to prevent the output signal of the PSS from deriving the excitation into heavy saturation. Here the limiter acts mainly to limit the output of the PSS to prevent it from acting to counter the action of the automatic voltage regulator (AVR) [14, 15]. For example, when load rejection happens in the system, the automatic voltage regulator (AVR) acts to reduce the terminal voltage when PSS action calls for a higher value of the terminal voltage. The negative limit of the PSS output is of importance during the back swing of the rotor after initial acceleration is over.

The output signal of the PSS is fed as a supplementary input signal, V_{supp}, to the regulator of the excitation system as shown in Fig. 2. The present trend in tuning PSS is to select the parameters for satisfactory performance under all possible conditions. Sometimes this can be impossible. Therefore, the self-tuning regulator principle is used.

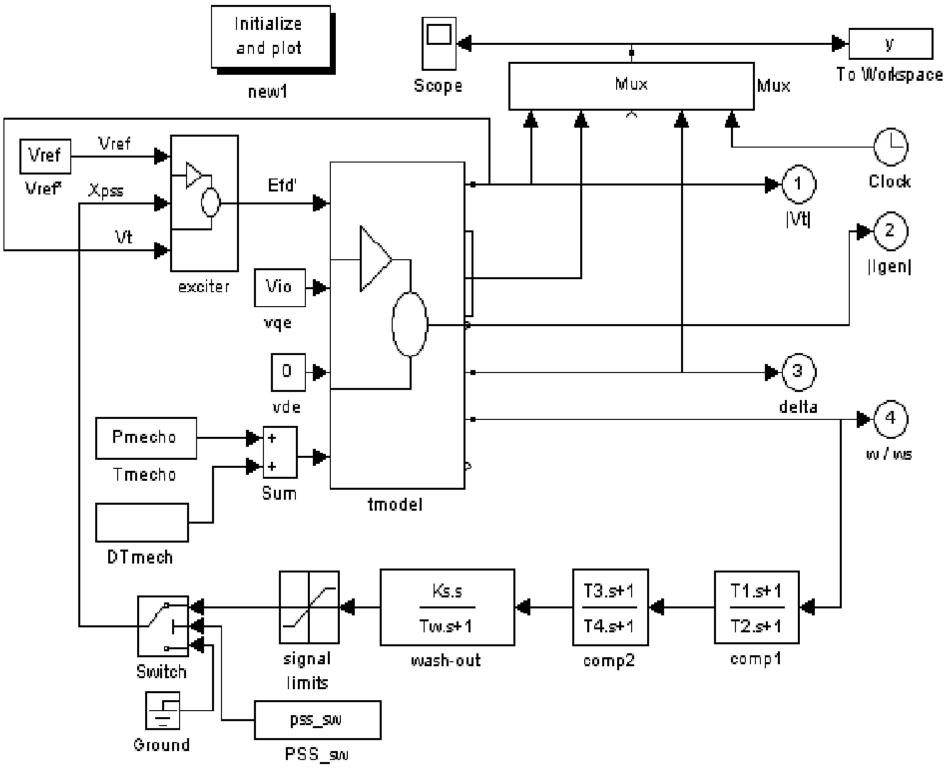

Fig. 4. Model of generator, Excitation and PSS in Matlab/Simulink.

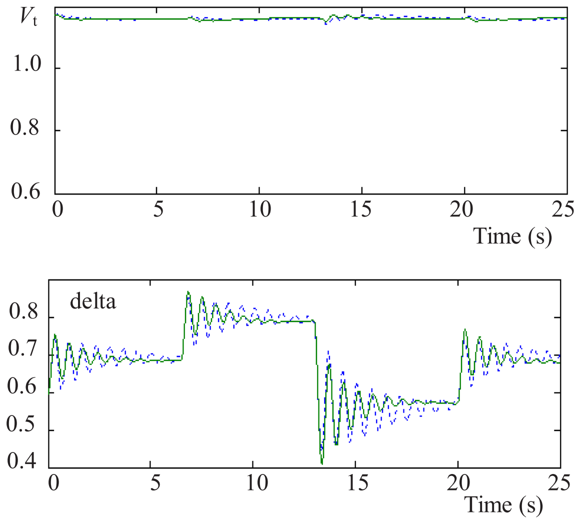

Fig. 5. Simulation results: dashed lines — without PSS, solid lines — with PSS.

Table 1. Parameters of two cascade lead stages PSS.

$Ks = 100.0$	Tw=1.3	T1=0.03	T2=0.003
$T3 = 0.03$	$T4 = 0.28$	Pss_limit$= 0.1$	

4 STUDY SYSTEM REPRESENTATION

Case 1: Single machine system:

Consider the single machine infinite bus system shown in Fig. 3. Two states are investigated. State one is when the generator has no PSS while the second state when the generator is equipped with PSS controller.

Matlab/Simulink has been used to simulate the dynamic performance of the system under study for both states [12]. In Fig. 4, the whole system representation of case 1 is shown with PSS parameters selected as in Table 1. The input signal to the PSS is selected as the normalized speed *ie* ν signal.

The simulation results are done at loading of $0.8+j0.6$. From simulated results of both the rotor angle and generator output voltage, the improvements of the voltage stability as well as angle stability are shown clearly. Different loading conditions can be similarly simulated without loss of perfection of the system stability.

Case 2: Yemeni Northern Part Network:

The northern part of the Yemeni network (Fig. 6) comprises two main generating steam stations sited at Ras-Katenib, near Hodiedah (Sea Port) city and another one at Al-Mukha in addition to a number of supplementary small scattered diesel generating units located at Sana'a, Taiz and Hodiedah cities. The transmission network comprises 850 km of double circuits of 132 kV overhead lines used to transmit electrical power between the coastal generating areas and the main cities in north part of the republic [7]. To perform the study using small-signal stability analysis [12], first the model of Section 2 is linearized around its equilibrium points. Then eigenvalues of the system matrix A are computed. These eigenvalues provide information on system stability. Table 2 for case two system, *ie* Yemeni electrical systems, are shown in

Table 2. Eigenvalues and damping ratios of northern part Yemeni system with and without PSSs

Open Loop Eigenvalues	Damping Ratio for Open Loop *ie* without PSS	Eigenvalues with PSS	Damping Ratio with PSS
		$-1.223 \pm j23.234$	0.3893
$-0.198 \pm j19.197$	0.0315	$-9.356 \pm j12.763$	1.4891
$-7.588 \pm j10.871$	1.2029	$-11.984 \pm j7.345$	1.9073
$-9.647 \pm j4.643$	1.5354	-4.168	0.6634
-2.798	0.4453	$\mathbf{-0.658}$	**0.1047**
0.282	$\mathbf{-0.0449}$	$-0.956 \pm j3.378$	0.1522
$-0.248 \pm j1.300$	0.0395	$-3.478 \pm j1.347$	0.5535
$-1.362 \pm j0.230$	0.2168	-3.855	0.6135
$-1.654 + j0.0$	0.2632	0.0, 0.0	0.0
0.0, 0.0	0.0	$-11.234 \pm j10.574$	1.7879
		$-10.578 \pm j12.643$	1.6835
		$-15.654 \pm j0.843$	2.4914

Table 2. The eigenvalues of the system without excitation controls are shown in the first column of Table 2. Examining the first column of Table 2 indicates an unstable system. The positive mode that evolves in Table 2, column one, is an undamped positive mode which grows with time and eventually will affect the system behavior.

To determine the source of such instability, sensitivity analysis is used which indicates that the instability is due to excitation field voltage with partially the regulators output voltage of the machines in the system [7]. In order to stabilize the system, each machine has equipped with a third-order PSS with the local normalized speed is used as its input. The effects of the two PSSs on the positive unstable modes are examined by computing the eigenvalues of the composite system with PSSs.

The PSS's parameters are indicated in Table 1, and in Table 2. The computed eigenvalues including the PSSs are tabulated in column two. Examination of column two of Table 2 shows the disappearance of the positive mode and more of the stability of the system. This result proves the effectiveness of the PSS in providing positive damping to oscillations. Also, damping ratios are provided to show the effectiveness of including such controllers on power system modeling. The two main generating stations are actually an aggregate two machine equivalents of a number of individual generators. The equivalents parameters are evaluated using the method outlined in [15, 16].

5 CONCLUSION

The application of a Power System Stabilizer (PSS) for both small and moderate scale power systems has been explored in this study. The study includes the dynamic model of PSS to investigate its dynamic effect in damping unstable modes evolved as a result of the generators rotor angle or as excitation system interaction. Different simulation techniques as Matlab/Simulink and small signal stability analysis have proved the improvement of both voltage and system dynamic stability by including PSS controller signals in power system representation.

Appendix 1. Nomenclature

V_t	Generator terminal voltage
E'_q	q-axis rotor voltage variable (pu)
E'_d	d-axis rotor voltage variable (pu)
I_d, I_q	d-, q-axis machine current (pu)
V_d, V_q	d-, q-axis machine voltage (pu)
X_d, X_q	d-, q-axis synchronous reactance (pu)
X_d, X_q	d-, q-axis transient reactance (pu)
T_{do}	d-, q-axis open-circuit time constant
δ	Angle of q-axis *wrt* system reference (rad)
ω_s	Synchronous speed (rad/s)
ν	Normalized speed (pu)
H, M	Inertia constant (s)
D	Damping coefficient (pu)
T_m	Input mechanical torque (pu)
E_{fd}	Eq Equivalent excitation voltage (pu)
V_R, R_f	Regulator output voltage and Feedback conpensator state (pu)
U_E	Stabilizing signal as an output of the PSS
X_{pss}	State variable of PSS system
T_1, T_2, T_3, T_4	Lead-Lag and Lag-Lead network parameters (sec)
K_s, T_w	Wash-out network parameters.

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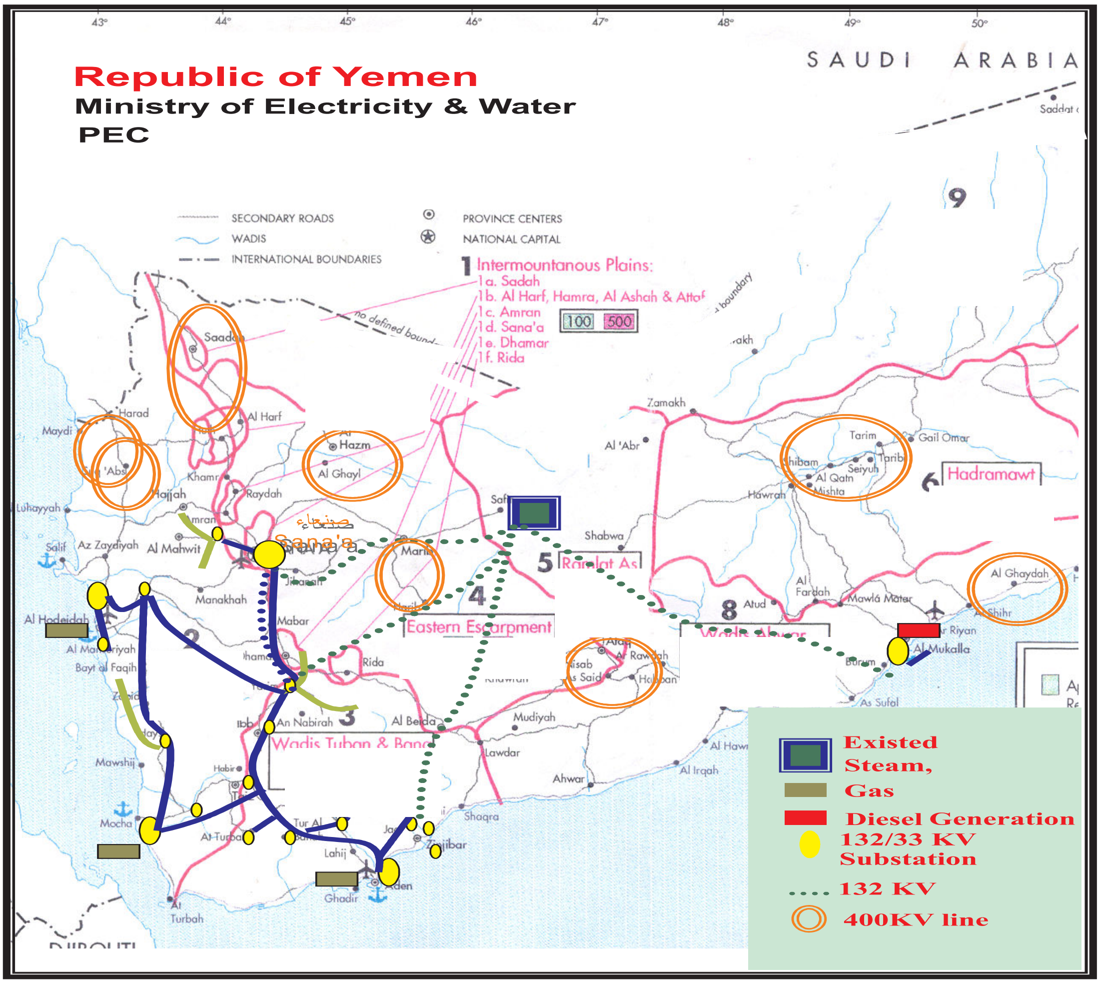

Fig. 6. Republic of Yemen Electrical Network.

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