A Modified Heffron-Phillip's Model for The Design of Power System Stabilizers

Gurunath Gurrala, and Indraneel Sen

***Abstract*—In this paper a modified Heffron-Phillip's (K-constant) model is derived for the design of power system stabilizers. A knowledge of external system parameters, such as equivalent infinite bus voltage and external impedances or their equivalent estimated values is required for designing a conventional power system stabilizer. In the proposed method, information available at the secondary bus of the step-up transformer is used to set up a modified Heffron-Phillip's (ModHP) model. The PSS design based on this model utilizes signals available within the generating station. The efficacy of the proposed design technique and the performance of the stabilizer has been evaluated over a range of operating and system conditions. The simulation results have shown that the performance of the proposed stabilizer is comparable to that could be obtained by conventional design but without the need for the estimation and computation of external system parameters. The proposed design is thus well suited for practical applications to power system stabilization, including possibly the multi-machine applications where accurate system information is not readily available.**

***Index Terms*—Heffron-Phillip's model, Power System Stabilizers(PSS),**

I. Introduction

ONE of the major problems in power system operation is related to the small-signal oscillatory instability caused by insufficient natural damping in the system. The most cost-effective way of countering this instability is to use auxiliary controllers called power system stabilizers (PSS), to produce additional damping in the system [1], [2]. Effective PSS design for large electric power systems is extremely laborious because of their highly nonlinear nature and constantly changing generation, transmission, and loading conditions. Over the years a variety of design procedures and algorithms [3] have been proposed for the design of power system stabilizers using both linearized and nonlinear models of power system. However, because of complex structures and real time computational requirements, most of these stabilizers have found little practical application.

The concept of classical PSS and their tuning procedures are well explored in [1], [2]. The conventional fixed gain stabilizers perform reasonably well if they have been tuned properly [4]. Though these stabilizers have simple robust structures, tuning them not only requires considerable expertise but also a knowledge of system parameters external to the generating station. These parameters may vary during normal operation of the power system. Even in the case of single machine infinite bus models, estimates of equivalent line impedance and the voltage of the remote bus are required. The PSS design also requires information of the rotor angle δ measured with respect to the remote bus. These parameters cannot be measured directly and need to be estimated based on reduced order models of the rest of the system connected to the generator. If the available information for the rest of the system is inaccurate, the conventionally designed PSS may result in poor system performance.

The method proposed for the PSS design in this paper is also based on the classical design technique. However, as opposed to a conventional stabilizer, the proposed PSS judges system disturbances such as changes in system configuration or variation in loads etc, based on the deviations in power flow, voltage and voltage angle at the secondary bus of the step-up transformer. The PSS tries to control the rotor angle measured with respect to the local bus rather than the angle δ measured with respect to the remote bus to damp the oscillations. All PSS design parameters are thus calculated from local measurements and there is no need to estimate or compute the values of equivalent external impedances, bus voltage and rotor angles at the remote bus. The performance of the proposed stabilizer is comparable to that of a conventional stabilizer that has been designed based on accurate system information. This information is not always available in practical systems. The paper consists of three parts: the first part describes the modelling of the power system, the second part describes the modified Heffron-Phillip's model and the proposed PSS design procedure and the third part describes the dynamic performance of the PSS over a range of operating and system conditions.

II. Modeling of Power System

For small-signal stability analysis, dynamic modeling is required for the major components of the power system. It includes the synchronous generator, excitation system, automatic voltage regulator (AVR) etc. Different types of models have been reported in the literature depending upon their specific application. A Single Machine Infinite Bus (SMIB) power system model as shown in fig.1 is used to obtain the linearized dynamic model [5] (Heffron Phillip's or K-constant model). Here, a single generator represents a single machine equivalent of a power plant (consisting of several generators). The generator is connected to a single or double circuit line through a transformer. The line is connected to

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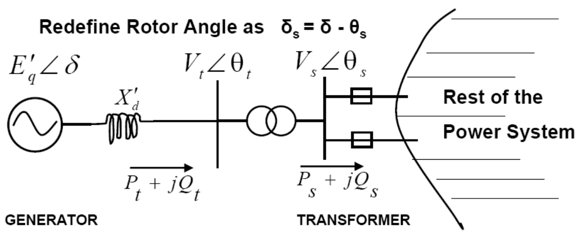

Fig. 1. A Single Machine Power System Model.

the rest of the power system which may be an infinite bus or another machine. The infinite bus, by definition, represents a bus with fixed voltage source. The magnitude, frequency and phase of the voltage are unaltered by changes in load (output of the generator). This is a simplified representation of a remote generator connected to a load center through a transmission line. IEEE Model 1.0 is used to model the synchronous generator [6] with a high gain, low time constant static exciter. The dynamic equations governing the system are as follows.

$$\dot{\delta} = w_B S_m \tag{1}$$

$$\dot{S}_m = \frac{1}{2H}\{T_{mech} - T_{elec} - DS_m\} \tag{2}$$

$$\dot{E}'_q = \frac{1}{T'_{do}}\left\{-E'_q + (X_d - X'_d)i_d + E_{fd}\right\} \tag{3}$$

$$\dot{E}_{fd} = \frac{1}{T_e}\{-E_{fd} + K_e(V_{ref} + V_{pss} - V_t)\} \tag{4}$$

$$T_{elec} = E'_q i_q + (X'_d - X'_q) i_d i_q$$

The variables have standard meaning and are listed in the Appendix. The above equations are based on rotor angle δ measured with respect to the remote bus E_b. To get the dynamic equations with respect to the secondary bus voltage $V_s\angle\theta_s$ of the step up transformer, all the expressions involving the rotor angle δ have to be expressed in terms of δ_s, where $\delta_s = \delta - \theta_s$. The expressions for δ_s and E'_q are as under

$$\begin{aligned} &\delta_s = \arctan \quad \frac{P_s(X_t+X_q)-Q_sR_a}{P_sR_a+Q_s(X_t+X_q)+V_s^2} \\ &\text{if} \quad \delta_s < 0 \text{ then } \delta_s = \pi - |\delta_s| \end{aligned} \tag{5}$$

$$\begin{aligned} E'_q = \frac{(X_t+X'_d)}{X_t}&\sqrt{V_t^2 - \left(\frac{X_q}{(X_t+X_q)}V_s\sin\delta_s\right)^2} \\ &-\frac{X'_d}{X_t}V_s\cos\delta_s \end{aligned} \tag{6}$$

III. Modified Heffron-Phillips Model and PSS design

The standard Heffron Phillips model can be obtained by linearizing the system equations around an operating condition. The development of the model is detailed in [6]. Here only the necessary steps to arrive at the modified HP model are given. From model 1.0 the following equations can be obtained

$$\begin{aligned} E'_q + X'_d i_d - R_a i_q = V_q \\ -X'_q i_q - R_a i_d = V_d \end{aligned} \tag{7}$$

The subscripts q and d refers to the q and d-axis respectively in Park's reference frame. The machine network interface is achieved by converting machine quantities in Park's frame to synchronously rotating Kron's reference frame. The machine terminal voltage in terms of the transformer secondary is given by

$$\begin{aligned} V_Q + jV_D &= (V_q + jV_d)e^{j\delta} \\ &= (i_q + ji_d)(R_t + jX_t)e^{j\delta} + V_s\angle\theta_s \end{aligned}$$

$$\therefore (V_q + jV_d) = (i_q + ji_d)(R_t + jX_t) + V_s\angle\theta_s\ e^{-j\delta}$$

Replacing δ by $\delta_s + \theta_s$ in the above equations gives

$$(V_q + jV_d) = (i_q + ji_d)(R_t + jX_t) + V_s\angle - \delta_s$$

Equating the real and imaginary parts of the above equation gives

$$\begin{aligned} V_q = R_t i_q - X_t i_d + V_s\cos\delta_s \\ V_d = R_t i_d + X_t i_q - V_s\sin\delta_s \end{aligned} \tag{8}$$

substituting (8) in (7) and rearranging gives

$$\begin{bmatrix} X'_d + X_t & -R_t \\ -R_t & X_q + X_t \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} V_s\cos\delta_s - E'_q \\ -V_s\sin\delta_s \end{bmatrix} \tag{9}$$

The system mechanical equations, electrical equations and eqn.(9) are linearized as in [6] to obtain the following modified K-constants.

$$K_1 = \frac{V_{s0}E_{q0}\cos\delta_{s0}}{X_q+X_t} + \frac{X_q-X'_d}{X_t+X'_d}V_{s0}\sin\delta_{s0}$$

$$K_2 = \frac{X_q+X_t}{X_t+X'_d}i_{q0};$$

$$K_3 = \frac{X_t+X'_d}{X_d+X_t};$$

$$K_4 = \frac{X_d-X'_d}{X_t+X'_d}V_{s0}\sin\delta_{s0};$$

$$K_5 = -\frac{X_qV_{d0}V_{s0}\cos\delta_{s0}}{(X_q+X_t)V_{t0}} - \frac{X'_dV_{q0}V_{s0}\sin\delta_{s0}}{(X_t+X'_d)V_{t0}}$$

$$K_6 = \frac{X_t}{X_t+X'_d}\frac{V_{q0}}{V_{t0}};$$

$$K_{v1} = \frac{E_{q0}\sin\delta_{s0}}{(X_t+X_q)} - \frac{(X_q-X'_d)I_{q0}\cos\delta_{s0}}{(X'_d+X_t)}$$

$$K_{v2} = -\frac{(X_d-X'_d)\cos\delta_{s0}}{(X'_d+X_t)}$$

$$K_{v3} = -\frac{X_qV_{d0}\sin\delta_{s0}}{(X_q+X_t)V_{t0}} + \frac{X'_dV_{q0}\cos\delta_{s0}}{(X_t+X'_d)V_{t0}}$$

$$\text{where} \quad E_{q0} = E'_{q0} - (X_q - X'_d)\,i_{d0}$$

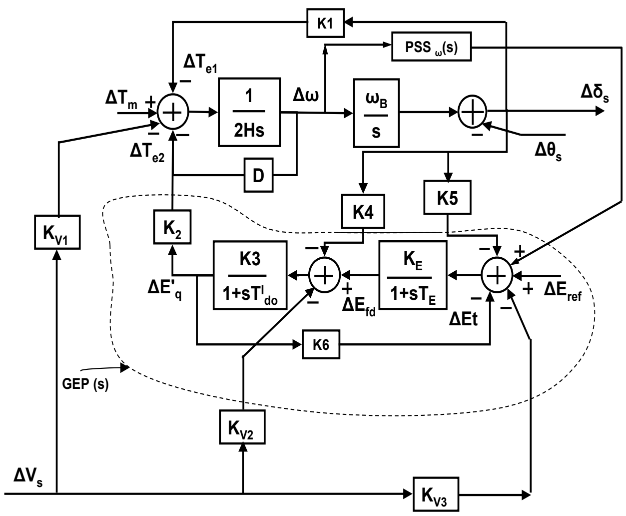

Fig. 2. Modified Heffron-Phillips model, the rotor angle is $\Delta\delta_s$

The modified Heffron-Phillip's model comprises six constants K_1 to K_6 whose definitions remain unchanged. However, they are no longer referenced to δ and E_b. It can be observed that the modified K-constants are also no longer the functions of the equivalent reactance X_e. They are functions of V_s, δ_s, V_t and machine currents. Therefore the modified K-constants can be now computed based on local measurements only. In this model, as V_s is not a constant, during linearization, three additional constants K_{v1} to K_{v3} are introduced at the torque, field voltage and terminal voltage junction points as shown in fig.2. The action of the PSS is effective through the transfer function block $GEP(s)$ as shown in fig.2 between the electric torque and the reference voltage input with variation in the machine speed assumed to be zero.

The expression for the transfer function $GEP(s)$ is given by

$$GEP\left(s\right) = \frac{K_2 K_3 EXC\left(s\right)}{\left(1 + sT'_{do}K_3\right) + K_3 K_6 EXC\left(s\right)} \tag{10}$$

where $EXC(s)$ is the transfer function of the excitation system. It can be of any exciter, but in this paper a high gain, low time constant static exciter is assumed. As system operating conditions change, the gain and phase characteristics of the transfer function $GEP(s)$ change. Ideally, the PSS transfer function should be reciprocal of $GEP(s)$ for providing a prescribed amount of damping with speed input. This would be purely a lead function that is not physically realizable. A practical approach is to have a lead-lag circuit that provides adequate compensation over the desired range of frequencies. Using the modified K-constants, stabilizers are designed using the tuning guidelines given by [2]. The stabilizer considered is a simple lead-lag compensator as shown in fig.3, with a washout filter. The time constants are selected such that the compensated phase lag of $GEP(s) \times PSS(s)$ around local mode frequency (about 7 rad/s i.e. 1.12 Hz is assumed) lies below 45^0 and

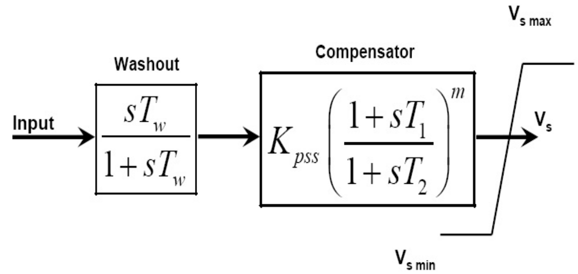

Fig. 3. Structure of PSS.

crossover of 90^0 point occurs beyond 22 rad/sec (3.5Hz) [2], [6]. The gain of the PSS is selected from the root-locus plot to give maximum damping to the concerned mode of the generator and any other (e.g. exciter mode) modes. The form of the compensator is assumed as given below

$$H(s) = K_{pss}\frac{\left(1 + sT_1\right)^m}{\left(1 + sT_2\right)}$$

where m is the number of lead-lag stages. The constants T_1 and T_2 can be obtained from the following equations.

$$\alpha = \frac{T_2}{T_1} = \frac{1-\sin\left(\frac{\beta}{m}\right)}{1+\sin\left(\frac{\beta}{m}\right)}$$

$$\beta = \text{Required phase compensation}$$

$$T_1 = \frac{1}{\Omega_i\sqrt{\alpha}}$$

$$T_2 = \alpha T_1$$

where Ω_i is the frequency of the mode of interest.

IV. Simulation Results and observations

The performance of the stabilizers designed by using modified K-constants is evaluated on a SMIB test system over a range of operating conditions as shown in table I. The system data is given in the Appendix. Conventional PSS is designed following the tuning guidelines [2] for $X_e = 0.4$p.u. The PSS data for both the conventional design and the proposed method are also given in the Appendix. The transformer reactance X_t is 0.1p.u. The total impedance between the generator bus and the infinite bus, denoted by X_e varies with system conditions. Fig.4 shows the phase plots of $GEP(s)$ with modified HP and conventional HP models. For the test system the center frequency is chosen as 3.5 Hz. Fig.5 shows the phase plots of conventional (CPSS) and proposed PSS and the compensated $GEP(s)$ of the plant in both cases. It is evident that the proposed PSS achieves exact compensation for the desired range of frequencies (0.1Hz to 2.5Hz).

Fig.6 shows the root locus plot of the plant by varying PSS gain with the proposed and conventional PSS. The gain K_{pss} is chosen as 13 for proposed PSS and 16 for CPSS. It can be observed from the figure that the chosen weights provide adequate damping for both the rotor and the exciter modes. The performance of the proposed PSS was tested at

TABLE I
RANGE OF OPERATING CONDITIONS FOR SMIB

X_e	P_t	Q_t	power factor
0.4-Nominal	1, 0.8, 0.8	0.2, 0.2, -0.2	lag, lag, lead
0.3-strong	all 0.8	0.41,0.23,-0.37	lag, lag, lead
0.8-weak	1, 0.8	0.5, 0.2	lag, lag

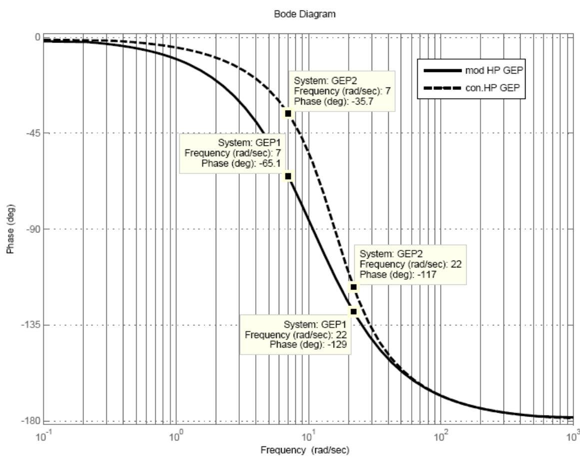

Fig. 4. GEP(s) plots for modHP $-$, original HP $--$

varying operating and system conditions. A few representative examples have been included in this paper.

Fig.7 shows the system response in terms of variation in slip speed S_m following a 10% step change at V_{ref} input of the generator. At this operating condition ($S = P + jQ = 1 + j0.2p.u.$,$X_e = 0.4p.u$) the system is unstable without a PSS. Fig.8 shows the system response for the same system condition, following a 3ϕ fault of 4 cycles duration at the transformer bus. Fault is cleared by tripping one of the parallel lines. In both the cases, the conventional and the proposed PSS have damped the system oscillations effectively.

Fig.9 relates to leading power factor operation with $S = 0.8 - j0.2p.u.$ and $X_e = 0.4p.u.$ System behavior is highly oscillatory in this case for a 10% step change at T_m input of the generator. The performance of the proposed PSS is much better than the conventional stabilizer under this condition.

Fig.10 shows system response in terms of S_m under relatively strong system ($X_e = 0.3p.u., S = 0.8 - j0.37$) and leading power factor conditions. The proposed PSS has shown comparable performance under lagging power factor conditions and better performance under leading power factor conditions when compared to the performance of the CPSS.

Fig.11 depicts very weak system ($X_e = 0.8p.u., S = 1 + j0.5\ p.u.$) conditions. Leading power factor operations are not possible under these conditions. The performance of both stabilizers are again comparable and the system oscillations have been effectively damped.

V. CONCLUSIONS

A modified Heffron Phillip's model has been derived for the design of power system stabilizers. The stabilizer is synthesized using information available at the local buses and makes

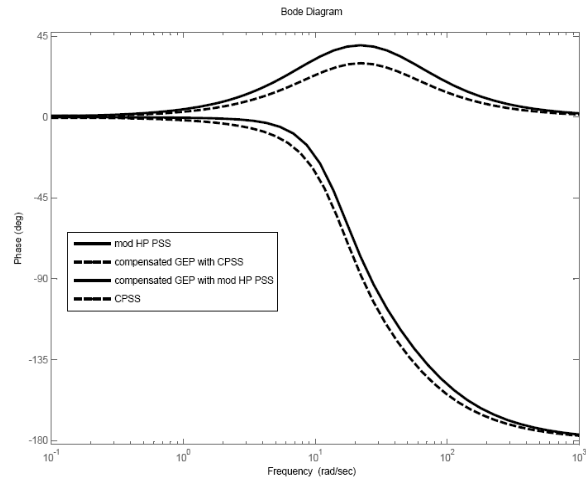

Fig. 5. compensated GEP(s) plots with Proposed PSS - and CPSS –

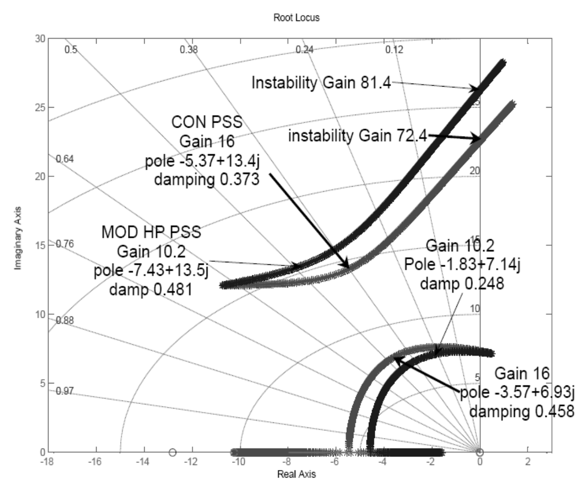

Fig. 6. root-locus plot of the plant with proposed PSS and CPSS.

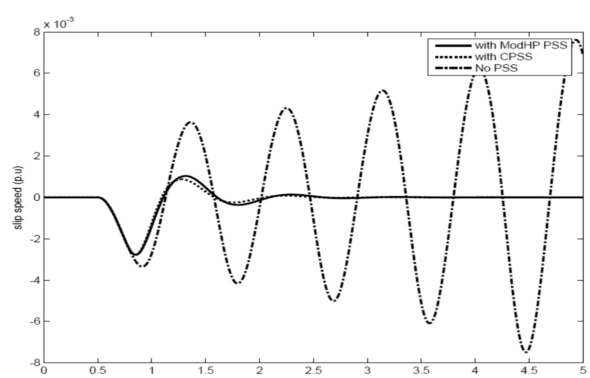

Fig. 7. System response for 10% step change in V_{ref},Nominal system.

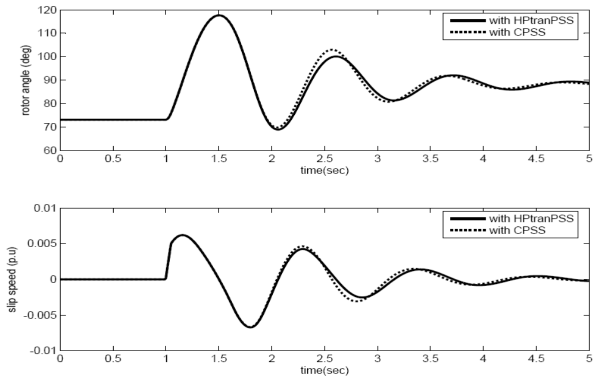

Fig. 8. System response for a 3ϕ fault at transformer,Nominal system.

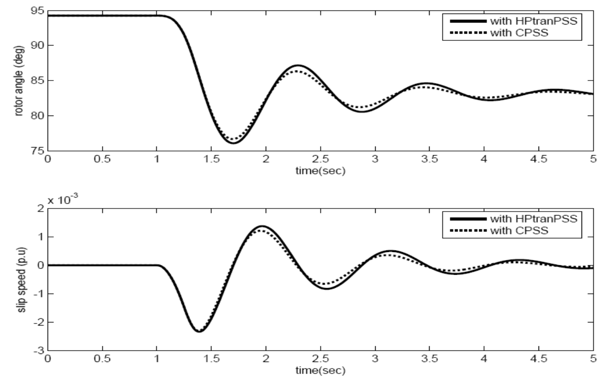

Fig. 11. System Response for 10% step change in V_{ref}, Weak System.

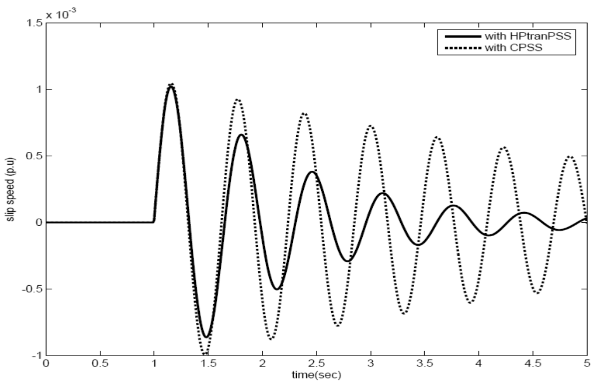

Fig. 9. System response for 10% step change in T_m,Nominal system, leading p.f.

no assumptions about the rest of the system connected beyond the secondary bus of the step up transformer. As system information is generally not accurately known or measurable in practice, the proposed method of PSS design is well suited for designing effective stabilizers at varied system conditions.

The performance of the proposed stabilizer is comparable to that of a conventional stabilizer which has been designed assuming that all system parameters are known accurately. As the proposed design is based on local measurements alone it may be possible to extend the proposed PSS design philosophy to multi-machine systems.

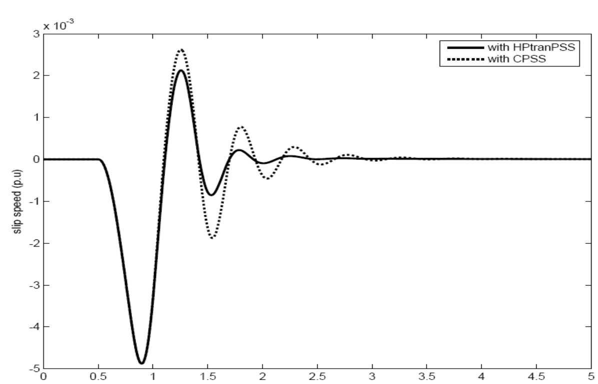

Fig. 10. System response for 10% step change in V_{ref}, Strong system, leading p.f.

APPENDIX

Machine Data:
$X_d = 1.6; X_q = 1.55; X'_d = 0.32; T'_{do} = 6; H = 5; D = 0; f_B = 60Hz; E_B = 1p.u.; X_t = 0.1$; Model 1.0 is considered for the synchronous machine.

Exciter data:
$K_e = 200$; $Te = 0.05s$; $E_{fdmax} = 6p.u.$; $E_{fdmin} = -6p.u.$;

CPSS data:
$T_1 = 0.078$; $T_2 = 0.026$; $K_{pss} = 16$; $T_w = 2$; $PSS\ output\ limits\ \pm 0.05$

ModHP-PSS data:
$T_1 = 0.0952$; $T_2 = 0.0217$; $K_{pss} = 13$; $T_w = 2$; $PSS\ output\ limits\ \pm 0.05$

variables definitions:
δ : Rotor angle.
δ_s : Rotor angle with respect to the secondary voltage of transformer.
S_m : Slip speed.
T_{mech} and T_{elec} : Mechanical and Electrical torques respectively.
D : Damping coefficient.
E'_q : Transient emf due to field flux-linkage.
i_d : d-axis component of stator current.
i_d : q-axis component of stator current.
T'_{do} : d-axis open circuit time constant.
X_d, X'_d : d-axis reactances.
X_q, X'_q : q-axis reactances.
E_{fd} : Field voltage.
K_e, T_e : Exciter gain and time constant.
V_t : Voltage measured at the generator terminal.
V_s : Voltage measured at the secondary of the transformer.
V_{ref} : Reference voltage.
V_{pss} : PSS input.
X_t, X_L : Transformer and transmission line reactances.

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