DESIGN OF POWER SYSTEM STABILIZERS BASED ON THE MODEL OF SINGLE MACHINE INFINITE BUS POWER SYSTEM

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ABSTRACT

Problem of damping electromechanical oscillations in electric power systems is not new. Since the 1950s, when power systems started to get bigger and ever more stressed, engineers have been looking for synchronous generator controllers that could improve damping of oscillations. The most popular tool for power system stability enhancement is the power system stabilizer (PSS) which provides an auxiliary control loop to the main automatic voltage regulator (AVR). PSS structure usually follows one of IEEE standards [1]. PSSs are usually of the single-input type with constant parameters (time-invariant) but two-input stabilizers are used too. PSS design is usually based on the compensation of plant frequencycharacteristics, optimization of defined quality indices, or shifting poles of the considered system to appropriate locations.The problem of the poorly damped low-frequency (0.1 - 2Hz) oscillations of power systems has been a matter of concern to power engineers, because they limit the power transfer capability in power systems. The power systems stability is also affected by these poorly damped oscillations and can lead to the system instability. The paper presents a design PSSs to enhance power systems stability and improve power transfer capability. MATLAB dynamic model was developed for a power system and lead-lag PSS structure is considered in the model. Damping torque technique is applied to tune the PSS parameters. The results of this technique have been verified by eigenvalue analysis and time-domain simulations. The simulations results show that the system time responses under different operating conditions are well damped with the designed PSS.

Keywords: Damping torque, Automatic Voltage Controller (AVR), Power System Stabilizers (PSS).

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APPENDIX

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_q: q-axis component of stator current.

T_{do}: d-axis open circuit time constant.

X_d: d-axis reactances.

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.

Vpss: PSS input.

X_t, X_L: Transformer and transmission line reactances.

1. INTRODUCTION

Disturbances, sustained power system oscillations, and their effective amelioration have for many years presented a major challenge to the electricity supply industry. This is especially the case in the context of the rapidly growing integration of distributed generation and loads into power transmission and distribution networks [2]. Much previous work [3] has centred round the question as to what effective role such widely used devices as the generator automatic voltage regulator (AVR) and power system stabilizer (PSS) play in the attenuation of these power system instabilities. Other related questions concern the best power system location for PSSs and how best to assess their proper tuning and robustness [4] in the face of changing power system operating conditions. The mathematical model presented for small scale stability state is a set of linear time invariant differential equations [2]. P.M. Anderson and A.A. Fouad, had mentioned, the stability under the condition of small load changes has been called steady state stability [3]. The concepts of synchronous machine stability as affected by excitation control and the phenomenon of stability of synchronous machines under small perturbations in the case of single machine connected to an infinite bus through external reactance has been presented by F.P.demello and C.Concordia [4]. These stabilizing requirements include the

voltage regulator gain parameters as well as the transfer function characteristics for a machine speed derived signal superposed on the voltage regulator reference for providing damping machine oscillations [5]. The functions of the AVR and the PSS in multimachine power systems are widely documented [3, 4]. As the name suggests, the AVR provides regulation or maintenance of the terminal voltage of the machine to which it is attached. In addition, a high-gain fast-response AVR improves large-signal transient stability in the sense that it increases the ability the power system to maintain synchronism when subjected to severe transient disturbances, for instance network faults. The traditional method of assessing AVR transient stability performance has been large-signal (nonlinear) time-domain simulation. High-gain fast-response AVR action can, however, lead to reduced damping of system electromechanical modes of oscillation. Standard ways of eliminating this loss of system damping are either to employ transient gain reduction [3] on the AVR or more commonly attach a PSS to appropriate machines[5]. The traditional method of analysing oscillatory instability is small-signal eigen-analysis [6-8]. Michael J. Basler, Richard C. Schaefer discusses power system instability and the importance of fast fault clearing performance to aid in reliable production of power [8]. In the past decades, the utilization of supplementary excitation control signals for improving the dynamic stability of power systems has received much attention. Extensive research has been conducted in such fields as effect of PSS on power system stability, PSS input signals, PSS optimum locations, and PSS tuning techniques. The k-constant model developed by Phillips and Heffron, is used to explain the small signal stability, high impedance transmission lines, line loading, and high gain, fast acting excitation systems. The paper discusses the various types of power system instability. It will cover the effects of system impedance and excitation on stability. Synchronizing torque and damping torque is discussed and a justification is made for the need for supplemental stabilization [1, 4, 7]. Kundur et al. presented a detailed analytical work to determine the parameters of phase- lead PSSs so as to enhance the steady-state as well as transient stability of both local and inter-area modes. These parameters included the signal washout, stabilizer gain, and the stabilizer output limits. They concluded that by proper tuning, the fixed-parameter PSS can satisfy the requirements for a wide range of system conditions and hence the need of adaptive PSS is of little incentive [9].

In this paper a comparison of AVR and AVR/PSS controllers is presented through small signal stability of power system comprising of one machine connected to infinite bus and modeled through six K-constants. The power system components such as synchronous machine, exciter, power system stabilizer, PID are also modeled after linearization of governing equations.

2. MODELLING 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 [6] (Heffron Phillip's or Kconstant 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 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:

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

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

$$\dot{S}_q' = \frac{1}{T_{do}'}\left[-E_q' + \left(X_d - X_d'\right)i_d + E_{fd}\right] \tag{3}$$

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

$$T_{elec} = E_q'i_q + \left(X_d' - X_q'\right)i_d i_q$$

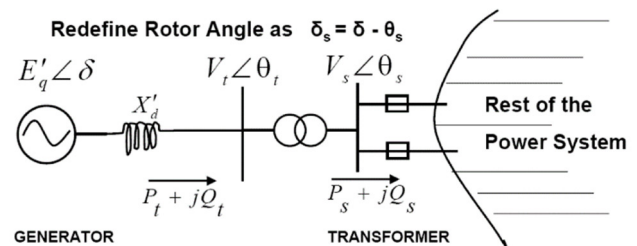**Redefine Rotor Angle as** $\delta_s = \delta - \theta_s$

Fig. 1. A Single Machine Power System Model

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 Eb. 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 δs, where $\delta_s = \delta - \theta_s$. The expressions for δs and Eq are as under

$$\delta_s = \arctan\frac{P_s(X_t + X_q) - Q_s R_a}{P_s R_a + Q_s(X_t + X_q) + V_s^2} \tag{5}$$

if $\delta_s < 0$ then $\delta_s = \pi - |\delta_s|$

$$E_q' = \frac{(X_t - X_d')}{X_t}\sqrt{V_t^2 - \left(\frac{X_q}{X_t + X_q}V_s \sin\delta_s\right)^2} - \frac{V_d'}{X_t}V_s \cos\delta_s \tag{6}$$

3. HEFFRON-PHILLIPS MODEL

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 [5], as shown in Fig. 2.
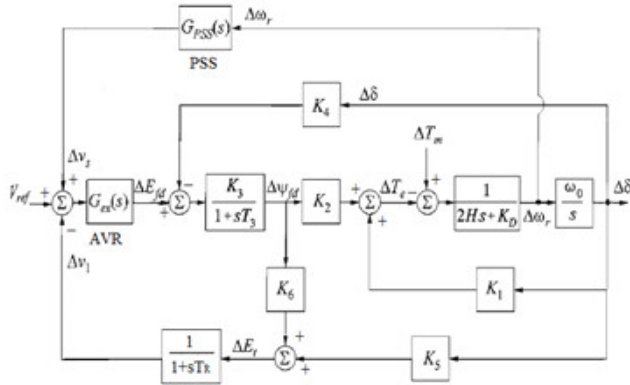

Fig. 2. Heffron Phillips mode

$$K_1 = \frac{E_{q0}E_0}{A}\left[r_e\sin\delta_0 + (X_e - X_d')\cos\delta_0\right]$$

$$\frac{i_{q0}E_0}{A}\left[(X_q - X_d')(X_e + X_q)\sin\delta_0 - r_e(X_q - X_d)\cos\delta_0\right]$$

$$K_2 = \frac{r_eE_{q0}}{A} + i_{q0}\left(1 + \frac{(X_e + X_q)(X_q - X_d')}{A}\right)$$

$$K_3 = \left(1 + \frac{(X_e + X_q)(X_q - X_d')}{A}\right)^{-1}$$

$$K_4 = \frac{E_0(X_d - X_d')}{A}\left((X_e + X_q)\sin\delta_0 - r_e\cos\delta_0\right)$$

$$K_5 = \frac{e_{d0}}{e_{t0}}X_q\left[\frac{r_eE_0\sin\delta_0 + (X_e + X_d')E_0\cos\delta_0}{A}\right]$$
$$+ \frac{e_{d0}}{e_{t0}}X_d'\left[\frac{r_eE_0\cos\delta_0 - (X_e + X_q)E_0\sin\delta_0}{A}\right]$$

$$K_6 = \frac{e_{q0}}{e_{t0}}\left(1 - \frac{X_d'(X_e + X_q)}{A}\right)^{-1} + \frac{e_{q0}}{e_{t0}}X_q\frac{r_e}{A}$$

$$A = r_e^2 + (X_e - X_d')(X_e + X_q)$$

At the inition condition, the starting value is

$$E_{q0} = \sqrt{(e_{t0} + I_{q0}X_q)^2 + (I_{p0}X_q)^2}$$

determined as follows: δ_0, E_{q0}, E_0, e_{d0}, e_{q0}.

$$E_0 = \sqrt{(e_{t0} - I_{d0}r_e - I_{q0}X_e)^2 + (I_{d0}X_e - I_{q0}r_e)^2}$$

$$\sin\delta_0 = \frac{e_{t0}I_{d0}(X_q + X_e) - r_eX_q(I_{d0}^2 - I_{q0}^2)}{E_{q0}E_0}$$

$$\cos\delta_0 = \frac{e_{t0}\left(e_{t0} - I_{q0}(X_q - X_e) - I_{d0}r_e\right)}{E_{q0}E_0} - \frac{X_eX_q(I_{d0}^2 + I_{q0}^2)}{E_{q0}E_0}$$

$$e_{q0} = \frac{e_{t0} + I_{q0}X_q}{E_{q0}}e_{t0}$$

$$e_{d0} = i_{q0}X_q$$

$$i_{q0} = \frac{I_{d0}(e_{t0} + I_qX_q) - I_{q0}I_{d0}X_q}{E_{q0}}$$

$$i_{d0} = \frac{I_{d0}^2X_q + I_{q0}(e_{t0} + I_{q0}X_q)}{E_{q0}}$$

Where:

K_1: change in electrical torque for a change in rotor angle with constant flux linkages in the d axis.

K_2: change in electrical torque for a change in d-axis flux linkages with constant rotor angle.

K_3: impedance factor for the case where the external impedance is a pure reactance X_e.

K_4: demagnetizing effect of a change in rotor angle.

K_5: change in terminal voltage with change in rotor angle for constant E_q'.

K_6: change in terminal voltage with change in E_q' for constant rotor angle.

It is important to recognize that, with the exception of K_3 which is only a function of the ratio of impedances, all other parameters change with loading, making the dynamic behavior of the machine quite different at different operating points. Since these parameters change in rather complex manner, it is difficult to reach general conclusions based on parameter values for one operating point only.

4. PSS DESIGN

As shown in Fig. 3 the PSS block diagram representation is composed of three blocks: a gain block, a signal washout block and phase compensation block. The stabilizer gain (K_{PSS}) function is to determine the amount of damping introduced by the PSS. The function of the phase compensation block is to provide the appropriate phase-lead characteristic to compensate for the phase lag between the exciter input and the generator electrical (air-gap) torque.
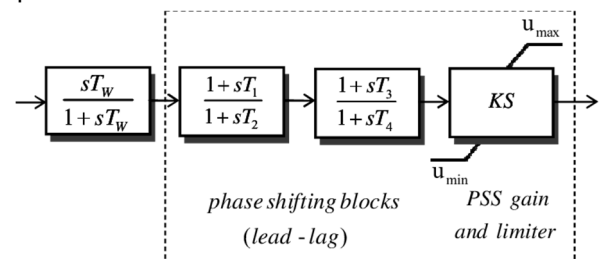

Fig. 3. The conventional PSS Design Model

In Fig. 3 two first-order blocks are used to achieve the desired phase compensation. In some cases, second-order blocks with complex roots have been used. Normally, the frequency range is 0.1 - 2Hz, and the phase-lead network should provide compensation over this entire frequency

range. The phase characteristic to be compensated changes with system conditions; therefore, a compromise is made and a characteristic acceptable for different conditions is selected.

Stability of the power system depends mainly on the damping of the torque. If any lack of sufficient damping torque occurs in the system, this would lead the system to oscillatory instability. The damping torque expression has been derived for SMIB power system and is given by:

$$T_\delta(s) = K_1 - \frac{K_2 K_3 \left[K_4(1+sT_R) + K_5 G_{ex}(s) \right]}{(1+sT_R)(1+sT_3) + K_3 K_6 G_{ex}(s)}$$

$$T_{PSS}(s) = K_1 - \frac{K_2 K_3 K_A K_{PSS}(1+sT_a)(1+sT_b)(1+sT_c)}{(1+sT_3)(1+sT_A)(1+sT_B) + K_3 K_6 K_A(1+sT_C)}$$

It can be seen that the damping torque Kd is mainly a function of the constants K_2, K_3 and K_5, where K_2 is the change in the electrical torque for a change in the flux linkages in the d-axis with considering a constant rotor angle, K_3 is the impedance factor in which the external impedance is a pure reactance, and K_5 is the change in the terminal voltage with respect to the change in the rotor angle with considering aconstant flux linkages in the d-axis. The K_3 is constant, is only function system reactance. K_6 is the change in terminal voltage with change in flux in d-axis linkage for constant rotor angle.

5. SIMULATION RESULTS

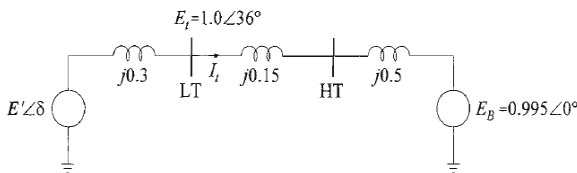The simulation was conducted on the following SMIB model:

Fig. 4. Single Machine Infinite Bus Power System

All parameters of AVR, PSS are presented in the following Table 1.

Table 1. Parameters of AVR, PSS are presented

Parameter	Value	Unit	Parameter	Value	Unit
P	0.9	pu	K_A	200	-
Q	0.3	pu	T_R	0.02	s
E_t	$1\angle 36^0$	pu	K_{PSS}	9.5	-
E_B	$0.995\angle 0^0$	pu	T_w	1.4	s
X_d	1.81	pu	T_1	0.154	s
X'_d	0.3	pu	T_2	0.033	s
X_q	1.76	pu	R_a	0.003	pu
X_1	0.16	pu	R_{fd}	0.0006	pu
H	3.5	s	L_{fd}	0.16	pu
T_{d0}	8	s	K_1	0.764	pu
L_{adu}	1.65	pu	K_2	0.865	pu
L_{aqu}	1.6	pu	K_3	0.323	pu
L_1	0.16	pu	K_4	1.4187	pu
T_3	2.365	s	K_5	-0.146	pu
			K_6	0.4168	pu

The synchronize torque and damping torque can be calculated as in the AVR only case:

$K_S = K_1 + K_{S(AVR)} = 0.9758$pu

$K_D = K_D + K_{D(AVR)} = -7.06$pu

With the introduction of PSS, the corresponding gain can be recalculated as:

$K_S = K_1 + K_{S(AVR)} + K_{S(PSS)}$

$\quad = 0.7643 + 0.21 - 0.145 = 0.8239$pu

$K_D = K_D + K_{D(AVR)} + K_{D(PSS)}$

$\quad = -7.06 + 22.77 = 15.71$pu

It is obvious to see that with PSS, the synchronize torque is reduced by 0.145 and still kept positive while the damping torque is increased by 22.7 times in comparison with the AVR only case, that would contribute significantly to the stability of the whole excitation system.
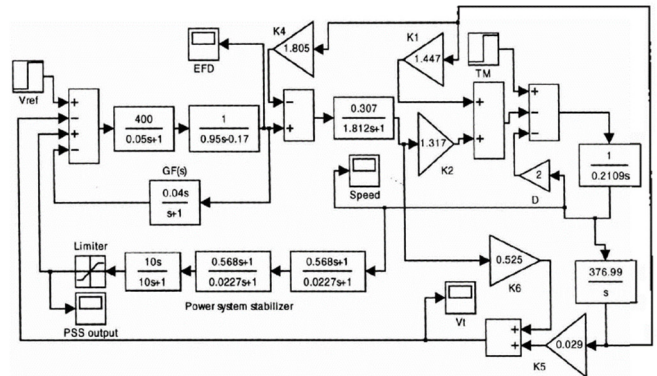

Fig. 5. Simulink simulation model

The simulation of the excitation model shown in Figure 6 results in the system's operation with MATLAB Simulink software (at time t = 19s, the voltage set for AVR changes 10% from 0.84pu to 0.94pu) for cases where the system has AVR only and AVR/PSS combination:
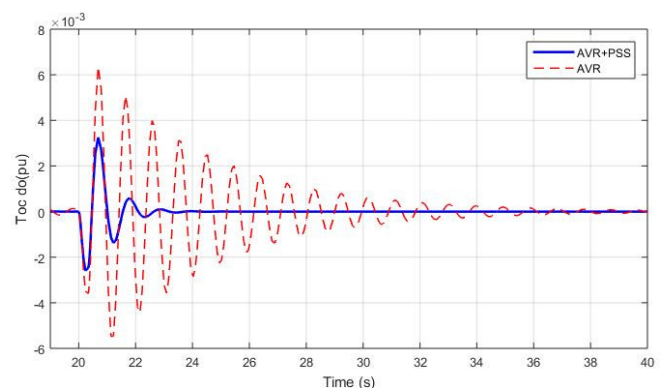

Fig. 6. Respond of generation rotor rotational speed

Fig. 6 shows the respond of the electrical power response P_e of the generator when there is only AVR and when there is AVR/PSS.
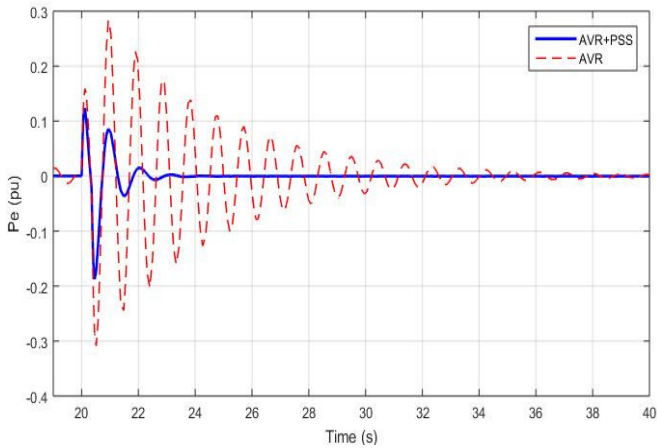
Fig. 7. Respond of electrical generator power P_e

Here are some conclusions that we are observed during the simulation process:

- when there is no PSS set, in the response to change in voltage, the power response graph and the generator's speed are experienced fluctuation. This oscillation has a frequency of about 6.5rad/s (about 1.03Hz).

- When the PSS has been adjusted to the appropriate phase compensation angle, the system has become stable. The speed response and electrical power of the generator both return to a stable value after about 3s.

- K_{PSS} is always proportional to the synchronous torque component $T_{\delta s}$ of the entire frequency range of oscillation. K_{PSS} is only proportional to the damping torque component in the small range of oscillation frequencies around 0.5Hz. In the frequency range of oscillations greater than 0.5Hz, when K_{PSS} increases, the component of resisting torque will be reduced.

6. EXPERIMENTAL RESULTS

Fig. 8. BanVe hydro turbine units - H1,H2

Experiments has been carried out to illustrates the performance of PSS during real world situation. Experiments were performed at Ban Ve Hydropower plant November 30 of 2020, before the end of scheduled maintenance of units1 and 2. The unit 1 is the study generator. The rating of the units 1 and 2 is 100MVA and 15.75kV. The performance of current AVR and AVR/PSS were checked under the following small sized disturbances of 0.05pu step change of reference voltage VT. Fig. 8 shows picture of the turbine unit 1 at the plant, while Figure 8 shows the software interface, written in Visual C# to collect the data from TU and TI of the current generator. Electrical Power is the value to be observe during the injection of small disturbance at VT.
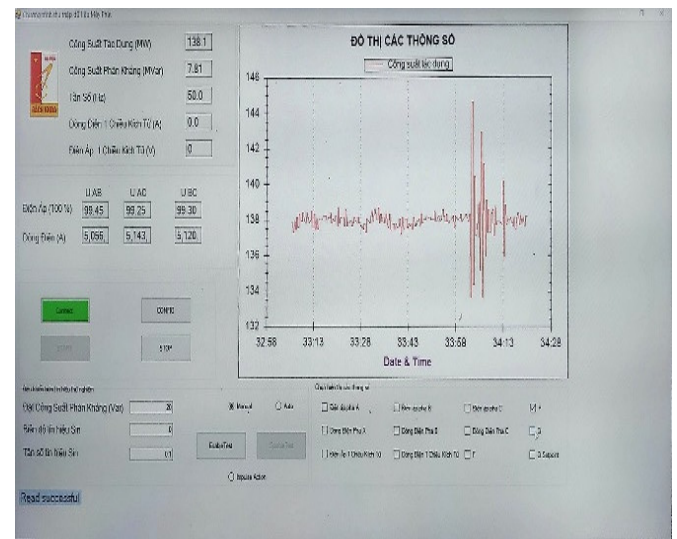

Fig. 9. Data log-in at the plant

Fig. 9 shows the real power output of the study unit after the disturbance. The mark indicates the time when the disturbances were applied to the system. As shown in Fig. 10, the damping of the study generator is as low as expected when only the AVR is used to take control.
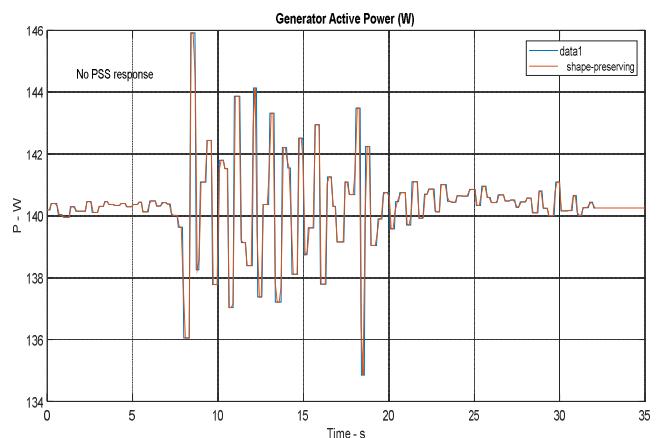

Fig. 10. Electrical Power respond during test (AVR case)

Figs. 11, 12 show the system respond of electrical power when the AVR/PSS is applied. The damping given by the PSS is pretty fast. As shown in the Fig. 11, the system damping is highly improved by changing the proper K_{PSS} gain.
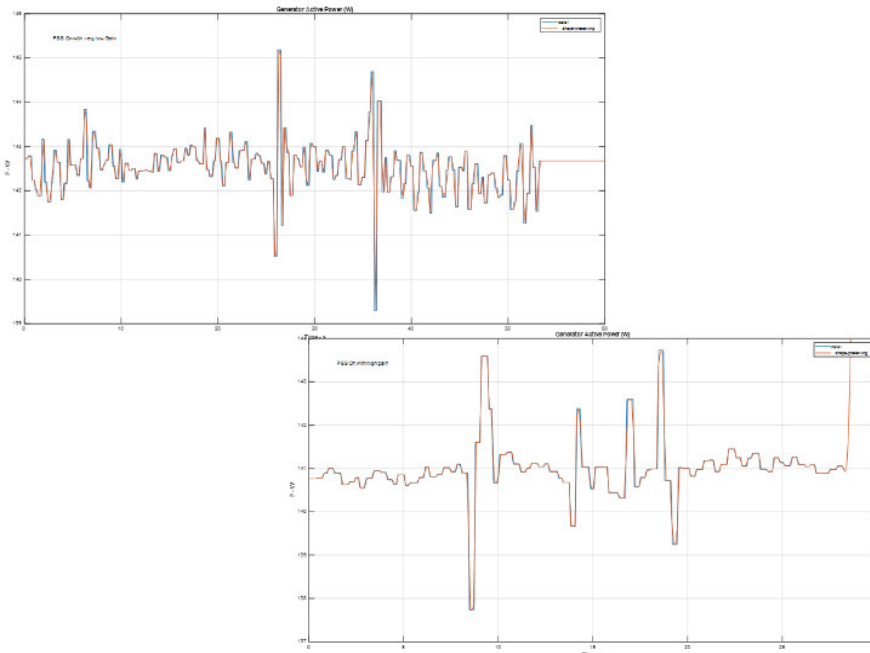
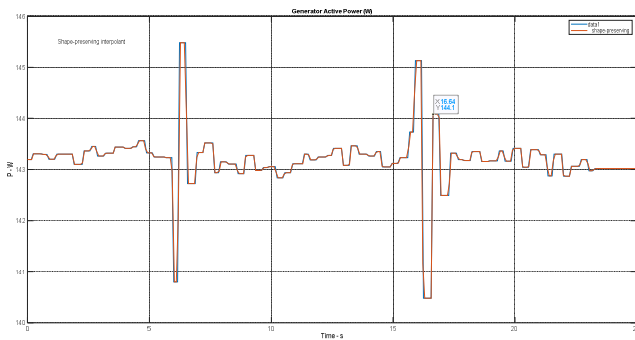Fig. 11. Electrical Power respond for the different Kpss gains

Fig. 12. Electrical Power respond for the optimal PSS gain (AVR/PSS case)

7. CONCLUSIONS

The small perturbation stability characteristics of a single machine supplying an infinite bus through external impedance have been explored by means of frequency response analyses, giving insights into effects of machine and system parameters, voltage regulator gain, and stabilizing functions derived from speed and working through the voltage reference of the voltage regulator.

The study has explored a variety of machine loadings, machine inertias, and system external impedances with a determination of the oscillation and damping characteristics of voltage or speed following a small disturbance in mechanical torque. An attempt has been made to develop some unifying concepts that explain the stability phenomena of concern, and to predict desirablephase and magnitude characteristics of stabilizing functions.

A novel 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 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.

Finally, the experiments have been conducted at BanVe Hydropower Plant to verify the proposed method. The results obtained is promising and the new method would be ready for futher testings in other EVN plants.

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