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Improvement of Dynamic Stability of a Single Machine Infinite-Bus Power System using Fuzzy Logic based Power System Stabilizer

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Abstract:— with constraints on data availability and for study of power system stability it is adequate to model the synchronous generator with field circuit and one equivalent damper on q-axis known as the model 1.1. This paper presents a systematic procedure for modelling and simulation of a single-machine infinite-bus power system installed with a Power System Stabilizer (PSS) and Fuzzy Logic Power System Stabilizer (FLPSS) where the synchronous generator is represented by model 1.1, so that impact of PSS on power system stability can be more reasonably evaluated. The model of the example power system is developed using MATLAB/SIMULINK which can be used for teaching the power system stability phenomena, and also for research works especially to develop generator controllers using advanced technologies. An analytical approach is developed for the determination of PSS parameters. The non-linear simulation results are presented to validate the effectiveness of the proposed approach.

Keywords:— MATLAB/SIMULINK, modelling and simulation, power system stability, single-machine infinite-bus power system, Power System Stabilizer, Fuzzy Logic Power System Stabilizer.

NOMENCLATURE

δ	Rotor angle of synchronous generator in radians
ω_B	Rotor speed deviation in rad/sec
S_m	Generator slip in p.u.
S_{mo}	Initial operating slip in p.u.
H	Inertia constant
D	Damping coefficient
T_m	Mechanical power input in p.u.
T_e	Electrical power output in p.u.
E_{fd}	Excitation system voltage in p.u.
T'_{do}	Open circuit d-axis time constant in sec
T'_{qo}	Open circuit q-axis time constant in sec
x_d	d-axis synchronous reactance in p.u.
x'_d	d-axis transient reactance in p.u.
x_q	q-axis synchronous reactance in p.u.
x'_q	q-axis transient reactance in p.u.

I. INTRODUCTION

Traditionally, for the small signal stability studies of a single-machine infinite-bus (SMIB) power system, the linear model of Phillips-Heffron has been used for years, providing reliable results [1]-[2]. It has also been successfully used for designing and tuning the classical power system stabilizers (PSS). Although the model is a linear model, it is quite accurate for studying low frequency oscillations and stability of power systems. With the advent of Flexible AC Transmission System (FACTS) devices [3], such as Thyristor Controlled Series Compensator (TCSC), Static synchronous compensator (STATCOM) and unified power flow controller (UPFC), the unified model of SMIB power system installed with a TCSC, STATCOM and a UPFC have been developed [4]-[6]. These models are the popular tools amongst power engineers for studying the dynamic behaviour of synchronous generators, with a view to design control equipment. However, the model only takes into account the generator main field winding and hence these models may not always yield a realistic dynamic assessment of the SMIB power system with FACTS because the generator damping winding in q-axis is not accounted for. Further, liner methods cannot properly capture complex dynamics of the system, especially during major disturbances. This presents difficulties for designing the FACTS controllers in that, the controllers designed to provide desired performance at small signal condition do not guarantee acceptable performance in the event of major disturbances.

Effective design and accurate evaluation of the PSS control strategy depend on the accuracy of modelling of this process. In [7], a systematic procedure for modelling, simulation and optimal tuning of PSS controller in a SMIB power system was presented where the MATLAB/SIMULINK based model was developed to design the PSS. However, the model only takes into account the generator main field winding and the synchronous machine was represented by model (1.0). This paper presents a higher-order synchronous machine model, which includes one damper winding along the q-axis, for a power system installed with a PSS and FLPSS.

Despite significant strides in the development of advanced control schemes over the past two decades, the conventional lead-lag (LL) structure controller as well as the classical proportional-integral-derivative (PID) controller and its variants, remain the controllers of choice in many industrial applications. These controller structures remain an engineer's preferred choice because of their structural simplicity, reliability, and the favourable ratio between performance and cost. Beyond these benefits, these controllers also offer simplified dynamic modelling, lower user-skill requirements, and minimal development effort, which are issues of substantial importance to engineering practice [8]-[9]. In [10], a comparative study about the PSS and FLPSS based design was presented, where it has been shown that that LL structured PSS with the controller parameters, gives the best system response compared to all other alternatives. In view of the above, a LL controller structure is used for the PSS controller.

The problem of PSS parameter tuning is a complex exercise. A number of conventional techniques have been reported in the literature pertaining to design problems of conventional power system stabilizers namely: the eigenvalue assignment, mathematical programming, gradient procedure for optimization and also the modern control theory. Unfortunately, the conventional techniques are time consuming as they are iterative and require heavy computation burden and slow convergence. In addition, the search process is susceptible to be trapped in local minima and the solution obtained may not be optimal [11].

This paper is organized as follows. In Section II, the modelling of power system under study, which is a SMIB power system with a PSS and FLPSS, is presented. The proposed controller structures and problem formulation are described in Section III. Simulation results are provided and discussed in Section IV and conclusions are given in Section V

II. POWER SYSTEM UNDER STUDY

The SMIB power system shown in Fig. 1 is considered in this study. The synchronous generator is delivering power to the infinite-bus through a double circuit transmission line. In Fig. 1, V_t and E_b are the generator terminal and infinite bus voltage respectively; X_T , X_L and X_{TH} represent the reactance of the transformer, transmission line per circuit and the Thevenin's impedance of the receiving end system respectively.

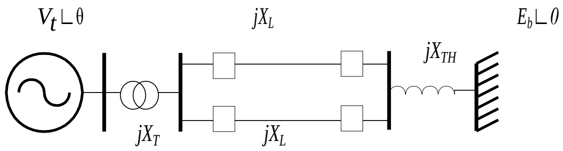

Fig. 1 Single-machine infinite-bus power system

A. Modelling the Synchronous Generator Infinite-bus Power System

The synchronous generator is represented by model 1.1, i.e. with field circuit and one equivalent damper winding on q-axis. The machine equations are [12]:

$$\frac{d\delta}{dt} = \omega_B(S_m - S_{m0}) \quad \rightarrow (1)$$

$$\frac{dS_m}{dt} = \frac{1}{2H}[-D(S_m - S_{m0}) + T_m - T_e] \quad \rightarrow (2)$$

$$\frac{dE'_q}{dt} = \frac{1}{T'_{d0}}[-E'_q + (x_d - x'_d)i_d + E_{fd}] \quad \rightarrow (3)$$

$$\frac{dE'_d}{dt} = \frac{1}{T'_{q0}}[-E'_d + (x_q - x'_q)i_q] \quad \rightarrow (4)$$

The electrical torque *Te* is expressed in terms of variables *E' d* , *E' q* , *id* and *iq* as:

$$T_e = E'_d i_d + E'_q i_q + (x'_d - x'_q)i_d i_q \quad \rightarrow (5)$$

For a lossless network, the stator algebraic equations and the network equations are expressed as:

$$E'_q + x'_d i_d = v_q \quad \rightarrow (6)$$

$$E'_d - x'_q i_q = v_d \quad \rightarrow (7)$$

$$v_q = -x_e i_d + E_b \cos\delta \quad \rightarrow (8)$$

$$v_d = x_e i_q - E_b \sin\delta \quad \rightarrow (9)$$

Solving the above equations, the variables *id* and *iq* can be obtained as:

$$i_d = \frac{E_b \cos\delta - E'_q}{x_e + x'_d} \rightarrow (10)$$

$$i_q = \frac{E_b \sin\delta - E'_d}{x_e + x'_q} \rightarrow (11)$$

The above notation for the variables and parameters described are standard and defined in the nomenclature. For more details, the readers are suggested to refer [11]-[12].

III. PROBLEM FORMULATION

A. Structure of the PSS

The structure of PSS-based damping controller is shown in Fig. 2. The input signal of the proposed controllers is the speed deviation (Δω), and the output signal is the V_{PSS} . The structure consists of a gain block with gain *KPSS*, a signal washout block and two-stage phase compensation blocks. The signal washout block serves as a high-pass filter, with the time constant *TW*, high enough to allow signals associated with oscillations in input signal to pass unchanged.

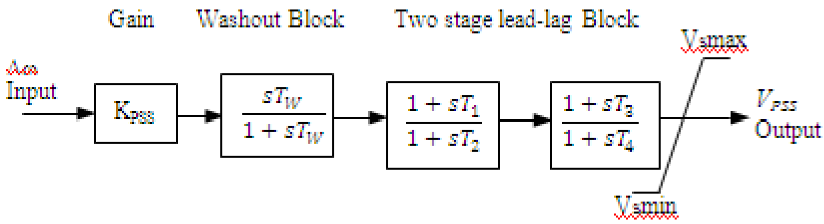

Fig. 2 Structure of PSS

From the viewpoint of the washout function, the value of *TW is* not critical and may be in the range of 1 to 20 seconds [12]. The phase compensation block (time constants *T1*, *T2* and *T3*, *T4)* provides the appropriate phase-lead characteristics to compensate for the phase lag between input and the output signals.

The block diagram of the PSS used in industry is shown in Fig 2. It consists of a washout circuit, dynamic compensator, torsion filter and limiter. PSS with guidelines for the selection of parameters (tuning) are given next.

It is to be noted that the major objectives of providing PSS is to increase the power transfer in the network, which would otherwise be limited by oscillatory instability. The PSS must also function properly when the system is subjected to large disturbances.

PSS have been used for over 20 years in Western systems of United States of America and in Ontario Hydro. In United Kingdom, PSS have been used in Scotland to damp oscillations in tie lines connecting Scotland and England. It can be generally said that need for PSS will be felt in situations when power has to be transmitted over long distances with weak AC ties. Even when PSS may not be required under normal operating conditions, they allow satisfactory operation under unusual or abnormal conditions which may be encountered at times. Thus, PSS has become a standard option with modern static exciters and it is essential for power engineers to use these effectively. Retrofitting of existing excitation systems with PSS may also be required to improve system stability.

B. PSS Design

The tuning of Power System Stabilizer can be performed using extensive analytical studies covering various aspects. While such studies are useful in optimizing the performance of PSS, satisfactory operation of PSS can be obtained by tuning the PSS.

1. Measure the open loop frequency response without PSS. This involves obtaining the transfer function between the terminal voltage and the AVR input (Vs) in frequency domain. As described earlier, the transfer function is approximately related to GEP(s).
2. Select PSS time constants by trial and error such that desired phase compensation is obtained. The guidelines for selecting the phase compensation are:
   a. Check that the compensated system (GEP(s) PSS(s)) has some phase lag at inter area modes.
   b. Verify the stabilizer time constant settings by field test which involves determination of points on a root locus. The local mode oscillations are stimulated by step changes to AVR reference, line switching or low level sinusoidal modulation (at local mode frequency) of the voltage reference. The effect of the PSS can be measured by comparing the damping with zero PSS gain and few low values of the gain which cause a noticeable change. The waveform recorded can give information on the frequency and damping ratio.
3. Perform the gain margin test. This consists of slowly increasing the stability gain until instability is observed which is characterized by growing oscillations at a frequency greater than the local mode. The oscillation can be monitored from PSS output. Once instability is detected the stabilizer is switched out of service. Reduction of stabilizer output limits during the test will ensure that safe operation of the generator is maintained.
4. The PSS gain can now be set to a lower value and a fraction of the instability gain. Typically the gain is set to 1/3 of the instability gain.

C. Fuzzy Logic PSS

The model of FLPSS refers on fuzzy logic controller block and to simplify model integrator block is also removed FLPSS model is as shown in Fig. 3

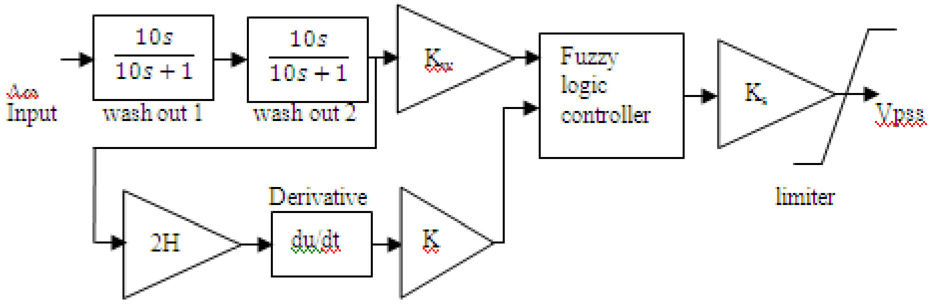

Fig. 3 FLPSS model

Fig. 3 shows that FLPSS consists of blocks, those are wash-out, gain (Kw, Kp, Ks), and limiter. Each part is explained as follows:

1. Wash Out
   This block consists of two wash-out filter with time constant 10 second.
2. Gain [Kw Kp Ks]
   Gain is needed to normalize the input and output of fuzzy logic controller.
3. Fuzzy Logic Controller
   Fuzzy Logic Controller has a function to produce control signal as an output appropriate with the input.
4. Limiter [Vsmin Vsmax]
   Limiter gives limitation of the PSS output.

In order to set fuzzy logic controller, input membership function, output membership function, rules, and gain tuning are definitive. Detail of input membership function, output membership function, rules, and gain tuning are as follows:

Input Membership Function

Each of input variables are classified by Input membership function consists of trapezoidal membership function and triangular membership function, described in Fig. 4.

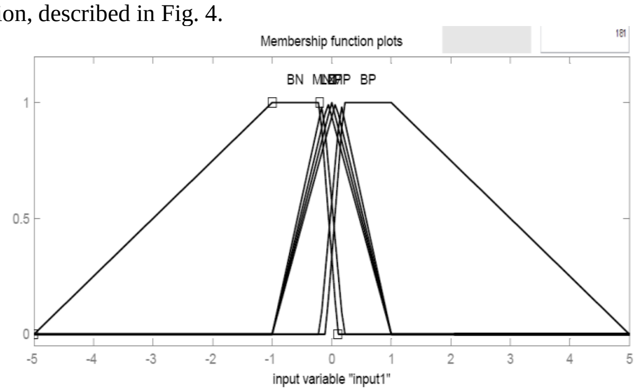

Fig. 4 Input Membership Function

Output Membership Function

Output membership function also consists of triangular membership function, described in Fig. 5.

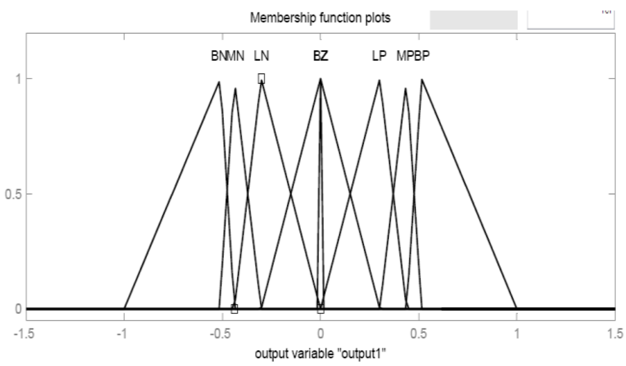

Fig. 5 Output Membership Function

Rules

Rules used by FLPSS are shown in Table I.

Table I: **Fuzzy Logic Rules**

dw/dpa	**BP**	**MP**	**LP**	**Z**	**LN**	**MN**	**BN**
BN	BZ	LN	MN	MN	BN	BN	BN
MN	LP	BZ	LN	MN	MN	BN	BN
LN	MP	LP	BZ	LN	LN	MN	BN
Z	BP	MP	LP	LZ	LN	MN	BN
LP	BP	MP	LP	LP	BZ	LN	MN
MP	BP	BP	MP	MP	LP	BZ	LN
BP	BP	BP	BP	MP	MP	LP	BZ

Gain Tuning

The gains of the proportional and derivative actions of the FLPSS are given by the following relations:

$$K_{PR} = K_S \times (F\{K_P\} + F\{K_W\}) \quad \rightarrow (12)$$

$$K_{DER} = K_S \times F\{K_P\} \quad \rightarrow (13)$$

With K_{PR}, K_{DER}, and F{} are proportional gain, derivative gain, and fuzzy operation, respectively. To obtain the gains K_w, K_p, and K_s a two steps method has been used. These two steps consist of adjusting K_p and K_w in order to normalize input and then tuning K_s to obtain best result. The value of K_w, K_p, and K_s are 0.55, 50 x K_p, and 3, respectively.

D. Problem Formulation

In the present study, a washout time constant of *TW*=10s is used. The controller gain *KPSS* and the time constants *T1*, *T2*, *T3* and *T4* are to be determined.

IV. RESULTS AND DISCUSSIONS

In order to optimally tune the parameters of the PSS and FLPSS, as well as to assess its performance and robustness under wide range of operating conditions with various fault disturbances and fault clearing sequences, the MATLAB/SIMULINK model of the example power system is developed using equations (2)–(11).

The objective function is evaluated for each individual by simulating the system dynamic model considering a three phase fault at the generator terminal busbar at t = 20 sec.

Simulation Results

In order to show the advantages of modelling the synchronous generator with PSS and tuning its Parameters in the way presented in this paper, simulation studies are carried out for the example power system subjected to various severe disturbances as well as small disturbance. The following cases are considered:

Case-1: Three-phase Fault Disturbance

A three phase fault is applied at the generator terminal busbar at t = 20 sec and cleared after 5 cycles. The original system is restored upon the fault clearance. To study the performance of PSS controller, two cases are considered; with and without PSS and FLPSS. The response without the controller (no control) is shown with blue line with legend NC, the responses with PSS is shown with green line with legend PSS and the responses with FLPSS is shown with red line with legend FLPSS.

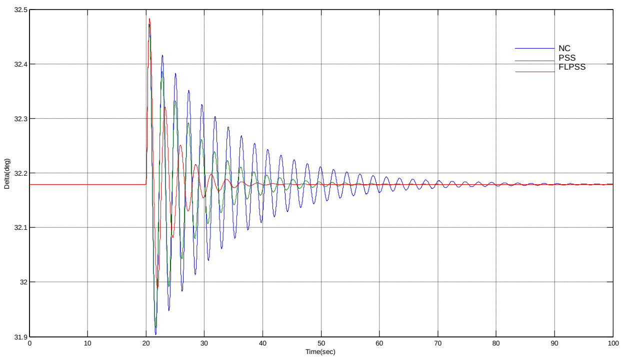

Fig. 6 Variation of power angle δ, without, with PSS and FLPSS for a 5-cycle three-phase fault disturbance (Case-1)

The system power angle response for the above contingency is shown in Fig. 6. It is clear from the Fig. 6 that, without controller even though the system is stable, power system oscillations are poorly damped.

It is also clear that, proposed PSS significantly suppresses the oscillations in the power angle and provides good damping characteristics to low frequency oscillations by stabilizing the system faster and the controller FLPSS is further damped oscillations by stabilizing the system much faster. Figs. 7 - 14 shows the variation of speed deviation $\Delta\omega$, electrical power Pe , voltages $E'\ d$, $E'\ q$,$E\ fd$, Vt , currents id and iq , respectively all with respect to time for the above mentioned contingency (Case-1).
It is clear from this figure that, the PSS and FLPSS improves the stability performance of the example power system and power system oscillations are well damped out.

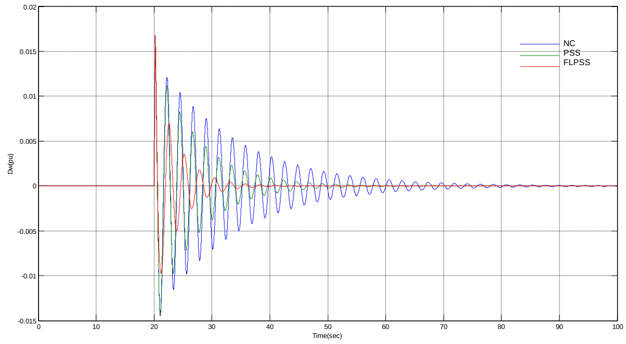

Fig. 7 Variation of speed deviation Δω : Case-1

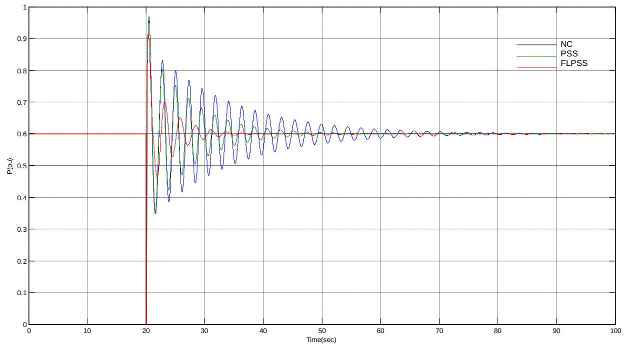

Fig. 8 Variation of electrical power *Pe* : Case-1

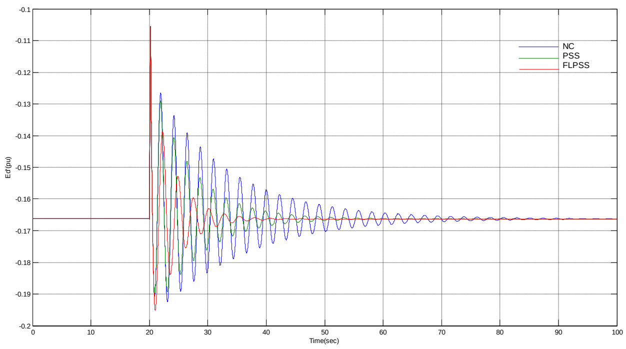

Fig. 9 Variation of voltage *E' d* : Case-1

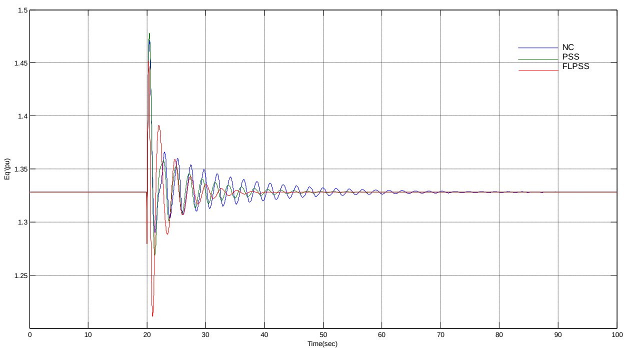

Fig. 10 Variation of voltage *E' q* : Case-1

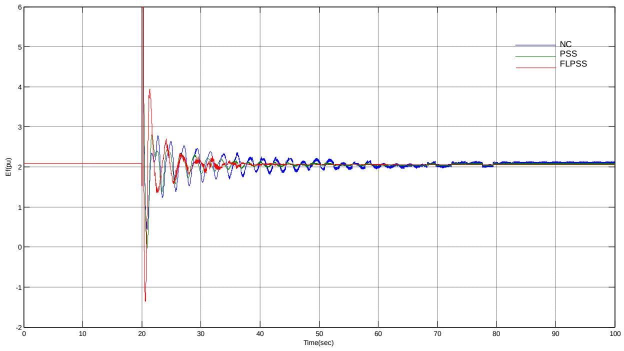

Fig. 11 Variation of voltage *Ef* : Case-1

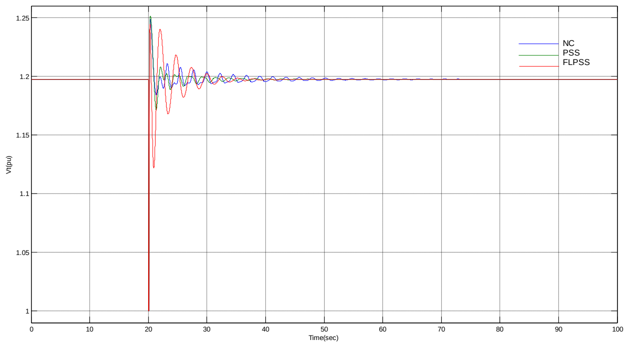

Fig. 12 Variation of terminal voltage *Vt* : Case-1

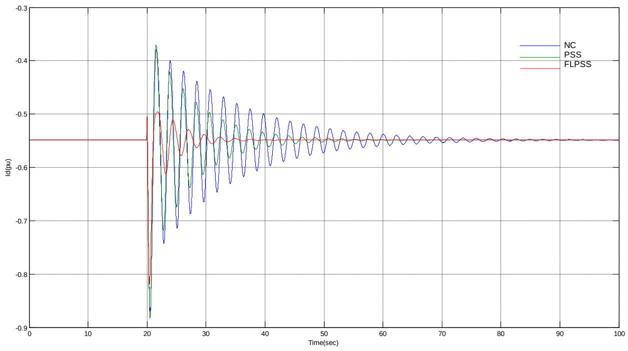

Fig. 13 Variation of current *Id* : Case-1

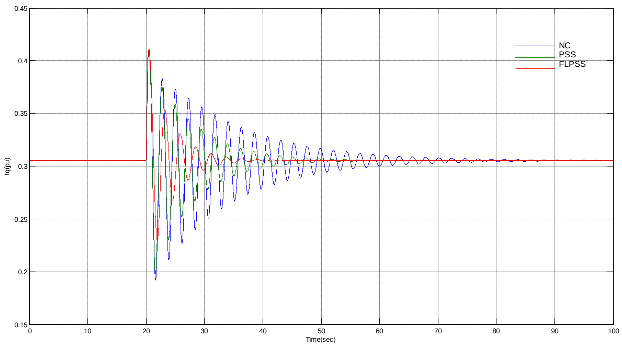

Fig. 14 Variation of current *Iq* : Case-1

Case-2: Line-outage Disturbance

In this case another severe disturbance is considered. One of the transmission line is permanently tripped out at t = 20 sec. The system response for the above contingency is shown in Figs. 15- 23.

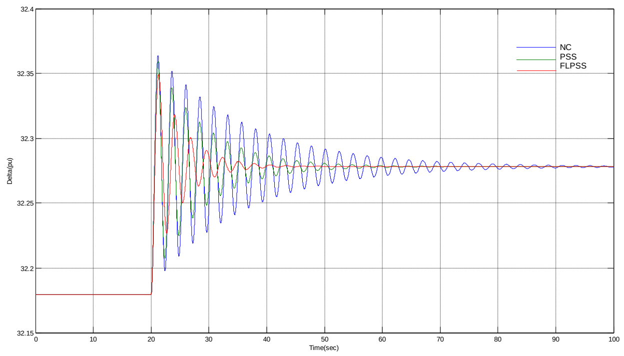

Fig. 15 Variation of power angle δ : Case-2

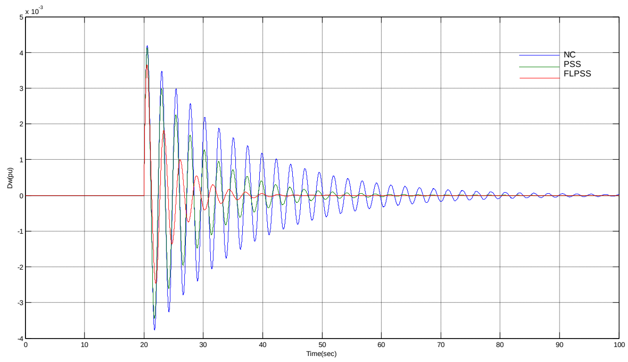

Fig. 16 Variation of speed deviation Δω : Case-2

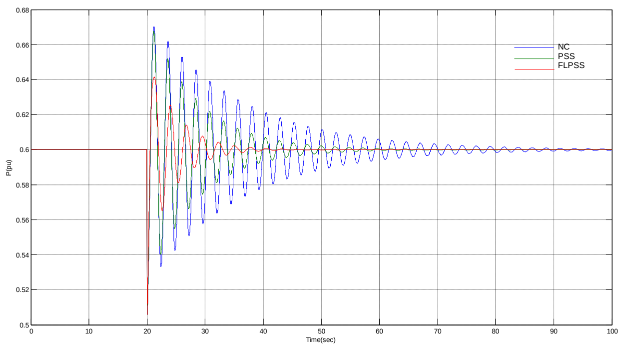

Fig. 17 Variation of electrical power *Pe* : Case-2

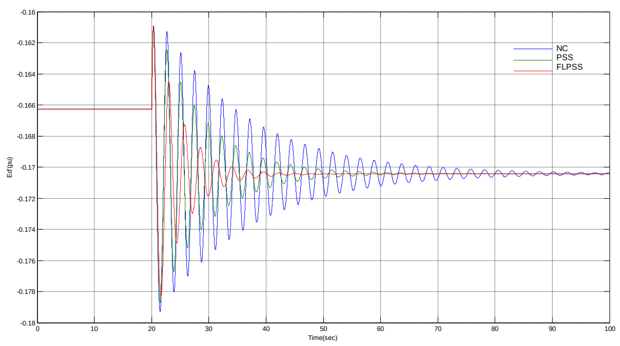

Fig. 18 Variation of voltage $E'd$: Case-2

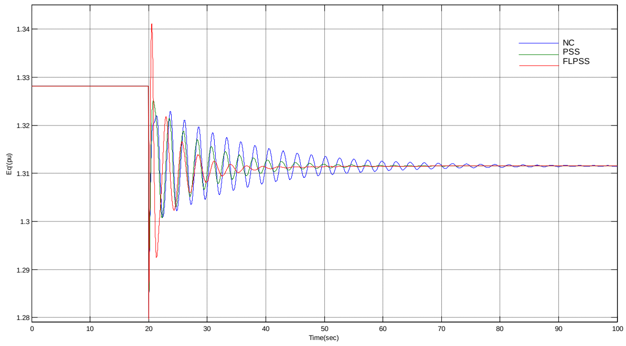

Fig. 19 Variation of voltage $E'q$: Case-2

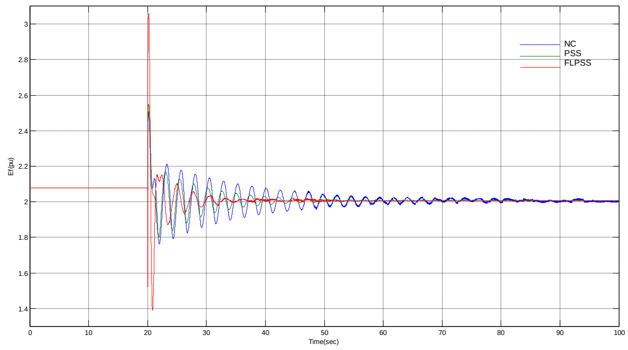

Fig. 20 Variation of voltage Ef : Case-2

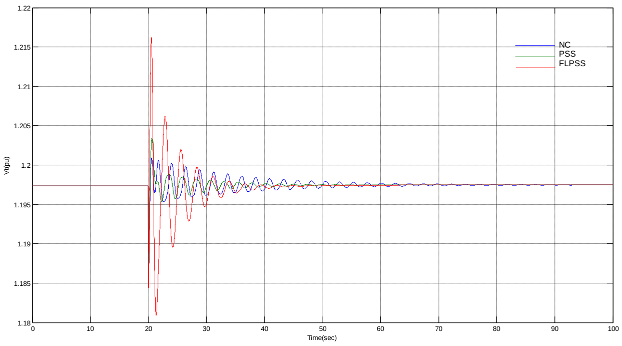

Fig. 21 Variation of terminal voltageVt : Case-2

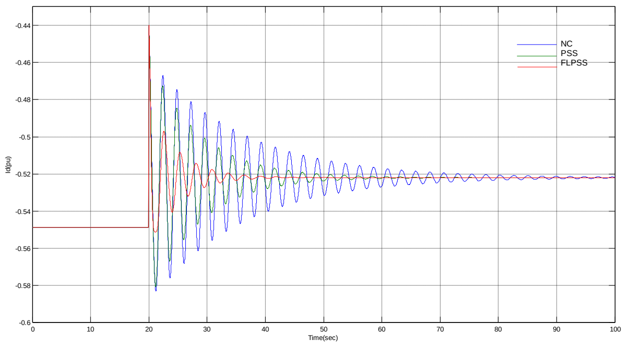

Fig. 22 Variation of line current Id: Case-2

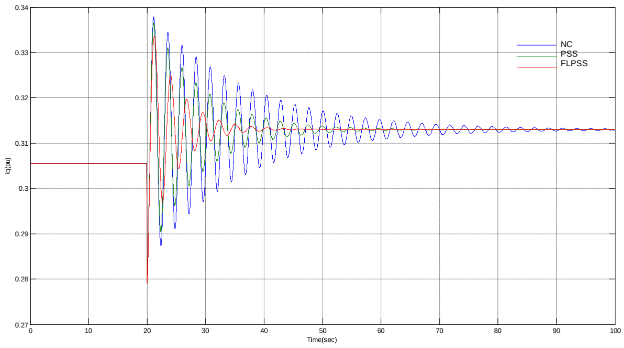

Fig. 23 Variation of line current *Iq*: Case-2

It is also clear from the Figs. that he PSS has good damping characteristics to low frequency oscillations and quickly stabilizes the system under this severe disturbance.

Case-3: Small Disturbance

In order to verify the effectiveness of PSS under small disturbance, the mechanical power input to the generator is decreased by 1 pu at t = 20 sec and the disturbance is removed at t = 50 sec. The system response under this small disturbance contingency is shown in Figs. 24-27.

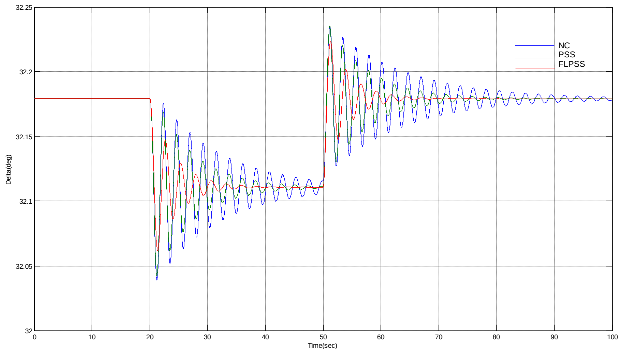

Fig. 24 Variation of power angle δ: Case-3

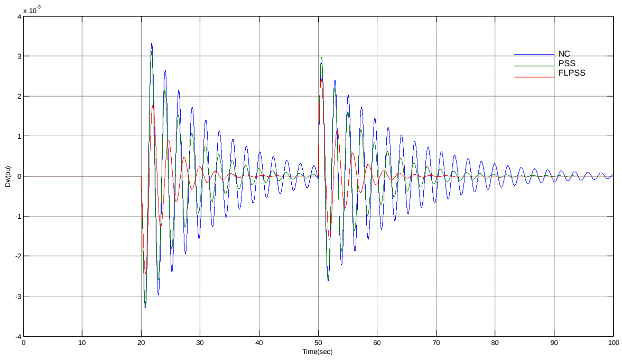

Fig. 25 Variation of speed deviation Δω : Case-3

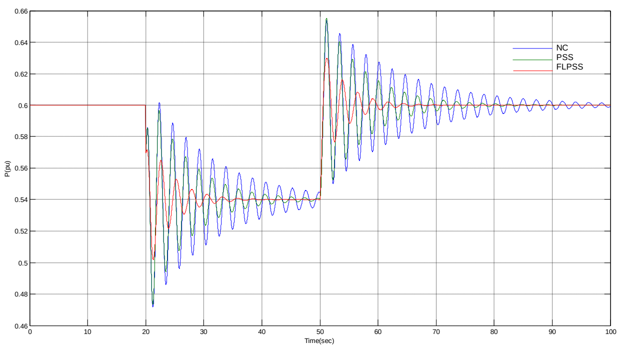

Fig. 26 Variation of electrical power *Pe* : Case-3

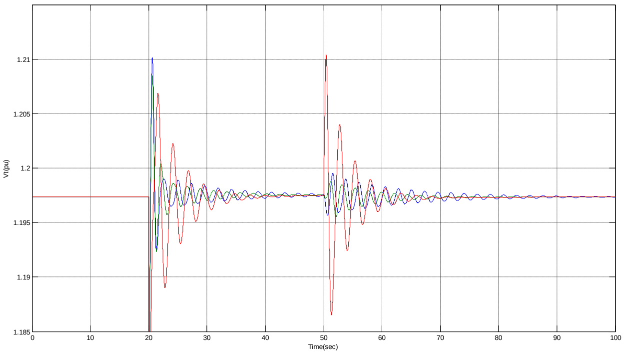

Fig. 27 Variation of terminal voltage*Vt* : Case-3

It is clear from the Figs. 21-24 that, the PSS has good damping characteristics to low frequency oscillations and quickly stabilizes the system under this small disturbance.

V. CONCLUSIONS

The MATLAB/SIMULINK model of a single-machine infinite-bus power system with a PSS and FLPSS controller presented in the paper provides a means for carrying out power system stability analysis and for explaining the generator dynamic behavior as affected by a PSS. This model is far more realistic compared to the model available in open literature, since the synchronous generator with field circuit and one equivalent damper on q-axis is considered. The controller is tested on example power system subjected to various large and small disturbances. The simulation results show that, the PSS and FLPSS improves the stability performance of the power system and power system oscillations are effectively damped out. Hence, it is concluded that the proposed model is suitable for carrying out power system stability studies in cases where the dynamic interactions of a synchronous generator of a PSS and FLPSS are the main concern.

APPENDIX

System data: All data are in pu unless specified otherwise.
Generator: H = 3.542, D = 0, Xd=1.7572, Xq=1.5845, X'd =0.4245, X'q =1.04, T'do = 6.66, T'qo=0.44, Ra=0, Pe=0.6, Qe=0.02224, δ0=44.370. Exciter: KA=400, TA=0.025 s
Transmission line: R=0, XL = 0.8125, XT=0.1364.
PSS: Wash-out network: Ka=15, Tw=10, Lead-lag network: T1=0.75, T2=0.3, Lag-lead network: T3=0.75, T4=0.3, Vs=±0.05.

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