COMPARATIVE STUDY BETWEEN REDUCED ORDER MODEL BASED ROBUST POWER SYSTEM STABILZERS

Ruchi Sharma, Dr. Kota Solomon Raju, Dr.Y.C.Sharma
Electronics Department
Vivekananda Global University, Jaipur, CSIR-CEERI, Pilani, VGU Jaipur, India.

ABSTRACT

In multi-machine power system the order of the states matrix is very large. The main objectives of order reduction is to design a controller of lower order which can effectively control the original high order system so that the overall system is of lower order and easy to understand. The state space matrices of the reduced order system are chosen such that the dominant eigenvalues of the full order system are unchanged. The other system parameters are chosen using the PSO with objective function to minimize the mean squared errors between the outputs of the full order system and the outputs of the reduced order model when the inputs are unit step. This paper presents a comparatively study of design of fast output sampling feedback controllers via reduced order model *using Particle PSO method, and Davison method technique* for multi-machine system**.**

KEYWORDS: Fast output sampling feedback, power system stabilizer, reduced order model, particle swarm optimization, Davison method.

1. INTRODUCTION

The dynamic stability of power systems is an important factor for secure system operation. Low-frequency oscillation modes have been observed when power systems are interconnected by weak tie lines. The low-frequency oscillation mode, which has poor damping in a power system, is also called the electromechanical oscillation mode and usually occurs in the frequency range of 0.1–2.0 Hz. The power system stabilizer (PSS) has been widely used for mitigating the effects of low- frequency oscillation modes.

The construct and parameters of PSS have been discussed in many studies. Currently, many plants prefer to employ conventional lead-lag structure PSSs, due to the ease of online tuning and reliability. The widely used conventional power system stabilizers (CPSS) are designed using the theory of phase compensation in the frequency domain and are introduced as a lead- lag compensator. The parameters of CPSS are determined based on the linearized model of the power system. In order to provide perfect damping over a wide operation range, the CPSS parameters should be fine tuned in response to both types of oscillations. Since power systems are highly nonlinear systems, with configurations and parameters which alter through time, the CPSS design based on the linearized model of the power system cannot guarantee its performance in a practical operating environment. The design of such PSSs requires the determination (or tuning) of few parameters for each machine viz. the overall dc gain, the wash out circuit time constant, and the various constants for the two lead networks.

The feedback gainsare piecewise constant, their method could be easily implemented and indicate a new possibility. Such a control law can stabilize a much larger class of systems than the static output feedback Due to the geographically control input for each machine should be a function of the output of that machine alone. This can be achieved PSS, to activate the proposed controller at same instant, a proper synchronization signal is required to be sent to diagonal gain matrix design for multi-machine power system [23-31].

2. MATERIAL AND METHODS

Small-signal stability is the ability of the power system to remain in synchronism under normal operating condition and regain an acceptable state of equilibrium when subjected to small disturbances. Since the disturbance is considered to be small, the equations that describe the resulting dynamics of the system may be linearized. Instability that may result is of two types:

1. Steady increase in generator rotor angle due to lack of synchronizing torque;
2. Rotor oscillations of increasing amplitude due to lack of sufficient damping torque.

In today's practical power systems, the small-signal stability problem is usually one of insufficient damping of system oscillations. For the analysis of small-signal stability, linearized models are generally considered to be adequate for representation of the power system and its various components.

BASIC CONCEPT

The basic function of a power system stabilizer is to extend the stability limits by modulating generator excitation, to provide damping to the oscillation of synchronous machine rotors relative to one another. The oscillations of concern typically occur in the frequency range of approximately 0.2 to 3.0 Hz, and insufficient damping of these oscillations may limit the ability to transmit the power. To provide damping, the stabilizer must produce a component of motor slip which is in phase with reference voltage variations. For input signal, the transfer function of the stabilizer must compensate for the gain and phase of excitation system, the generator and the power system, which collectively determine the transfer function from the stabilizer output to the component of mechanical speed. This can be modulated via excitation system [1].

PERFORMANCE OBJECTIVES

Power system stabilizers can extend power transfer stability limits which are characterized by lightly damped or spontaneously growing oscillations in the 0.2 to 3.0 Hz frequency range. This is accomplished via excitation control to contribute damping to the system modes of oscillations. Consequently, it is the stabilizer's ability to enhance damping under the least stable conditions, i.e., "the performance conditions", which is important. Additional damping is primarily required under the conditions of weak transmission and heavy load as occurs, for example, when attempting to transmit the power over long transmission lines from the remote generating plants or relatively weak tie between systems. Contingencies, such as line outage, often precipitate such conditions. Hence, system normally having adequate damping can often benefit from stabilizers during such conditions.

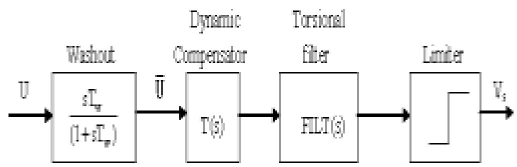

Figure 1: Block diagram of PSS [1].

CLASSICAL STABILIZER IMPLEMENTATION PROCEDURE

The block diagram used in industry is shown in Fig. 2.1[4]. It consists of a washout circuit, dynamic compensator, torsional filter and limiter. The washout circuit is provided to eliminate steady-state bias in the output of PSS which will modify the generator terminal voltage. The PSS is expected to respond only to transient variations in the input signal (rotor slip) and not to the dc offset in the signal. The washout circuit acts essentially as a high pass filter and it must pass all frequencies that are of interest.

Implementation of a power system stabilizer implies adjustment of its frequency characteristic and gain to produce the desired damping of the system oscillations in the frequency range of 0.2 to 3.0 Hz. The transfer function of a generic power system stabilizer having washout circuit and a dynamic compensator may be expressed as

$$H(s) = K_s \frac{sT_w(1+sT_1)(1+sT_3)}{(1+sT_w)(1+sT_2)(1+sT_4)} \quad (2.1)$$

where, K_s represent stabilizer gain.

The stabilizer frequency characteristic is adjusted by varying the time constant T_w, T_1, T_2, T_3 and T_4. The output of PSS must be limited to prevent the PSS acting to counter the action of AVR.

A number of sequential and simultaneous approaches for the tuning of these parameters have been reported in literature although these approaches have been used and produce satisfactory results regarding the damping of local modes of oscillation; their outcome may not be the optimal. This is due to the restrictive assumption made and the intuitive nature of the design process. A power system stabilizer can be made more effective if it is designed and applied with the knowledge of associated power system characteristics. Power system stabilizer must provide adequate damping for a range of frequencies of the power system oscillation modes. To begin with, simple analytical models, such as that of a single machine connected to an infinite bus system, can be useful in determining the frequencies of local mode oscillations. Power system stabilizer should also be designed to provide stable operation for the weak power system conditions and associated loading. A designed stabilizer must ensure for the robust performance and satisfactory operation with an external system reactance ranging from 20% to 80% on the unit rating [5].

MULTI-MACHINE POWER SYSTEM ANALYSIS

Analysis of practical power system involves the simultaneous solution of equations consisting of synchronous machines and the associated excitation system and prime movers, interconnecting transmission network, static and dynamic load (motor loads), and other devices such as HVDC converters, static var compensators. The dynamics of the machine rotor circuits, excitation systems, prime mover and other devices are represented by differential equations. The result is that the complete system model consists of large number of ordinary differential and algebraic equations.

Model 1.0 is assumed for synchronous machines by neglecting the damper windings. In addition, the following assumptions are made for simplicity [4].

1. The loads are represented by constant impedances.
2. Transients saliency is ignored by considering $x_q = x'_d$.
3. Mechanical power is assumed to be constant.
4. E_{fd} is single time constant AVR.

STATE SPACE MODEL OF 10 MACHINE AND 39 BUS POWER SYSTEM (MACHINE MODEL 1.0): GENERATOR EQUATIONS

The machine equations (for k^{th} machine) are

$$pE'_{qk} = \frac{1}{T'_{d0k}}\left[-E'_{qk} + (x_{dk} - x'_{dk})i_{dk} + E_{fdk}\right],$$

$$p\delta_k = w_B (S_{mk} - S_{mk0}),$$

$$pS_{mk} = \frac{1}{2H_k}\left[-D_k (S_{mk} - S_{mk0}) + P_{mk} - P_{ek}\right]$$

The state space model of a 10-machine 39 bus system as shown in Fig. 2.5 can be obtained using machine data, line data and load flow data as given in [1] as

$$\dot{\bar{x}} = [A]\bar{x} + [\bar{B}](\Delta\bar{V}_{ref} + \Delta\bar{V}_s),$$

$$\bar{y} = [C]\bar{x},$$

Where

$x = [x_1, x_2, ..., x_{10}]^T$, and

$y = [y_1, y_2, ..., y_{10}]^T$.

x_k (k=1,10) denotes the states of k^{th} machine, and y_k (k=1,10) denotes the output of the k^{th} machine.

The elements (sub matrices of 10 × 10) of A matrix depend on the machine and network parameters.

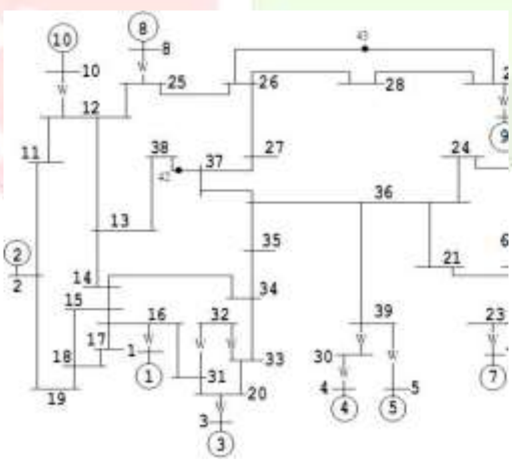

Figure 2: Single line diagram of 10 machines and 39 bus System [1].

REVIEW ON FAST OUTPUT SAMPLING METHOD

With Fast output sampling approach, it is possible to simultaneously realize a given state feedback gain for a family of linear, observable models. This approach requires increasing the low rank of the measurement matrix of an associated discretized system, which can be achieved by sampling the output several times during one input sampling interval, and constructing the control signal from these output samples. Such a control law can stabilize a much larger class of systems than the static output feedback. In fast output sampling feedback technique gain matrix is generally full. This results in the control input of each machine being a function of outputs of all machines.

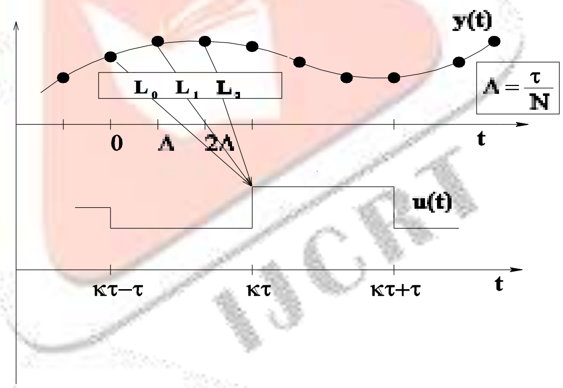

Figure 3: Fast Output Sampling Method.

In this technique an output feedback law is used to realize a discrete state feedback gain by multirate observations of the output signal. The control signal is held constant during each sampling interval τ. Let (Φ, Γ, C) be the system [42] sampled at rate $1/\Delta$ where $\Delta = \tau/N$. Output measurements are taken at time instants $t = l\Delta, l = 0,1,\ldots\ldots, N-1$. The control signal u(t), which is applied during the interval, $k\tau \le t < (k+1)\tau$ is then constructed as a linear combination of the last N output observations [66-67].

Consider a plant described by a linear model

$$\dot{x} = Ax + Bu$$
$$y = Cx \quad (4.1)$$

with (A,B) controllable and (C,A) observable. Assume the plant is to be controlled by a digital controller, with sampling time ∨ and zero order hold, and that a sampled data state feedback design has been carried out to find a state feedback gain F such that the closed loop system

$$x(k\tau + \tau) = (\Phi_\tau + \Gamma_\tau F)x(k\tau) \quad (4.2)$$

system having at time t= k τ the input has desired properties. Hence $\Phi_\tau = e^{A\tau}$ and $\Gamma_\tau = \int_0^\tau e^{As} ds B$. Instead of using a state observer, the following sampled data control can be used to realize the effect of the state feedback gain F by output feedback. Let $\Delta = \tau/N$ and consider

$$u(t) = [L_0, L_1, \ldots, L_{N-1}] \begin{bmatrix} y(k\tau - \tau) \\ y(k\tau - \tau + \Delta) \\ \vdots \\ y(k\tau - \Delta) \end{bmatrix} = Ly_k \quad (4.3)$$

For $k\tau \le t < (k+1)\tau$, where the matrix blocks L_i represent output feedback gains, and the notation L, y_k has been introduced for convenience. Note that $1/\tau$ is the rate at which the loop is closed, whereas output samples are taken at the N-times faster rate $1/\Delta$. This control law is illustrated in fig. 2.6.

To show how a fast output sampling controller can be designed to realize the given sampled-data state feedback gain, we construct a fictitious, lifted system for static output feedback. Let (Φ, Γ, C) denote the system at the rate $1/\Delta$ where $\Delta = \tau/N$.

Consider the discrete-time

$u_k = u(k\tau)$, state $x_k = x(k\tau)$ and output y_k as

$$x(k+1) = \Phi_\tau x_k + \Gamma_\tau u_k \quad (4.4)$$
$$y(k+1) = C_0 x_k + D_0 u_k. \quad (4.5)$$

where C_0 and D_0 are defined as

$$C_0 = \begin{bmatrix} C \\ C\Phi \\ . \\ . \\ C\Phi^{N-1} \end{bmatrix}, \quad D_0 = \begin{bmatrix} 0 \\ C\Gamma \\ . \\ . \\ C\sum_{j=0}^{N-2}\Phi^{j}\Gamma \end{bmatrix}$$

Let F be an initial state feedback gains such that the closed loop system matrix $(\Phi_\tau + \Gamma F)$ has no eigenvalues at the origin. Then one can define a fictitious measurement matrix,

$$C(F, N) = (C_0 + D_0F)(\Phi_\tau + \Gamma_\tau F)^{-1} \qquad (4.6)$$

which satisfies the fictitious measurement equation

$$y(k) = Cx(k) \qquad (4.7)$$

Let ν denote the observability index of (Φ, C). N is chosen to be greater than or equal to ν. So that any state feedback gain can be realized by a fast output sampling gain L.

The control law is of form

$$u_k = Ly_k \qquad (4.8)$$

For the output feedback gain L to realize the effect of F it must satisfy

$$x_{k+1} = (\Phi_\tau + \Gamma_\tau F)x_k = (\Phi_\tau + \Gamma_\tau LC)x_k \qquad (4.9)$$

i.e. $LC = F$ (4.10)

The controller obtained from the above equation will give desired behavior, but might require excessive control action. To reduce this effect we relax the condition that L exactly satisfy the above linear equation and include a constraint on the L

$$\|L\| < \rho_1, \quad \|LD_0 - F\Gamma_\tau\| < \rho_2, \quad \|LC - F\| < \rho_3 \qquad (4.11)$$

LMI Formulation [67] of above eqns. is

$$\begin{bmatrix} -\rho_1^2 I & L \\ L^T & -I \end{bmatrix} < 0$$

$$\begin{bmatrix} -\rho_2^2 I & (LD_0 - F\Gamma_\tau) \\ (LD_0 - F\Gamma_\tau)^T & -I \end{bmatrix} < 0 \qquad (4.12)$$

$$\begin{bmatrix} -\rho_3^2 I & (LC-F) \\ (LC-F)^T & -I \end{bmatrix} < 0$$

If the initial state is unknown, there will be an error $\Delta u_k = u_k - Fx_k$ in constructing the control signal under state feedback. One can verify that the closed loop dynamics are governed by

$$\begin{bmatrix} x_{k+1} \\ \Delta u_{k+1} \end{bmatrix} = \begin{bmatrix} \Phi_\tau + \Gamma_\tau F & \Gamma_\tau \\ 0 & LD_0 - F\Gamma_\tau \end{bmatrix} \begin{bmatrix} x_k \\ \Delta u_k \end{bmatrix} \qquad (4.13)$$

To see this, apply the coordinate transformation

$$T = \begin{bmatrix} I & 0 \\ F & I \end{bmatrix} \qquad (4.14)$$

to the equation

$$\begin{bmatrix} x_{k+1} \\ \Delta u_{k+1} \end{bmatrix} = \begin{bmatrix} \Phi_\tau & \Gamma_\tau \\ LC_0 & LD_0 \end{bmatrix} \begin{bmatrix} x_k \\ \Delta u_k \end{bmatrix} \qquad (4.15)$$

Thus, one can say that the eigenvalues of the closed loop system under a fast output sampling control law are those of $(\Phi_\tau + \Gamma_\tau F)$ together with those of $(LD_0 - F\Gamma_\tau)$.

MODEL ORDER REDUCTION USING PSO ALGORITHM

Consider the following n^th order LTI system:

$$\dot{x}_f(t) = A_f x(t) + B_f u(t) \quad (6.4)$$

$$y_f(t) = C_f x(t) + D_f u(t) \quad (6.5)$$

Where $x_f \in \Re^n$ is the state vector, $u \in \Re^p$, and $y_f \in \Re^m$ are the input and output vectors, respectively. The matrices A_f, B_f, C_f, and D_f are the full order system matrices with their appropriate dimensions. Let the eigenvalues of the above full order system is given as:

$$-\lambda_1 < -\lambda_2 < .... < -\lambda_n . \quad (6.6)$$

On the other hand, consider the reduced order LTI system with order r:

$$\dot{x}_r(t) = A_r x(t) + B_r u(t) \quad (6.7)$$

$$y_r(t) = C_r x(t) + D_r u(t) \quad (6.8)$$

$x_r \in \Re^r$ is the state vector of the reduced order system, $u \in \Re^p$, and $y_r \in \Re^m$ are the input and output vectors, respectively. The matrices A_r, B_r, C_r, and D_r are the reduced order system matrices with their appropriate dimensions. The eigenvalues of reduced order system are chosen to be the dominant eigenvalues of the full order system given as:

$$-\lambda_1 < -\lambda_2 < .... < -\lambda_r . \quad (6.9)$$

The A_r matrix is chosen to be diagonal matrix with the dominant eigenvalues are assigned as the diagonal elements.

The elements of other matrices are chosen by PSO algorithm.

In order to describe the steps of the PSO algorithm for MOR, we will define the given parameters and the necessary specifications.

Various parameters setting:

1. Set the full order system parameters i.e. N_{full}=40.
2. Set appropriate level step inputs to the system.
3. Simulate the outputs y_f, of the full order system with a suitable sampling time.
4. Choose a suitable order of the reduced order system based on the dominant eigenvalues i.e. N_r=10.
5. Set the PSO parameters:
   a. The size of the particle, P=200.
   b. The number of particles in the swarm, M=25.
   c. The counter of iteration (I = 1) and the maximum number of iterations, Lmax=100.
6. A reasonable range for the parameters should be chosen. This requires specifications of the minimum and maximum values for each parameter.
7. A good fitness function that is well representative of the parameters is crucial in the PSO algorithm. The mean-squared error

$$MSE = \frac{1}{N} \sum_{k=1}^{m} \sum_{i=1}^{N} [y_f(k,i) - y_r(k,i)]^2 \quad (6.10)$$

where N is the number of samples, m is the number of outputs, $y_f(k, i)$ is the

i^{th} sample of the k^{th} output of full order system and $y_r(k,i)$ is the i^{th} sample of the k^{th} output of reduced order system.

In this paper, the fitness function used in the PSO algorithm is the minimization of mean-squared error (MSE),

Fitness = min (MSE) (6.11)

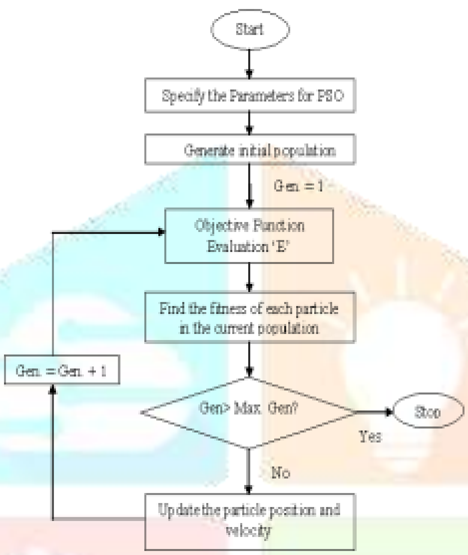

Figure 4: Flowchart for PSO

3. RESULTS AND DISCUSSION

A SIMULINK based block diagram including all the nonlinear blocks is generated using machine model 1.0 [42-44]. The output slip signal with robust decentralized gain L and a limiter is added to V_{ref} signal. The output must be limited to prevent the PSS acting to counter action of AVR. Different operating points are taken as the different models.
The location of fault considered for various models is given in Table 1:

Table 1: Location of faults: 10 machine and 39 bus system

S.No.	Model	Fault at Bus
1	Model1	Bus16
2	Model 2	Bus 13
3	Model 3	Bus 11
4	Model 4	Bus 9
5	Model 5	Bus 7
6	Model 6	Bus 17
7	Model 7	Bus 19
8	Model 8	Bus 21

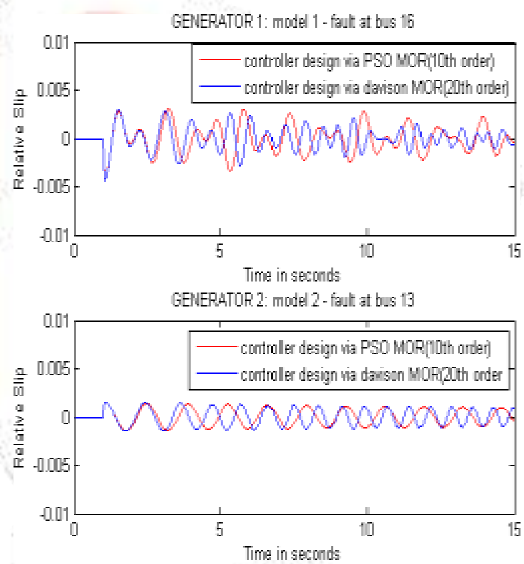

Figure 5: Closed loop responses with fault using decentralized fast output sampling feedback controller via reduced order Model.

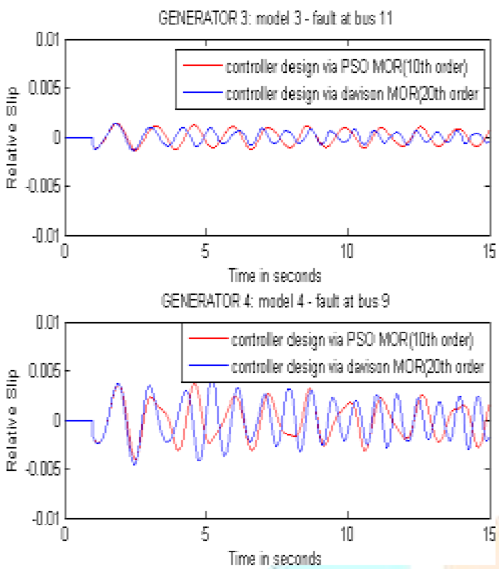

Figure 6: Closed loop responses with fault using decentralized fast output sampling feedback controller via reduced order Model.

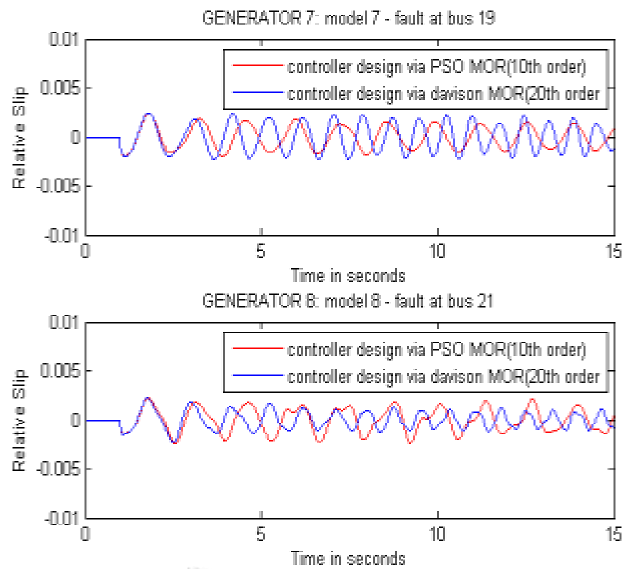

Figure 8: Closed loop responses with fault using decentralized fast output sampling feedback controller via reduced order Model.

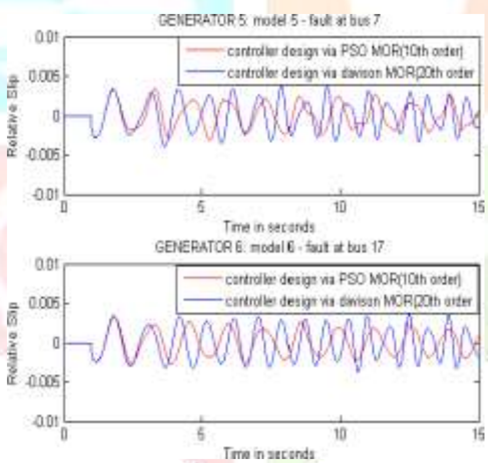

Figure 7: Closed loop responses with fault using decentralized fast output sampling feedback controller via reduced order Model.

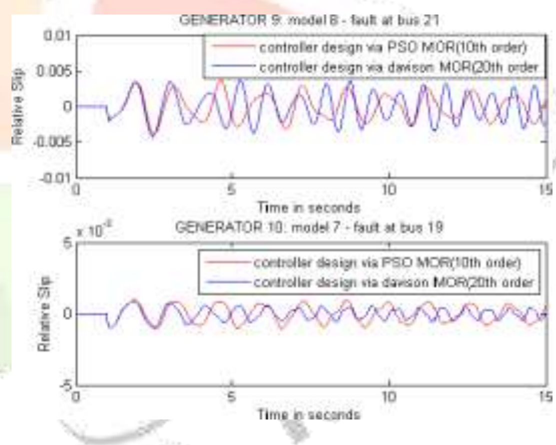

Figure 9: Closed loop responses with fault using decentralized fast output sampling feedback controller via reduced order Model.

4. CONCLUSION

This work presents a comparatively study of design of fast output sampling feedback controllers via reduced order model using Particle Swarm Optimization (PSO) method and Davison method for multi-machine system stability enhancement. Particle swarm optimization (PSO) model reduction method gives very good results in the design of Power System Stabilizers and also economic and less complexity in designing of power system stabilizers comparatively Davison method. The proposed method results are satisfactory response to damp out the oscillations.

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