Dynamic Stability Control of Sudan National Grid Using Power System Stabilizer

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Abstract: Application of power system stabilizers (PSS), as supplementary control signals for the excitation system in order to damp the low frequency, generator angle, speed variation, generator power, voltage magnitude and power flow oscillations. This paper presents the application of robust decentralized power system stabilizer (PSS) design approaches, for Sudan power system which consists of 41 machines with 167 buses. The paper mainly focus on operator testing of robust decentralized control techniques for power systems, and the optimal control approach to robust control design. Results of robust decentralized control design approaches are defined by using state space model equations. Also for testing dynamic stability Lyapunov theorem is used. The simulations were carried out using symmetrical fault and results presented by Power System Analysis Toolbox, MATLAB.

Keywords: *Decentralized control; power system stabilizers; State space model; Lyapunov theorem.*

1. INTRODUCTION

The main function of the electric power system is to supply electric energy to the end customer in an efficient way [1]. This power system is dynamic and nonlinear in nature and works in a changing environment. These changes may produce oscillations which in certain situations can cause instability or oscillatory performance [2]. The power system stabilizer (PSS) is a supplementary excitation controller used to damp oscillations in the power system. Power system stabilizer (PSS) controller design, methods of combining the PSS with the excitation controller (AVR), and investigation of many different input signals, and the vast field of tuning methodologies [3].

This paper is an investigation for modifying the input of a specific type of PSS as applied to a power system, and is not intended to serve as an exhaustive review of the domain of PSS application to make optimum control of Sudan grid. Once the oscillations are damped, the thermal limit of the tie-lines in the system may then be approached. This supplementary control is very beneficial during line outages, large power transfers and faults [1],[4]. However, power system instabilities can arise in certain circumstances due to negative damping effects of the PSS on the rotor. The reason for this is that PSSs are tuned around a steady-state operating point, their damping effect is only valid for small excursions around this operating point. During severe disturbances, a PSS may

actually cause the generator under its control to lose synchronism in an attempt to control its excitation field [5].
This paper mainly focuses on testing operation of robust decentralized control techniques for power systems, and the optimal control approach to robust control design. These tests are obtained by using state space equations and stability and Lyapunov theorem. The paper is organized as follows: Section II power system stabilizer state space object, Section III systems and control, Section IV simulation results and Section V summery and conclusion.

2. POWER SYSTEM STABILIZER STATE SPACE OBJECT

– System Model

Consider the general structure of the ith– generator together with the PSS block in a multi-machine power system shown in **Fig. 1**. The input of the ith - controller is connected to the output of the washout stage filter, which prevents the controller from acting on the system during steady state. Power system stabilizers commonly have transfer functions of the form [6].

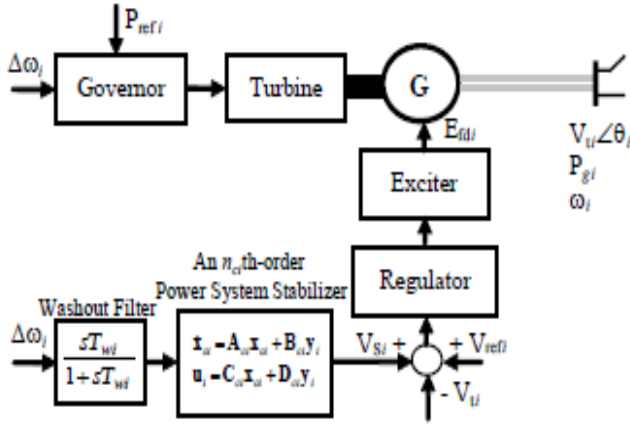$$P(s) = K_s \frac{sT_W(1+sT_1)(1+sT_2)}{(1+sT_W)(1+sT_3)(1+sT_4)} \qquad (1)$$

Fig. 1. General structure of the ith - generator together with the PSS structure and washout stage in a multi-machine power system
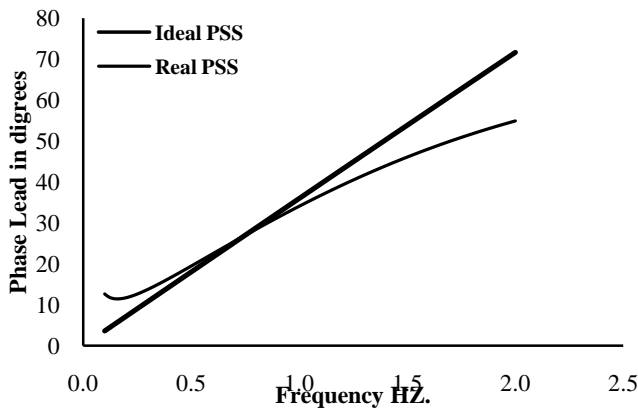

Fig. 2. Ideal and real PSS phase lead

A state space object representing this transfer function may be formed by multiplying state space objects by a scalar, a washout and two lead/lags.

To design a power system stabilizer, a system model with the generator rotor states removed is required. The input to the system is the voltage reference of the generator at which the power system stabilizer is to be placed. The output is the generator electrical power. The ideal power system stabilizer phase lead is given by the negative of the response of speed. The ideal and real PSS phase leads are shown in **Fig. 2**.

3. SYSTEMS AND CONTROL

The goals of control system achieve some objectives. Generally speaking, the control objectives can be classified to ensure either stability or optimality, or both of a system [7]. Stability means that the system will not 'blow up'; that is, the output of the system will not become unbounded as long as its input is bounded. This is a basic requirement of most systems that we encounter. Optimality means that the system performance will be optimal in some sense.

To achieve stability or optimization, some control needs are to be used. Generally speaking, two types of control can be used: (1) feedback or closed-loop control; and (2) open-loop control.

3.1. State Space Model

In classical control theory, a transfer function is used to describe the input and output relation of a system, and hence serves as a model of the system. If the system to be controlled is nonlinear, or time-varying, or has multiple inputs or outputs, then it will be difficult, if not impossible, to model it by a transfer function [8]. Therefore, for nonlinear, time-varying, or multi-input–multi-output systems, we often need to use state space representation to model the systems. The state variables of a system are defined as a minimum set of variables, such that the knowledge of these variables at any time t_0, plus the information on the input subsequently applied, is sufficient to determine the state variables of the system at anytime $t > t_0$. If a system has n state variables, say that the order of the system is n. And often use an n-dimensional vector x to denote the state variables: $x \in \mathcal{R}^n$. Use of $u \in \mathcal{R}^m$ to denote the m-dimensional input variables and $y \in \mathcal{R}^p$ to denote p-dimensional output variables. A state space model of a system can then be written as the general state space models to describe systems by the state equations (2) and the output equations (3)[8].

$$\dot{x} = f(x, u, t) \tag{2}$$

$$y = g(x, u, t) \tag{3}$$

Where f: $\mathcal{R}^n \times \mathcal{R}^m \times \mathcal{R} \to \mathcal{R}^n$ and g: $\mathcal{R}^n \times \mathcal{R}^m \times \mathcal{R} \to \mathcal{R}^p$ are nonlinear functions. Most practical systems are nonlinear. However, many nonlinear systems can be approximated by linear systems using linearization methods [8].

3.2. Stability and Lyapunov Theorem

Consider a general nonlinear system

$$\dot{x} = Ax \tag{4}$$

$x \in \mathcal{R}^n$ are the state variables and $A : \mathcal{R}^n \to \mathcal{R}^n$ is a (nonlinear) function. We assume that A is such that the system (4) has a unique solution $x(t)$ over $[0, \infty]$ for all initial conditions $x(0)$ and that the solution depends continuously on $x(0)$. A vector $x_0 \in \mathcal{R}^n$ is an equilibrium point of the system (4) if

$$A(x_0) = 0 \tag{5}$$

Without loss of generality, assume that $x_0 = 0$ is an equilibrium point of the system (4); that is, A(0)= 0. Otherwise we can perform a simple state transformation $z = x - x_0$ to obtain a new state equation

$$\dot{z} = \tilde{A}(z) = A(z + x_0) \tag{6}$$

Where $z_0 = 0$ is an equilibrium point $(\tilde{A}(0) = A(x_0) = 0)$. Clearly, the solution of the differential equation (4) shows that if $x(0) = 0$, then $x(t) = 0$, for all $t > 0$. However, this solution may or may not be stable [4].

3.3. Stability

The equilibrium point $x_0 = 0$ of the system (4) is stable if for all $\varepsilon > 0$, there exists a $\delta\varepsilon > 0$ such that

$$\|x(0)\| < \delta\varepsilon \Rightarrow \|x(t)\| < \varepsilon \;\; \forall t \geq 0 \tag{7}$$

3.4. Controller for Nonlinear Systems

We consider the nonlinear system

$$\dot{x} = fx + B_u u \tag{8}$$

$$y = C_y x \tag{9}$$

Where x: $\mathcal{R}_+ \rightarrow \mathcal{R}^n$ is the state variable, u: $\mathcal{R}_+ \rightarrow \mathcal{R}^n$ is the control variable, and y: $\mathcal{R}_+ \rightarrow \mathcal{R}^q$ is the measured or sensed variable. We assume the function f: $\mathcal{R}^n \rightarrow \mathcal{R}^n$ satisfies f(0) = 0 and

$$\frac{\partial f}{\partial x} \epsilon C_0 \{A_1 \ldots \ldots \ldots A_m\} \tag{10}$$

Where $A_1, \ldots, Am$ are given. Looking for a stabilizing controller of the form

$$\dot{\bar{x}} = f(\bar{x}) + B_u u + L(C_y\bar{x} - y), \;\; u = K\bar{x} \tag{11}$$

The matrix K is estimated-state feedback gain and L (the observer gain) such that the closed-loop system is stable [4].

$$\begin{bmatrix} \dot{x} \\ \dot{\bar{x}} \end{bmatrix} = \begin{bmatrix} f(x) + B_u K\bar{x} \\ -LC_y x + f(\bar{x}) + (B_u K + LC_y)\bar{x} \end{bmatrix} \tag{12}$$

The closed-loop system (12) is stable if it is quadratically stable, which is true if there exists a positive-definite matrix $\tilde{P} \epsilon \mathcal{R}^{2n \times 2n}$ such that for any nonzero trajectory $x, \bar{x}$, we have:

$$\frac{\partial}{\partial t} \begin{bmatrix} x \\ \bar{x} \end{bmatrix}^T \tilde{P} \begin{bmatrix} x \\ \bar{x} \end{bmatrix} < 0 \tag{13}$$

That is true if there exist P, Q, Y, and W such that the LMIs

$$Q > 0,$$

$$A_i Q + QA_i^T + B_u Y + Y^T B_u^T < 0 \tag{14}$$

$$i = 1, \ldots \ldots, M$$

And $P > 0$

$$A_i^T P + PA_i + WC_y + C_y^T W^T < 0 \tag{15}$$

$$i = 1, \ldots \ldots, M$$

To every P, Q, Y and W satisfying these LMIs, there corresponds a stabilizing controller of the form (11), obtained by setting $K = Y\,Q^{-1}$ and $L = P^{-1}W$. We can obtain equivalent conditions in which the variables Y and W do not appear. These conditions are that some $P > 0$ and $Q > 0$ satisfy for some σ and μ.

$$A_i Q + QA_i^T < \sigma B_u B_u^T, i = 1, \ldots, M \tag{16}$$

and

$$A_i^T P + PA_i < \mu C_y^T C_y, i = 1, \ldots, M \tag{17}$$

By homogeneity can freely set $\sigma = \mu = 1$. For any P > 0, Q > 0 satisfying [9].

3.5. Optimal Control

After stabilizing a system, the next thing is to optimize the system performance. This topic is not only important in its own right, but also serves as the basis of our optimal control approach to robust control design. The formulation an optimal control problem for a general nonlinear system

$$\dot{x} = f(x, u) \tag{18}$$

so as to minimizing the following cost functional the Hamilton–Jacobi–Bellman equation

$$J(x, u) = \int_t^{t_f} L(x, u)\, d\tau \tag{19}$$

Where t is the current time, t_f is the terminating time, $x = x(t)$ is the current state, and $L(x, u)$ characterizes the cost objective.

3.6. Optimal Control Approach

The main focus of this paper is the optimal control approach to robust control design. To discuss this approach, we present the optimal control approach for linear systems. The system to be controlled is described by

$$\dot{x} = A(\rho)x + Bu \tag{20}$$

Where p represents uncertainty. The goal is to design a state feedback to stabilize the system for all possible p within given bounds. The solution to this robust problem depends on whether the uncertainty satisfies a matching condition, which requires that the uncertainty is within the range of *B*. If the uncertainty satisfies the matching condition, then the solution to the robust control problem always exists and can be obtained easily [10].

3.7. H_∞ and H_2 control

In particular, H_∞ denotes the Banach space of all complex valued functions *F: C→C* that are analytic and bounded in the open right half of the complex plane and are bounded on the imaginary axis *jR* with its H_∞ norm defined as

$$\|F\|_\infty = \frac{sup}{\omega \in R} |F(j\omega)| \tag{21}$$

H_2 denotes the Hilbert space of all complex valued functions *F: C→C* that are analytic and bounded in the open right half of the complex plane, and the following integral is bounded

$$\int_{-\infty}^{\infty} \overline{F(i\omega)}\, F(j\omega) d\omega < \infty \tag{22}$$

The H_2 norm can then be defined as

$$\|F\|_2 = \sqrt{\frac{1}{2\pi}\int_{-\infty}^{\infty}\overline{F(i\omega)}\,F(j\omega)\,d\omega} \qquad (23)$$

Closed-loop system is stable if the H_∞ norm of the loop is less than one. From the small-gain theorem, we can determine the bounds on the uncertainty that guarantee the stability of the perturbed system [11].

4. SIMULATION RESULTS

The application of robust decentralized dynamic output control design approaches to control system of Sudan grid, which consists of 41 generators and 167 bus bars specifically control to study the fundamental behavior of large interconnected power systems including inter-area oscillations [12]. Each generator is equipped with standard exciter and governor controllers. The parameters for the standard exciter and governor controllers used in the simulation were taken from Electrical and distribution companies. All generators for these simulations represented by their fifth-order models with rated terminal voltage of 10.5 kV, 11 kV and 13.8 kV. Speed signals from each generator are used for robust decentralized dynamic output control through the excitation systems. The load condition at transmission line (Khartoum-Kuku) of [P_{L1}= 104 MW, Q_{L1}= 56 MVar]. The former system describes as a hierarchical interconnection of 41subsystems; the latter represents the interactions among the subsystems. In each subsystem the controller structure was augmenting. The minimization problem was formulated by applying power system stabilizer of linear objective function involving LMIs and coupling BMI constraints. Each subsystem was applied robust (sub)-optimal decentralized second-order PSS, for a relative accuracy of $\varepsilon = 10^{-6}$. Speed signals from each generator and the outputs of the PSS, together with the terminal voltage error signals, which are the input to the regulator of the exciter, are used as regulated signals within this power system stabilizer framework. The main focus of this paper is the optimal control approach to robust control design. The complex of control system is used to control nonlinear system. A transfer function is used to describe the input and output relation of a system and hence serves as a model of the system.

The result of application shown in **Figs 3-15** taken by applying Symmetrical fault at transmission line near bus bars 28-63, The transient responses of generators on Marrwi electrical-station with and without the PSSs in the system are an example. To further assess the effectiveness of the proposed approaches regarding the robustness, the transient performance indices were computed for constant total load in the system. The test of robust decentralized dynamic output control design approaches, applied by Bode diagram are shown in **Fig 3**, multivariable frequency responses are shown in **Fig 4**, and root locus with feedback gain are shown in **Fig 5**, root locus without PSSs are shown in **Fig 6** and root locus with PSSs are shown in **Fig 7**.

The transient performance indices for compass of rotor angle terms of inter-area mode without and with is shown in **Figs. 8** and **9**, respectively, all bus magnitude voltage without and with PSSs is shown in **Figs 10** and **11**, respectively, generator angle θ_{gi} is shown in **Fig 12**, generator speed deviation ω_{gi} is shown in **Fig 13**, generator power Pg_i is shown in **Fig 14**, generator terminal voltages V_{ti} **Fig 15**, at transmission line near bus bars 28-63, are computed using the Matlab Power System Toolbox. These transient performance indices are used as a qualitative measure of system behavior following any disturbances including controller actions. Moreover, for comparison purpose, these indices are normalized to the base operating condition for which the controllers have been designed:
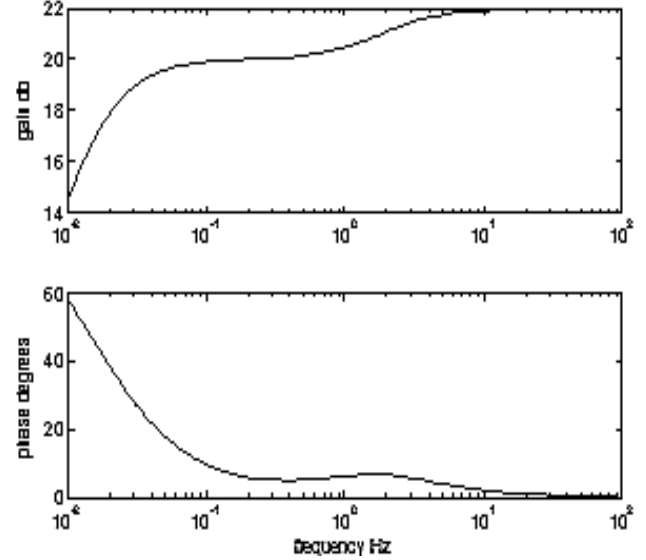

Fig. 3. Bode diagram of a power system stabilizer's frequency response
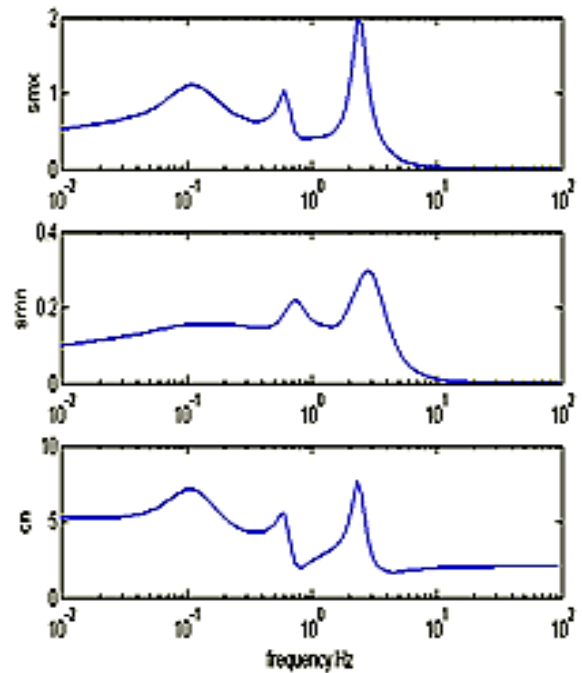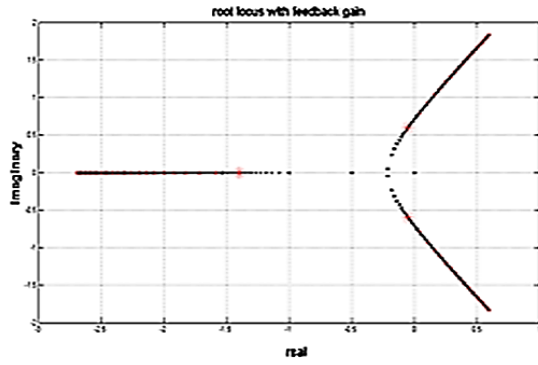

Fig. 4. Multivariable frequency responses of Sudan Grid

Fig. 5. Root locus with feedback gain
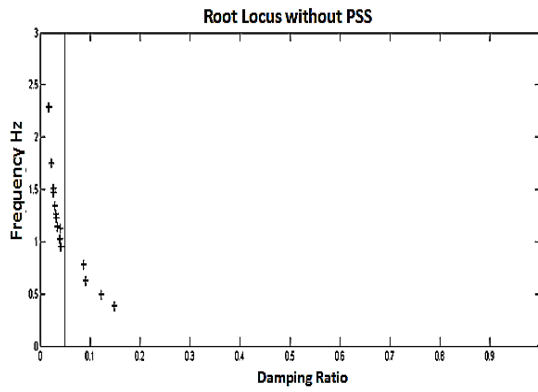

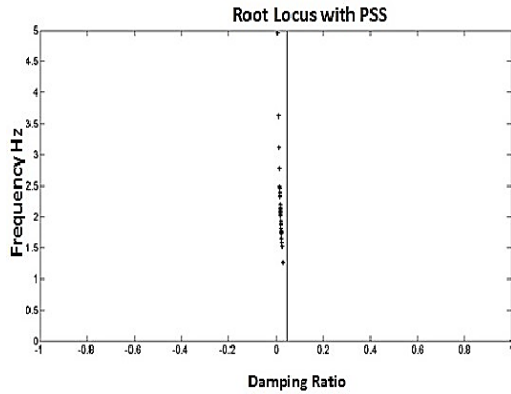**Fig. 6.** Calculated modes of Marrwi hydro-turbine without PSS

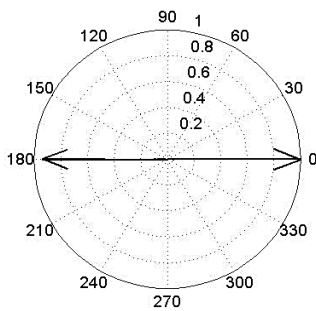**Fig. 7.** Calculated modes of Marrwi hydro-turbine with PSS

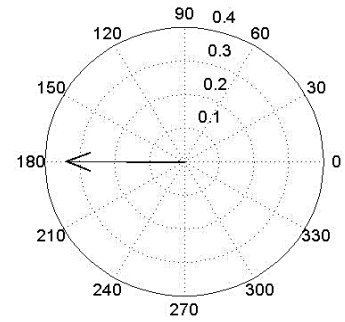**Fig.8.** Compass of rotor angle terms of inter-area mode eigenvector of Marrwi hydro-turbine without PSS at fault

Fig. 9. Compass of rotor angle terms of inter-area mode eigenvector of Marrwi hydro-turbine with PSS at fault
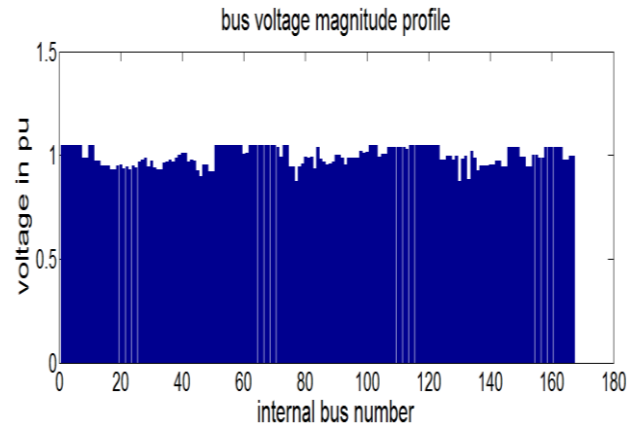

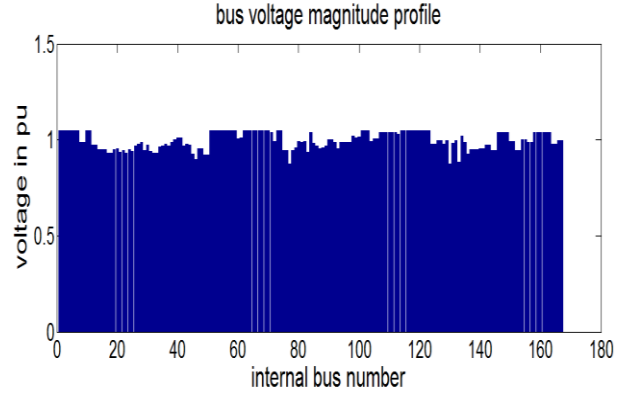**Fig. 10.** All bus magnitude voltage without PSS at fault

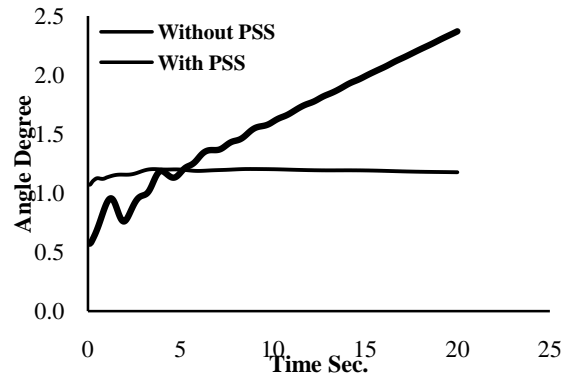**Fig. 11.** All bus magnitude voltage with PSS at fault

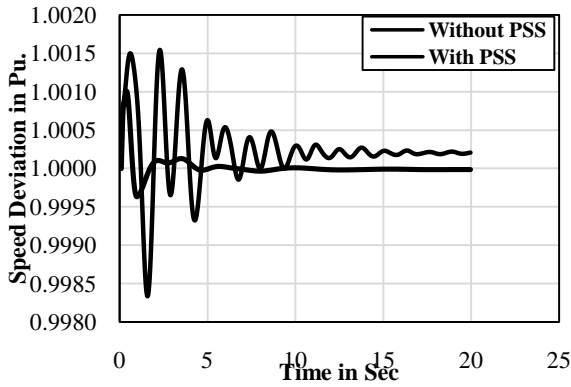**Fig. 12.** Machine angle of Marrwi hydro-turbine without and with PSS at fault

Fig. 13. Generator speed deviation of Marrwi hydro-turbine without and with PSS at fault
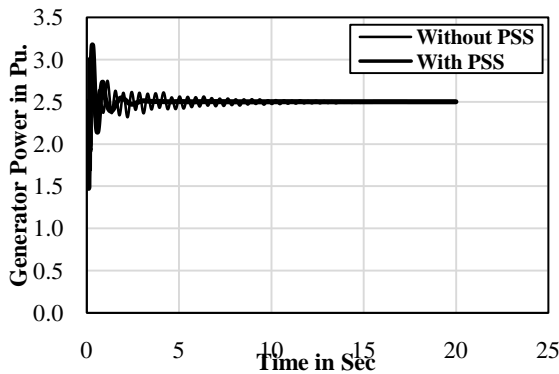

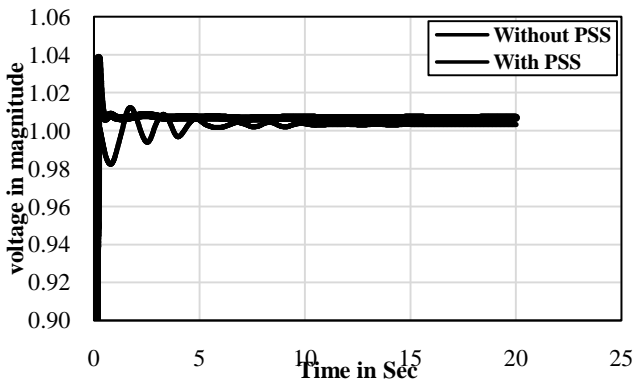**Fig. 14.** Generator electrical power of Marrwi hydro-turbine without and with PSS at fault

Fig. 15. Generator voltage of Marrwi hydro-turbine without and with PSS at fault

5. CONCLUSIONS

The PSS controller is a supervisory level controller that can track system inter-area dynamics online. The application of PSS controller design aims to improve the damping of inter-area oscillations. One of the primary requirements of a good decentralized application is that the resulting PSS should be robust enough to wide variations in system parameters, at the same time being computationally manageable.

The uncertainty of the dynamics in the internal and external systems produced the global decoupled control subsystem structure that not only breaks the system into decoupled subsystems but also provides a single effective control that is not vulnerable to disturbances or competition from other controls.

This paper examines several tests of application PSS for damping power system swings. A model of the Sudan system with more PSSs for stabilization, is used as the test system. It is found that decentralized controllers provide good damping enhancement to the interarea modes. The robust control has also been tested for symmetrical fault, and has performed well. The resulting PSS can guarantee the stability and performance over a large range of plants with arbitrarily fast changing parameters. The nonlinear simulations show that these independently designed decentralized PSSs cooperate well in a wide operating range and have better damping characteristics. The PSS performance was tested and simulated on a 41 generator, 167 buses system, and Marawi electrical plant was taken as an example. The testing of this system showed positive results. The LMI controller worked well and provided a reasonable amount of damping to the inter-area modes.

The optimal control stability by using PSS control design technique is based on state space theory, stability and Lyapunov theory and optimal control theory. Simulation results presented in section IV show that the proposed design is robust and its objectives are met for the investigated systems.

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