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Application of a nonlinear hybrid controller in multi-machine power system based on a power system stabilizer

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Abstract

The power system stabilizer (PSS) is used to generate supplementary control signals for the excitation system in order to dampen low frequency oscillations. This paper presents an approach to designing a hybrid power system stabilizer (HPSS), which is a parallel combination of a conventional PSS and a nonlinear control system, to enhance transient stability for multi-machine power systems. The effectiveness and applicability of the proposed approach are examined using a standard multi-machine power system. The nonlinear system simulation results show that the HPSS is more effective than the conventional PSS in damping oscillations.

Keywords: Power system stabilizer, Hybrid structure, Multi-machine power system, Nonlinear hybrid control

1. Introduction

Power system stabilizers (PSS) [20] and flexible ac transmission system (FACTS) devices [17, 27] are applied to increase system stability. PSS is widely used in existing power systems in order to contribute to enhancing the dynamic stability of power systems for damping low frequency oscillations [4, 15].

Many different control techniques have been applied to PSS to solve the problem of system dynamic response [10, 3]. An objective function and algorithm to obtain a set of optimal PSS parameters that include a feedback signal of a remote machine and local and remote input signal ratios for each machine in a multi-machine power system under various operating conditions is proposed in [23]. A technique for designing fixed parameter decentralized PSSs for interconnected power systems is proposed in [9], where local information available at each machine in the multi-machine environment is used to tune parameters of PSS. A method based on the reference model controller for designing coordinated PSS is presented in [24], where the damping of the reference model and consequently the damping of the designed PSS do not depend on the frequency of oscillations. A space recursive least square algorithm developed for the tuning of PSS parameters on single-machine infinite-bus power system based PID is proposed in [11] to meet vulnerable conditions.

Synergetic control theory is purely analytical and is based on nonlinear models. It provides asymptotic stability and uses essential properties of nonlinear dynamic dissipative systems. Many papers have been published in the field of synergetic control theory [7, 2]. In [6] the dynamic characteristics of the proposed PSS based on synergetic control theory are studied in a typical single-machine infinite-bus power system and compared with cases with a conventional PSS and without a PSS. A nonlinear PSS based on synergetic control theory that has strong robustness and adaptability to external disturbances is presented in [25], where the deviations of generator rotor speed and active power are used to combine a manifold. Decentralized improved synergetic excitation controllers for synchronous generators to enhance transient stability and obtain satisfactory voltage regulation performance of power systems are proposed in [26]. An adaptive fuzzy PSS based on robust synergetic control theory and terminal attractor techniques is developed in [1], where fuzzy logic systems are used to approximate the unknown power system dynamic functions without calling upon the usual model linearization and simplifications.

This paper presents a hybrid power system stabilizer (HPSS), which is composed of a nonlinear control system and conventional systems. The validity of the proposed method is examined in simulation studies. The remainder of this paper is organized as follows: Section 2 of this paper discusses the general design procedure for the controller of a plant using synergetic control theory. The mathematical model of a single machine-infinite bus power system is

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presented in Section 3. Section 4 presents the design of the power system stabilizer based on synergetic control theory. In Section 5 nonlinear HPSS system is implemented in a standard (IEEE) power system machine. Simulation results are obtained using the conventional PSS and the hybrid control system in section 6. Section 7 concludes the paper.

2. Synergetic Control Synthesis Procedure

The design procedure based on synergetic control theory follows the analytical design of the aggregated regulators (ADAR) method [12]. The general synergetic synthesis procedure is reviewed in this section. Generally, we consider an n-dimension nonlinear dynamic system that can be described by the following equation.

$$\frac{dx}{dt} = f(x, u, t) \tag{1}$$

where x is the system state variable vector, u is the control vector, and t is the time. A controller, which produces the control vector u, is used to force the system to operate in a desired manner. The synergetic synthesis of the controller begins by defining a macro-variable given in (2):

$$\psi = \psi(x, t) \tag{2}$$

where ψ is the macro-variable and $\psi(x, t)$ is a user-defined function of system state variables and independent time. The objective of the synergetic controller is to direct the system to operate on the manifold.

$$\psi = 0 \tag{3}$$

The characteristics of the macro-variable can be chosen by the designer according to the control specifications such as the control objective, the settling time, limitations in the control output, and so on. In a trivial case, the macro-variable can be a simple linear combination of the state variables. The same process can be repeated, defining as many macro-variables as control channels. The macro-variable is evolved in the desired manner by introducing a constraint that is expressed in the following equation T:

$$T\dot{\psi} + \psi = 0 \qquad T > 0 \tag{4}$$

where T is a controller parameter that indicates the converging speed of the closed-loop system to the manifold specified by that the macro-variable equals to zero. Taking into account the chain rule of differentiation that is given by:

$$\frac{d\psi(x,t)}{dt} = \frac{\partial\psi(x,t)}{\partial t}.\frac{dx(t)}{dt} \tag{5}$$

Substitution of (1) and (2) into (4) yields:

$$T\frac{\partial\psi(x,t)}{dt}f(x,u,t) + \psi(x,t) = 0 \tag{6}$$

Upon solving (6) for u, the control law can be found as:

$$u = g(x, t, \psi(x, t), T) \tag{7}$$

From (7), it can be seen that the control output depends not only on the system state variables, but also on the selected macro-variable and time constant T. In other words, the designer can choose the characteristics of the controller by selecting a suitable macro-variable and a time constant T.

When synthesizing the controller, each manifold introduces a new constraint on the state space domain and reduces the order of the system by one, working in the direction of global stability. From the synthesis procedure of the synergetic controller shown above it is clear that the synergetic controller works on the full nonlinear system and does not need any linearization or simplification on the system model at all, as is required when traditional control theory is applied. By appropriate selection of macro-variables, the designer can obtain the following interesting characteristics for the final system: global stability, parameter insensitivity and noise suppression.

It is interesting to note that the synergetic control law guarantees global stability on the manifold. This means that, once the manifold is reached, the system is not supposed to leave it even for large-signal variations. This condition ensures that the system will keep the reduced-order characteristic, but does not guarantee the global stability of the system itself. It is necessary for the designer to select an appropriate manifold so that the new restricted system will have the required stability characteristics. The procedure summarized here can be easily implemented as a computer program for automatic synthesis of the control law for complex power systems or it can be performed by hand for simple systems that have a small number of state variables such as the system studied here.

3. Power System Model

The block diagram of the single machine infinite bus power system is shown in Fig. 1. U_B and U_T are the voltages of the infinite bus and generator terminal bus, respectively [14] The synchronous generator is equipped with an IEEE type-ST1 exciter [13] The output real power and terminal voltage at the generator terminals are measured and fed to the controller. The outputs of the controller (system control inputs) are fed into the generator-exciter and governor-valve. The dynamic of the generator can be expressed by the following differential equations [21, 8]:

$$\frac{d}{dt}\delta = \omega_b(\omega_r - 1) \tag{8}$$

$$\frac{d}{dt}\omega_r = \frac{1}{J_M}[T_M - T_E - K_D(\omega_r - 1)] \tag{9}$$

$$\frac{d}{dt}E_q^{'} = \frac{1}{T_{do}^{'}}[E_F - E_q^{'} + (X_d^{'} - X_d)i_d] \tag{10}$$

where δ is angle load, J_M is the generator inertia constant, K_D is the inherent damping constant, ω_r is angular velocity, T_E is output electrical torque, T_M is input mechanical torque,

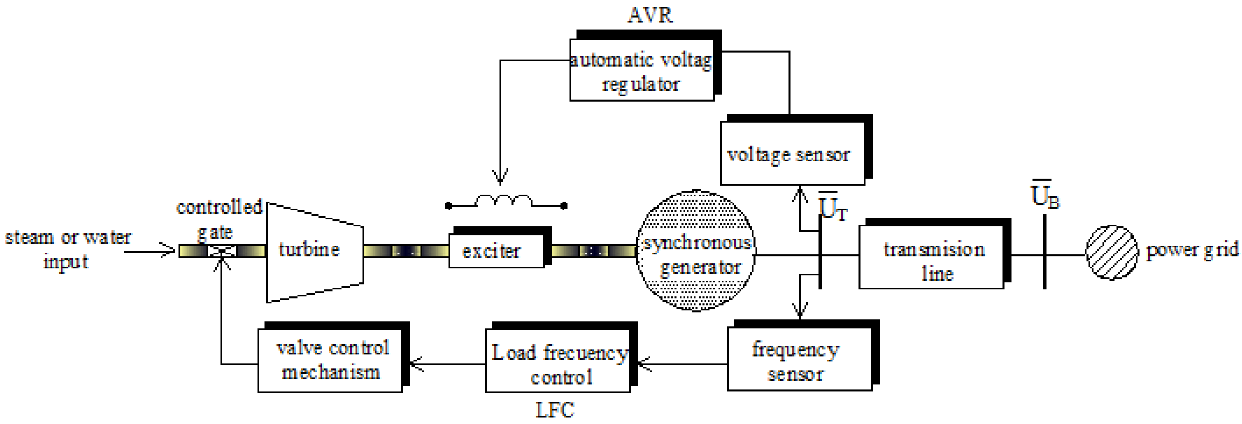

Figure 1: Control block diagram of the power system

E_q' is voltage proportional to direct axis flux linkages, X_d' is direct axis transient reactance, i_d is the direct axis component of armature current, T_{do}' is the d-axis open circuit transient time constant, X_d is direct axis component reactance and ω_b is the base electrical angular velocity [19].

Let K_E and T_E be the AVR gain and its time constants respectively. The equation describing it can be written as [16, 18]:

$$\frac{d}{dt}E_F = \frac{1}{T_E}[-E_F + K_E(U_R - U_T)] \tag{11}$$

where E_F is the field voltage (exciter output voltage), U_T is the terminal voltage magnitude and U_R is reference voltage.

A common structure for PSS is reported in Fig. 3, where Δ denotes minor perturbation or deviation in the variable from the steady-state value, U_W is output signal of washout filter and U_S is PSS output signal. It consists of an amplifier block of gain constant K_P, a block having a washout time constant T_w and one or two lead-lag compensators.

4. PSS Design Using synergetic Control Theory

Since the main goal of the PSS is to stabilize the rotational speed of the generator, the deviation of the rotational speed from the synchronous speed is used as a stabilizing signal. To damp the power oscillation, the active electrical power output is also used as an input to the PSS. Therefore the synergetic synthesis of the power system stabilizer begins by defining a macro-variable given in:

$$\Psi_1 = k_1(\omega - \omega_{REF}) - (P_E - P_{REF}) \tag{12}$$

where k_1 is a positive coefficient, ω_{REF} and PREF are the reference values for the rotational angular speed and active electrical power output of the generator, respectively. The objective of the synergetic controller is to direct the system to operate on the manifold $\psi_1 = 0$. The synergetic control law is shown by [5, 22]:

$$u_{PSS} = \frac{1}{k_E}E'_q + \frac{E'_q - U\cos\delta}{k_E X'_{dT}}(X_d - X'_d) - U_R$$
$$-\frac{T'_{do}E'_q\cos\delta}{k_E\sin\delta}2\pi f_0(\omega-1)+\frac{T'_{do}k_1X'_{dT}}{k_E V\sin\delta}\frac{1}{2H}[P_M-P_E-D(\omega-1)]+$$
$$\frac{T'_{do}X'_{dT}}{k_E U\sin\delta}\frac{1}{T_1}[k_1(\omega-\omega_{REF}) - (P_E - P_{REF})] \tag{13}$$

The expression for u_{PSS} is the desired control action for the power system stabilizer. The control law (12) forces the state variable trajectory to satisfy (12). According to this equation, the trajectory converges to manifold $\omega_1 = 0$ with a time constant T_1 and then stays on the manifold $\omega_1 = 0$ at all future times. So, from this time on, the state trajectory satisfies the equation:

$$\Psi_1 = k_1(\omega - \omega_{REF}) - (P_E - P_{REF}) = 0 \tag{14}$$

This equation establishes a linear dependence between the two output variables ω and P_E, thereby reducing by one the order of the system. Moving on this manifold the trajectory eventually converges to the desired steady-state: $\omega = \omega_{REF}$, $P = P_{REF}$. A geometric interpretation of the control law in the phase plane is shown in Fig. 4.

The steady-state operating point is the origin, where the error goes to zero. Control (12) represents a straight line through the origin with slope $1/k_1$. The system operating point converges to the straight line (the manifold) and then moves along it to the origin. It is worthwhile to note that the stabilizing signal P_E is actually a combination of the state variables in the state space, although it is an output variable of the plant.

Here, as is shown, actual power and speed error are important, but if we want to use the damping with higher dynamics and the derivation of error near to zero, we can add the factor of variations of axis speed from a set (filter+ compensator) to (12) as a hybrid control. Due to the existence of PID compensators, we can predict that the system has low

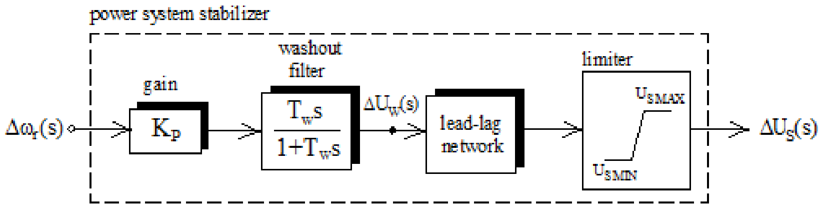

Figure 2: Block diagram of power system stabilizer

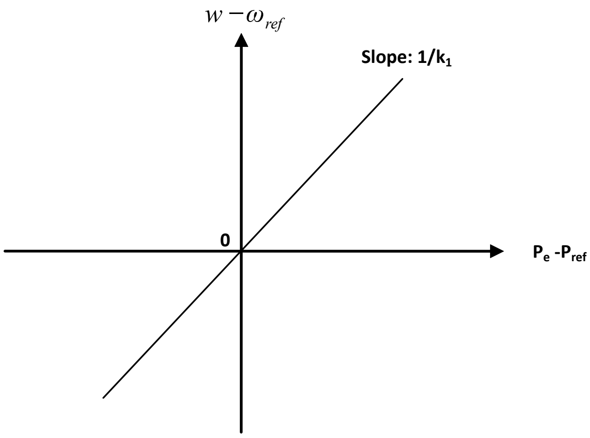

Figure 3: Geometric interpretation of control

continuous error. This issue can be expressed as:

$$U_{PSS-N} = u_{PSS} + K\frac{As+1}{Bs+1} \times \frac{Cs+1}{Ds+1} \times \frac{Es+1}{Fs+1} D\omega_r \quad (15)$$

As is shown in (15), by filtering and compensating for the signal of rotor axis changes we can implement a proper control signal in PSS format to the system to stabilize the damping torque. Equation (15) was used to increase control quality. Due to the existence of PID compensators, we can surmise that the system has low continuous error.

5. System Under Study

Electromechanical oscillations between continuous synchronous generators are an inherent phenomenon in power systems. Damping these oscillations is an important issue and is a basic factor for the safety of system performance. Power system stabilizers provide a supplement control signal to the excitation system for damping these oscillations and improving dynamic performance. The study of system stability divides into three categories with respect to disturbance type and range: permanent stability, dynamic stability and transient stability. This paper focuses on dynamic and transient stability; hence this issue is studied by presenting PSS power system stabilizers. Power system stabilizers are used to provide damped torque in synchronous machines through producing supplement control signals to the excitation system in order to neutralize two kinds of oscillations.

Table 1: System Parameters

Generator	900 MVA, 60 Hz, 20 kV, X_d=1.8, X'_d=0.3, P=4, R_s=0.00025, P_{ref3}=P_{ref4}=0.798889 pu
Transformer	900 MVA, 60 Hz, 20/230 kV, Dyn, R=$10^{-9}\Omega$, L=0.15 H
Load	1767 MW, 100M Var C_c=265 MVar (compensator)
Line	L_1=L_6=25 Km, L_2=L_5=10 Km L_3= L_4=220 Km L=1.4 mH, C=0.08774 mF

Short-time dynamic stability is usually examined in times of about 20-30 seconds after disturbance. But transient stability, which is examined in initial times after disturbance, occurs as a result of sudden and severe disturbances in the system (like a short circuit), so the main focus in this paper is on transient disturbances. For transient stability, the worst kind of disturbance is a (symmetrical) three phase short circuit. Therefore, in order to examine the stability of a power system one should examine system stability when a sudden disturbance like a (symmetrical) three phase short circuit presents. As a result of one sudden disturbance in one multi-machine power system, electrical power in every machine changes, which demands a sufficient response. If the system is considered ideal and a disturbance such as a short circuit leads to mechanical power becoming more than electrical power, then this issue causes accelerator force which increases as a result of speed and the power angle generator. This accelerator power can be defined as following:

$$P_a = P_m + P_e \quad (16)$$

as a result of accelerator power, we can define the equation of the system thus:

$$\alpha = \frac{d\omega}{dt} = \frac{d^2\delta}{dt^2} = \frac{\pi.f^\circ}{H}(P_m + P_e) \quad (17)$$

Here α, δ, ω, H show angle acceleration, power angle (angle getting ahead of the driving force of machine, over voltage), angle speed of rotor and inertia constant of the machine in the power based system, respectively. Hence it is very important to investigate accelerator power as regards stability in the context of system disturbance.

Here, an IEEE standard four-machine system was selected to test given stabilizers whose characteristics and framework are shown in Fig. 5. The test system is a two-area system in which each area has two synchronous generators.

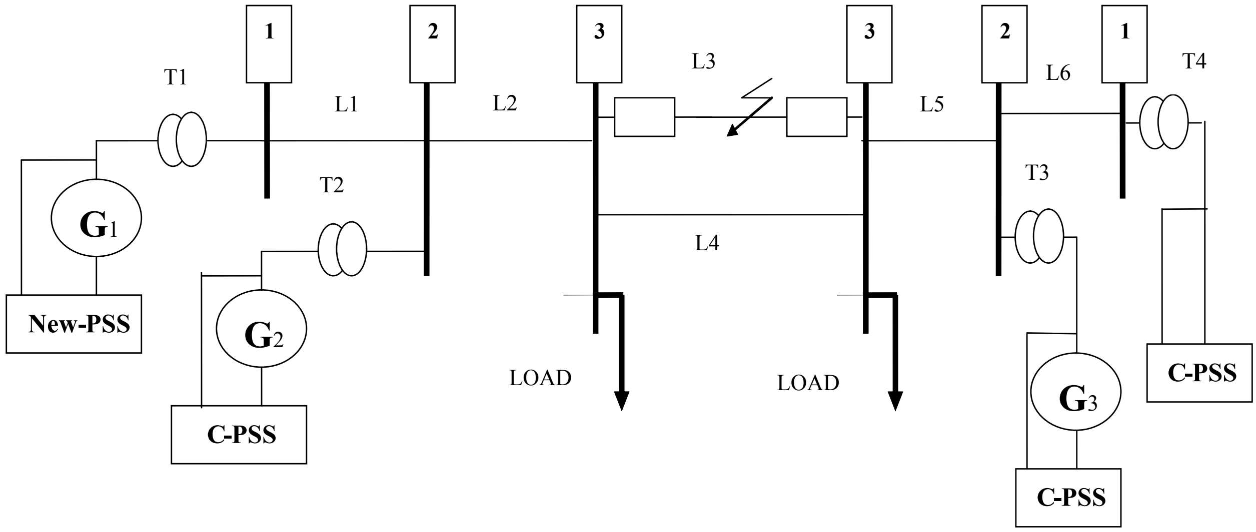

Figure 4: IEEE standard four-machine system

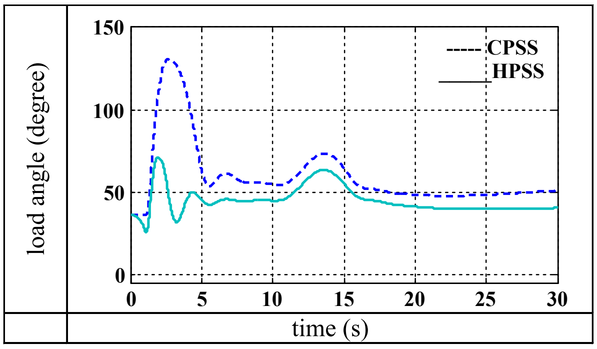

Figure 5: Angle change response with respect to machine 4

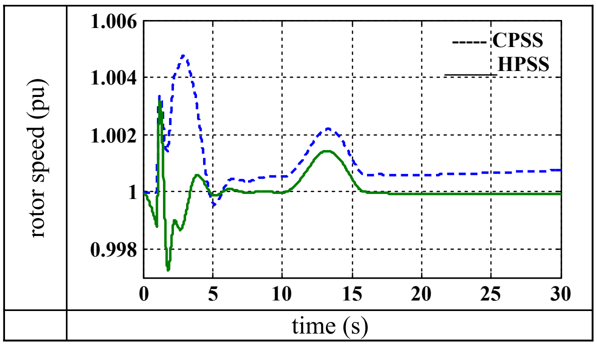

Figure 6: Rotor speed response

The system parameters are given in Table 1. The system topology with respect to line 4 is symmetrical. A simple turbine generator is used in each generator. Total system load is 1767 MW and 100 $MVAR$.

6. Simulation Results and Discussion

A three phase error occurs in 3 lines in the first second of testing. Here, machine 1 is examined and the kinds of stabilizers in issue are tested on it and other machines contain conventional constant stabilizers. As mentioned, one test on stability is a symmetrical three phase short circuit L_3 which it quickly removes through power breakers. L_3 occurs on a line separate from the system. Figs. 5–13 are graphs of simulation results obtained for HPSS nonlinear hybrid stabilizer and CPSS conventional stabilizer under condition of a short at 1 second and change reference mechanical power at 10 and 13 seconds to machine 1. Fig. 5 shows the rotor angle response of the synchronous generator G1 with respect to machine 4 from where it can be seen that the HPSS response (solid line) is faster than CPSS (dashed line). The HPSS reduces the overshoot and makes the system reach steady-state faster. The synchronous generators operate at synchronous speed, as shown in Fig. 6. When using HPSS, the oscillations occurring from three phase short circuit at 1 second need 4 seconds for damping but, according to Fig. 6, when using CPSS, it achieves damping after more oscillations (after 6 seconds).

As is observed in these figures, the graph shows the speed of the CPSS system containing permanent error and it also shows the derivation of speed graph so the damping of oscillations in the two systems can be seen.

The PSS output signal is a voltage added to the generator-exciter input. The output signal of PSS is shown in Fig. 6. It is shown that the magnitude of the output of the HPSS was greater than that of the CPSS after transmission line L_3 was tripped. The generator field voltage is shown in Fig. 6.

Fig. 6 which reflects the power property of the accelerators in bot stabilizers shows that HPSS has faster damping power than CPSS. The electrical power is shown in Fig. 6. Another important factor in transient stability analysis is the post-fault steady-state voltage. Fig. 6 presents the terminal voltage response of G1. Fig. 13 shows the line power from buses 3

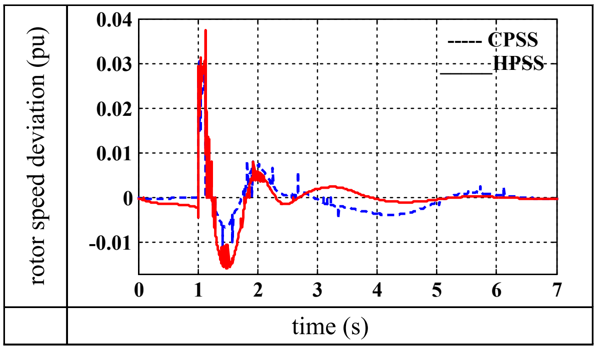

Figure 7: Speed deviation response

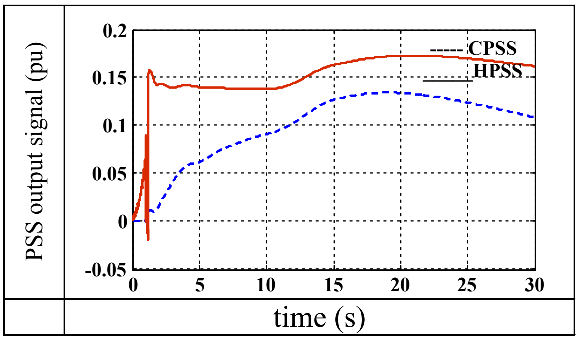

Figure 8: PSS output signal response

to 4. It shows that HPSS is similar to CPSS for steady-state condition. The simulation results show that HPSS is more effective than CPSS in damping the oscillations of the rotor angle, rotor speed, and electrical power output. This also verifies that HPSS compensated for the large disturbance better than CPSS.

7. Conclusion

Power systems are inherently variable and nonlinear systems are needed to control them, and especially the stability process to counter disturbances such as short circuits.

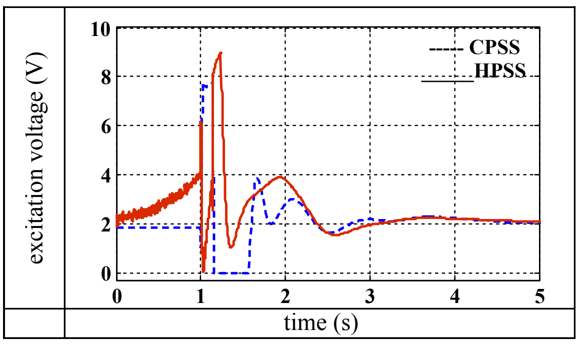

Figure 9: Generator field voltage response

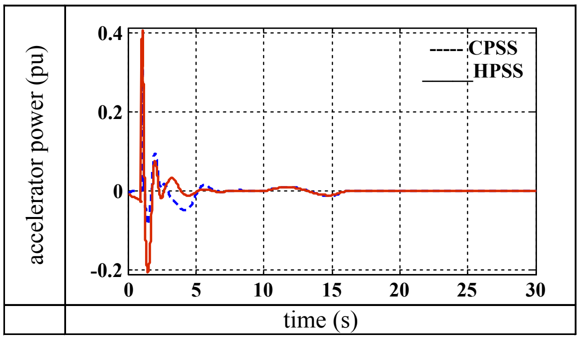

Figure 10: Accelerator power response

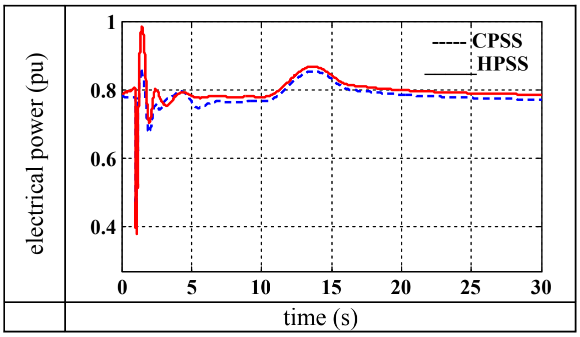

Figure 11: Electrical power response

There is a need for reliable stabilizer systems to control systems in different conditions. This paper proposes an HPSS nonlinear hybrid stabilizer that can use the advantages of CPSS conventional systems, harnessing advanced and nonlinear systems together. The hybrid system by improving stability will enhance the performance of the power system. The results show that HPSS has suitable control in terms of system stability under different conditions with respect to the dynamics of appropriate and quick response. The proposed design of HPSS presents a flexible system assisting a nonlinear controller.

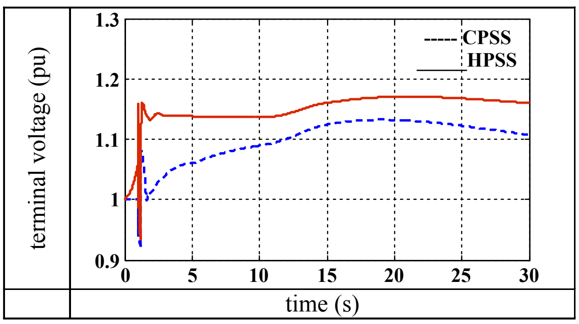

Figure 12: Terminal voltage response

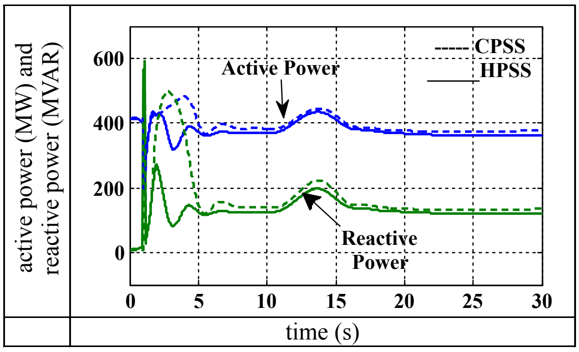

Figure 13: Active and reactive power bus 3 to bus 4 response

References

[1] Z Bouchama, N Essounbouli, MN Harmas, A Hamzaoui, and K Saoudi. Reaching phase free adaptive fuzzy synergetic power system stabilizer. *International Journal of Electrical Power & Energy Systems*, 77: 43–49, 2016.

[2] Said Djennoune and Maamar Bettayeb. Optimal synergetic control for fractional-order systems. *Automatica*, 49(7):2243–2249, 2013.

[3] Igor Erceg, Damir Sumina, Stjepan Tusun, and Martina Kutija. Power system stabilizer based on pointwise min-norm control law. *Electric Power Systems Research*, 143:215–224, 2017.

[4] Naz Niamul Islam, MA Hannan, Azah Mohamed, and Hussain Shareef. Improved power system stability using backtracking search algorithm for coordination design of pss and tcsc damping controller. *PloS one*, 11(1):e0146277, 2016.

[5] Zhenhua Jiang. Design of power system stabilizers using synergetic control theory. In *Power Engineering Society General Meeting, 2007. IEEE*, pages 1–8. IEEE, 2007.

[6] Zhenhua Jiang. Design of a nonlinear power system stabilizer using synergetic control theory. *Electric Power Systems Research*, 79(6): 855–862, 2009.

[7] Zhenhua Jiang and Roger A Dougal. Synergetic control of power converters for pulse current charging of advanced batteries from a fuel cell power source. *IEEE Transactions on Power electronics*, 19(4):1140–1150, 2004.

[8] Vahid Keumarsi, Mohsen Simab, and Ghazanfar Shahgholian. An integrated approach for optimal placement and tuning of power system stabilizer in multi-machine systems. *International Journal of Electrical Power & Energy Systems*, 63:132–139, 2014.

[9] Ajit Kumar. Power system stabilizers design for multimachine power systems using local measurements. *IEEE Transactions on Power Systems*, 31(3):2163–2171, 2016.

[10] MA Mahmud, MJ Hossain, and HR Pota. Transient stability enhancement of multimachine power systems using nonlinear observer-based excitation controller. *International Journal of Electrical Power & Energy Systems*, 58:57–63, 2014.

[11] A Ragavendiran, R Gnanadass, and K Ramakrishnan. A new sparls algorithm for tuning power system stabilizer. *International Journal of Electrical Power & Energy Systems*, 68:327–335, 2015.

[12] Enrico Santi, Antonello Monti, Donghong Li, Karthik Proddutur, and Roger A Dougal. Synergetic control for dc-dc boost converter: implementation options. *IEEE Transactions on industry applications*, 39(6): 1803–1813, 2003.

[13] GAZANFAR SHAHGHOLIAN, AMIN RAJABI, BAHRAM KARIMI, and MOHAMMAD REZA YOUSEFI. Design of power system stabilizer based on sliding mode control theory for multi-machine power system. 2010.

[14] Gh Shahgholian. Review of power system stabilizer: Application modeling analysis and control strategy. *Int J Tech Phys Probl Eng*, 5:41–52, 2013.

[15] Gh Shahgholian and J Faiz. The effect of power system stabilizer on small signal stability in single-machine infinite-bus. *International Journal of Electrical and Engineering*, 4(2):45–53, 2010.

[16] Ghazanfar Shahgholian. Development of state space model and control of the statcom for improvement of damping in a single-machine infinite-bus. *International Review of Electrical Engineering*, 4(6), 2009.

[17] Ghazanfar Shahgholian and Zahra Azimi. Analysis and design of a dstatcom based on sliding mode control strategy for improvement of voltage sag in distribution systems. *Electronics*, 5(3):41, 2016.

[18] Ghazanfar Shahgholian and Amir Movahedi. Coordinated control of tcsc and svc for system stability enhancement using anfis method. *International Review on Modelling and Simulations*, 4(5), 2011.

[19] Ghazanfar Shahgholian and Amir Movahedi. Coordinated design of thyristor controlled series capacitor and power system stabilizer controllers using velocity update relaxation particle swarm optimization for two-machine power system stability. *Revue Roumaine Des Sciences Techniques*, 59(3):291–301, 2014.

[20] Ghazanfar Shahgholian and Amir Movahedi. Power system stabiliser and flexible alternating current transmission systems controller coordinated design using adaptive velocity update relaxation particle swarm optimisation algorithm in multi-machine power system. *IET Generation, Transmission & Distribution*, 10(8):1860–1868, 2016.

[21] Ghazanfar Shahgholian, Amir Movahedi, and Jawad Faiz. Coordinated design of tcsc and pss controllers using vurpso and genetic algorithms for multi-machine power system stability. *International Journal of Control, Automation and Systems*, 13(2):398–409, 2015.

[22] Young-Dae Son, Tae-Won Heo, Enrico Santi, and Antonello Monti. Synergetic control approach for induction motor speed control. In *Industrial Electronics Society, 2004. IECON 2004. 30th Annual Conference of IEEE*, volume 1, pages 883–887. IEEE, 2004.

[23] Sheng-Kuan Wang. A novel objective function and algorithm for optimal pss parameter design in a multi-machine power system. *IEEE transactions on power systems*, 28(1):522–531, 2013.

[24] Abdolazim Yaghooti, Majid Oloomi Buygi, and Mohamad Hassan Modir Shanechi. Designing coordinated power system stabilizers: A reference model based controller design. *IEEE Transactions on Power Systems*, 31(4):2914–2924, 2016.

[25] Ping Zhao, Wei Yao, Shaorong Wang, Jinyu Wen, and Shijie Cheng. Decentralized nonlinear synergetic power system stabilizers design for power system stability enhancement. *International Transactions on Electrical Energy Systems*, 24(9):1356–1368, 2014.

[26] Ping Zhao, Wei Yao, Jinyu Wen, L Jiang, Shaorong Wang, and Shijie Cheng. Improved synergetic excitation control for transient stability enhancement and voltage regulation of power systems. *International Journal of Electrical Power & Energy Systems*, 68:44–51, 2015.

[27] Xuehua Zhao, Liping Shi, Libing Chen, Zhenglong Xia, and AR Bendre. Modeling and current control strategy for a medium-voltage cascaded multilevel statcom with lcl filter. *Journal of Power Technologies*, 95(1):1, 2015.