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# Decentralized Synergistic Control of Multi-Machine Power System Using Power System Stabilizer

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**Abstract**

Many researchers have proposed small signal analysis methods and numerous power system stabilizers designed by system linearization. In these approaches, it is assumed that disturbances are so small and the linear approximation error of a nonlinear power system remains in an acceptable range. However, the approximation can restrict the validity of linearized models to a neighborhood of equilibrium points. In this paper, in order to reduce the concerns related to the linearization of the power system and damping of electromechanical oscillations, the synergistic nonlinear control method has been used. In addition, a decentralized control strategy was proposed for the use of power system stabilizers in multi-machine power systems. The relation between generators was modelled as a function of variables and its effects on a single machine connected to an infinite bus power system were examined under various disturbances. Also, three test systems were used to verify the efficiency of the proposed decentralized synergetic method. The simulation results showed that the proposed power system stabilizer was more effective than other stabilizers such as a multi-band power system stabilizer in local and inter-area mode oscillations and under different disturbances.

**Keywords:** Decentralized control, power system stabilizer (PSS), multi-machine power system.

## 1. INTRODUCTION

Considering the high complexity of electrical power systems and their importance in the development of infrastructures, increasing attention has been paid to careful designs with elevated stability margins [1,2]. Moreover, small signal stability problems, usually due to small-magnitude and low-frequency electromechanical oscillations that occur during a long period in the system, have been investigated since the middle of the last century [3,4]. Dynamic instability in the form of low-frequency oscillations was first observed in 1977 in a Hong Kong power

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system. This problem was resolved by desensitizing excitation responses within main generation units. In 1984, the connection of this system to a South China power system enabled the recording of severe oscillations in tie lines. For example, one of the worst oscillations could register the amplitude of 90 MW and last for 50 s under a nominal transmission power of 120 MW in the tie line. Such dynamic instabilities impose unnecessary limitations on the power systems performance [5].

In the last decade, numerous methods have been proposed for ensuring the stability of electrical power systems. One of the most effective and economic methods is the use of a power system stabilizer (PSS), which can generate supplementary control signals and thereby enable a generator's excitation system to reduce oscillations [6]. A conventional PSS (CPSS) was also designed using phase compensation techniques in the frequency domain. The CPSSs operates with a lead–lag compensator, whose parameters are obtained from a linear power system model. Furthermore, this type of stabilizer can add a supplementary control signal to the excitation system of a generator in accordance with the speed deviation of generator rotor [7]. The CPSSs remain as one of the most widely used stabilizers [8,9], but their design basis, that is linear power systems, presents certain problems. In a nonlinear power system by considering the inevitable changes in system parameters and situations, the appropriate operation of CPSSs, especially in a highly dynamic operating environment, cannot be guaranteed [10,11].

Since a large disturbance can create dangerous effects on the power system, using non-linear control can improve the performance of the controller. Additionally, centralized control methods are inappropriate because of the difficulty of information transmission among different parts of a system, especially in multi-machine power systems. Therefore, the use of decentralized control is proposed for modeling complex power systems [12,13]. To enhance the operation of the CPSSs, researchers have proposed several methods for designing the CPSS parameters. These approaches include artificial intelligence techniques such as fuzzy logic [14], neural networks [15,16], and artificial optimization algorithms [17], and nonlinear control methods including direct feedback linearization [18] and strong multi-objective optimization [19].

In this paper, decentralized synergetic control theory is used to design a controller that enables the analysis of a synergetic control method [20]. The proposed method in [21], indicated that the given method was superior to the sliding mode method. The synergetic control theory for the nonlinear control of permanent magnet synchronous motors and DC–DC boost converters was also discussed in [22], and the synergetic nonlinear PSS for a single-machine infinite bus (SMIB) system was described in [23]. An enhanced decentralized synergetic excitation system has been similarly developed to improve transient stability and voltage regulation in power systems [24]. In this regard, authors in [25] presented a PSS underlain by particle swarm optimization and used synergetic control theory to compare centralized synergetic PSSs (SPSSs) with the CPSSs. The given comparison was simulated on a single-machine power system and a 3-machine 9-

bus power system. In another study, the researchers formulated a method for designing decentralized SPSSs [26]. Accordingly, the designed SPSS was compared with a CPSS through simulations on two different power systems.

This work considered a decentralized SPSS in a SMIB system under three fault conditions: a three-phase short-circuit fault, a step change in input mechanical power, and a step change in reference terminal voltage. The SPSS was then examined under three types of multi-machine power systems: a 3-machine 9-bus power system, a 2-area 4-machine power system, and an IEEE 14-bus power system. To evaluate the controller performance in multi-machine power systems, the decentralized SPSS was compared with three PSSs used in previous studies.

This paper proposes a novel decentralized nonlinear model synergetic control procedure for excitation control in multi-machine power systems. A key characteristic of the proposed procedure is simultaneous consideration of the relationship between generators as a function of local variables as well as the use of decentralized method instead of centralized methods used in previous studies. The rest of this paper is organized as follows. Section 2 explains the general controller design method that is based on the synergetic control theory. Section 3 discusses the mathematical model of the SMIB system. Section 4 presents the novel decentralized control for designing power system stabilizer on the basis of synergetic control theory for multi-machine power systems. Section 5 discusses the simulation results for the SMIB system and the three multi-machine power systems. Section 6 concludes the paper.

## 2. SYNERGETIC CONTROL

Synergetic control theory, derived from the analytical design of aggregated regulators is underlain by two principles: (A) creating values (manifold or hyper-plane) that remain stable a dynamic system should move towards such values and (B) creating a system that moves towards the created values; in other words, a system is constantly reminded about these values [27]. Let us consider a nonlinear system in the following state-space form:

$$\dot{x} = f(x,u,t) \tag{1}$$

where x and u respectively represent a system's state variable vector and input vector, and t denotes time. The main variable of φ (x,t) is also considered a function of system state variables and time. In this respect, the control objective is to force the system to operate under a value of φ=0. This can also serve as a function of systemstate variables or include any other variables incorporated into the system. The system's achievement of φ=0 depends on the desired control characteristics and the variables used in constructing φ(x, t). Furthermore, φ is determined using the following equation:

$$\alpha \dot{\varphi} + \varphi = 0 \tag{2}$$

where α denotes a positive control parameter that shows the duration at which φ converges to zero. By simplification, we have:

$$\alpha \frac{d\varphi(x,t)}{dx} f(x,u,t) + \varphi(x,t) = 0 \tag{3}$$

Appropriately, defining φ and α enables the output to create movement conditions imposed on the selected values for stabilizing the system. Solving the equation (3) for u yields the input vector as follows:

$$u = g(x,t,\varphi(x,t),\alpha) \tag{4}$$

The synergetic control that can affect the nonlinear system does not require linearization or simplification. It should be noted that the limitations of synergistic control operate to reduce the order of the system, leading to global power system stability.

## 3. POWER SYSTEM MODEL

A linear diagram of the SMIB was depicted in Fig. 1. In this system, a synchronous generator is connected to a very large power network (infinite bus) through a transformer and two parallel transmission lines. Then, the synchronous generator power is supplied by a turbine and a governor and the generator is excited by an external excitation system. The excitation system is also controlled by an automatic voltage regulator (AVR) and a PSS.

It is assumed that the governor functions in an excessively slow manner in this system, but it can minimally affect the dynamics of the machine, and the mechanical power is constant as well. Moreover, given that the voltage control system (comprising the AVR, PSS, and excitation system) is much faster than other dynamic components of the system, the PSS and the AVR outputs can be used as inputs of the excitation system in a transient state. Within a power system consisting of n generators, a third-order model is considered for the generators, each equipped with an excitation system that has a PSS. The dynamic model of the $i^{th}$ generator with an excitation controller that includes dynamic and electrical equations is as follows [28,29]:

$$\dot{\delta}_i(t) = 2\pi f_0(\omega_i(t) - 1) \tag{5}$$

$$\begin{aligned}\dot{\omega}_i(t) &= \frac{-D_i}{2H_i}(\omega_i(t) - 1) \\ &- \frac{1}{2H_i}(P_{mio} - P_{ei}(t))\end{aligned} \tag{6}$$

$$\begin{aligned}\dot{E}'_{qi}(t) &= \frac{1}{T'_{doi}}[E_{fdi}(t) \\ &-(x_{di} - x'_{di})I_{di} \\ &-E'_{qi}]I_{qi}\end{aligned} \tag{7}$$

where $\delta_{io}$, $\omega_{io}=1$, $P_{eio}$ respectively refer to initial values for the rotor angle, angular speed and active power of $i^{th}$ generator. $y_{1i}$, $y_{2i}$ and $y_{3i}$ are also defined as follows: $y_{1i}=\delta_i-\delta_{io}$, $y_{2i}=\omega_i-1$ and $y_{3i}=P_{ei}-P_{eio}$. In addition, the dynamic model of $i^{th}$ generator should be written as follows:

$$\dot{y}_{1i} = 2\pi f_0 y_{2i} \tag{8}$$

$$\dot{y}_{2i} = \frac{-D_i}{2H_i}y_{2i} - \frac{1}{2H_i}y_{3i} \tag{9}$$

By defining $w_{fi}$ and $c_i$ as follows:

$$\begin{aligned}w_{fi} &= k_{ei}I_{qi}u_{fi} \\ &-(x_{di} - x'_{di})I_{qi}I_{di} \\ &-P_{mio} - T'_{doi}Q_{ei}y_{2i}\end{aligned} \tag{10}$$

$$\begin{aligned}c_i &= E'_{qi}\sum_{j=1}^{n}\dot{E}'_{qi}B_{ij}\sin(\delta_i - \delta_j) \\ &+E'_{qi} \\ &\sum_{j=1}^{n}E'_{qi}B_{ij}\cos(\delta_i - \delta_j)(\omega_j)\end{aligned} \tag{11}$$

where $k_e$ represents gain of the exciter (pu), $\beta_{ij}$ refers to elements of susceptance matrix, $u_f$ is associated with controller input to exciter, and $P_{mio}$ stands for the mechanical input power in pu (assumed to be constant). We have:

$$\dot{y}_{3i} = \frac{-1}{T'_{doi}} y_{3i} + \frac{1}{T'_{doi}} w_{fi} + c_i \qquad (12)$$

where $c_i$ represents the coupling between the $i^{th}$ subsystem and the rest of the system. $u_{fi}$ is obtained from equation (10), which is a feasible approach because $I_{qi} \neq 0$. Moreover, the $i^{th}$ coupling term can be modeled as a polynomial function of the active power generated by the $i^{th}$ subsystem. This function is expressed as follows:

$$c_i \cong d_{1i} y_{3i} + d_{2i} y_{3i}^2 \qquad (13)$$

where $d_{1i}$ and $d_{2i}$ are unknown constants that are used to define the adaptation law [30].

## 4. POWER SYSTEM STABILIZER

To evaluate the multi-machine power system equipped with a decentralized SPSS, three types of PSSs were examined. These stabilizers included a CPSS whose inputs w-ere speed variations, a PSS whose inputs were power variations in the accelerator, and a multi-band PSS (Fig. 2).

## 5. PSS DESIGN USING DSCT

In the previous section, a subsystem was delineated using equations (9), (10), and (12). The $\varphi_i$ of the $i^{th}$ generator was also defined through the scheme presented by Li and Slotine [31]:

$$\phi_i = \omega_o \left( k_{ci} - \frac{-D_i}{2H_i} \right) y_{2i} - \frac{\omega_o}{2H_i} y_{3i} + k_{ci}^2 y_{1i} \qquad (14)$$

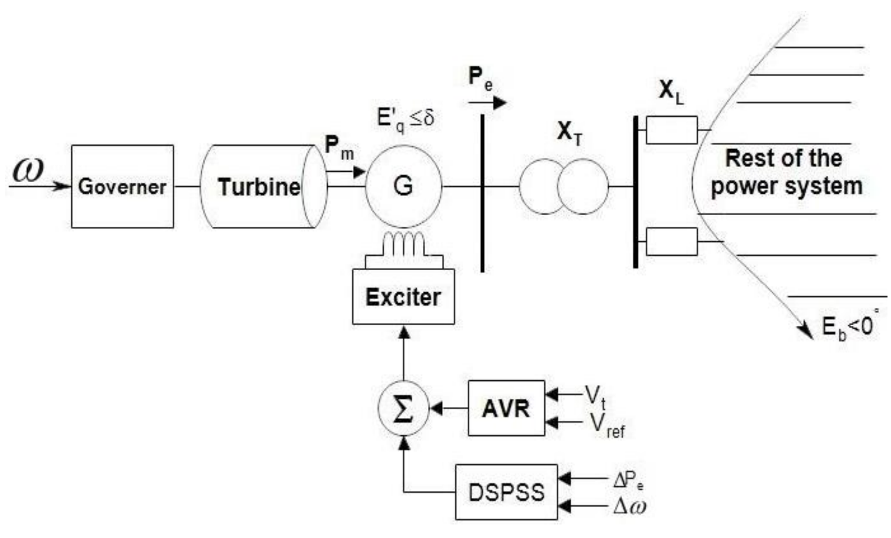
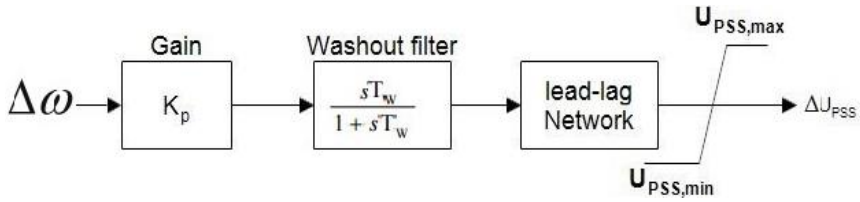



***Fig. 1. Linear diagram of single machine power system connected to infinitive bus.***

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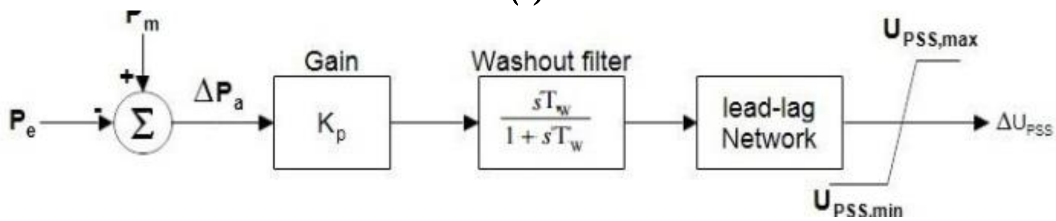


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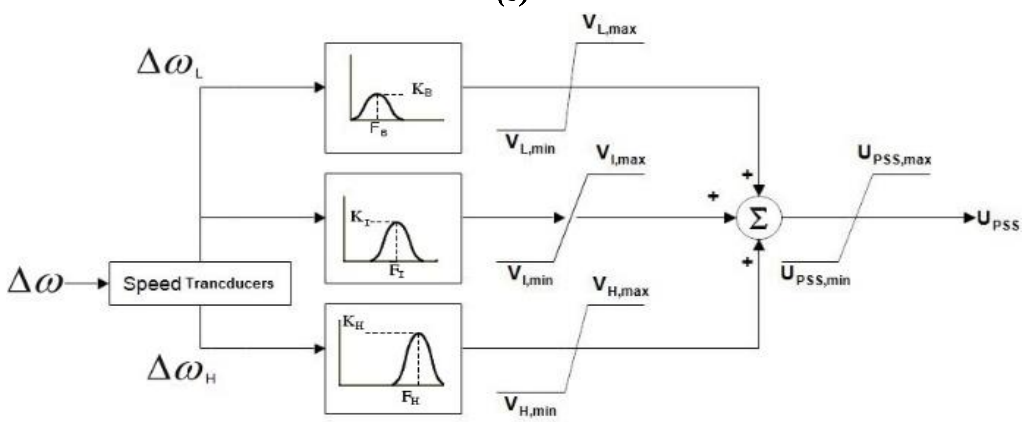



*(c)*

***Fig. 2. Power system stabilizer, (a) Conventional power system stabilizer whose input is speed variations ($\Delta\omega$), (b) Conventional power system stabilizer whose input is power variations of the accelerator ($\Delta P_a$), (c) Multi band power system stabilizer.***

Thus, the values could evolve until the system achieved global stability via equation (14). Then, the $k_{ci} \geq 0$ was observed. In this respect, the approximate equation (13) could be converted into $\hat{c}_i = \hat{d}_{1i} y_{3i} + \hat{d}_{2i} y_{3i}^2$ where $\hat{d}_{1i}$ and $\hat{d}_{2i}$ were the estimates of $d_{1i}$ and $d_{2i}$, respectively. With this assumption and by substituting equation (14) into equation (3) and using equations (12) and (13), the Lyapunov function could be defined as follows:

$$\bar{w} = \frac{1}{2}\phi_i^2 + \frac{1}{2}(d_{1i} - \hat{d}_{1i})^2 \Gamma_{1i}^{-1} + \frac{1}{2}(d_{2i} - \hat{d}_{2i})^2 \Gamma_{2i}^{-1} \quad (15)$$

where $\Gamma_{1i}$ and $\Gamma_{2i}$ are the adaptive gains. Differentiating equation (15) also yielded, where:

$$\dot{\hat{d}}_{1i} = \Gamma_{1i}\phi_i y_{3i}^2 \quad (16)$$

$$\dot{\hat{d}}_{2i} = \Gamma_{2i}\phi_i y_{3i}^2 \quad (17)$$

Substituting equations (12), (17), and (18) with equation (16) and solving these equations for $W_{fi}$ could result in the following variable:

$$w_{fi} = y_{3i} + 2H_i T'_{doi} (k_{ci} - \frac{D_i}{2H_i} + \frac{1}{\alpha_i}) \dot{y}_{2i} + H_i T'_{doi} (k_{ci}^2 + \frac{k_{ci}}{\alpha_i}) y_{2i} + \frac{2H_i T'_{doi} k_{ci}^2}{\omega_o \alpha_i} y_{1i} - T'_{doi} \hat{d}_{1i} y_{3i} - T'_{doi} \hat{d}_{2i} y_{3i}^2 \quad (18)$$

Equation (16) guaranteed system stability. The $W_{fi}$ also consisted of two terms, the first one leading a subsystem towards the desired values and satisfying $\varphi_i=0$, and the second term canceling out the coupling effects on the $i^{th}$ subsystem (This is important in multi-machine power systems.). By substituting equation (10) with equation (19), we derived the supplementary control signal serving as the PSS output and the input of the excitation system as follows:

$$u_{fi} = \frac{1}{k_{ei} I_{qi}} (P_{mio} + (x_{di} - x'_{di}) I_{qi} I_{di} + T'_{doi} Q_{ei} y_{2i} + (1 - T'_{doi} \hat{d}_{1i}) y_{3i} - T'_{doi} \hat{d}_{2i} y_{3i}^2 + \frac{2H_i T'_{doi} k_{ci}^2}{\omega_o \alpha_i} y_{1i} + 2H_i T'_{doi} (k_{ci} - \frac{D_i}{2H_i} + \frac{1}{\alpha_i}) \dot{y}_{2i} + 2H_i T'_{doi} (k_{ci}^2 + \frac{k_{ci}}{\alpha_i}) y_{2i}) \quad (19)$$

Selecting controller gains of $K_{ei}$, $\Gamma_{1i}$, $\Gamma_{2i}$, and $K_{ci}$ appropriately could also enable the efficient damping of power angle oscillations.

## 6. SIMULATION RESULTS

In this subsection, four power system models were used to evaluate the effects of the proposed decentralized nonlinear synergetic power system stabilizer and to compare it with other impressive stabilizers.

### 6.1. SMIB Power System

In this scenario, three fault conditions were imposed to evaluate the system. Under each fault condition, a system without a PSS, a system with a CPSS (consisting of gain, a washout filter, two lead–lag compensators, and a limiter), and a system with the decentralized SPSS were compared. The values of the parameters used in the simulation were presented in Table 1. The three fault conditions were as follows:

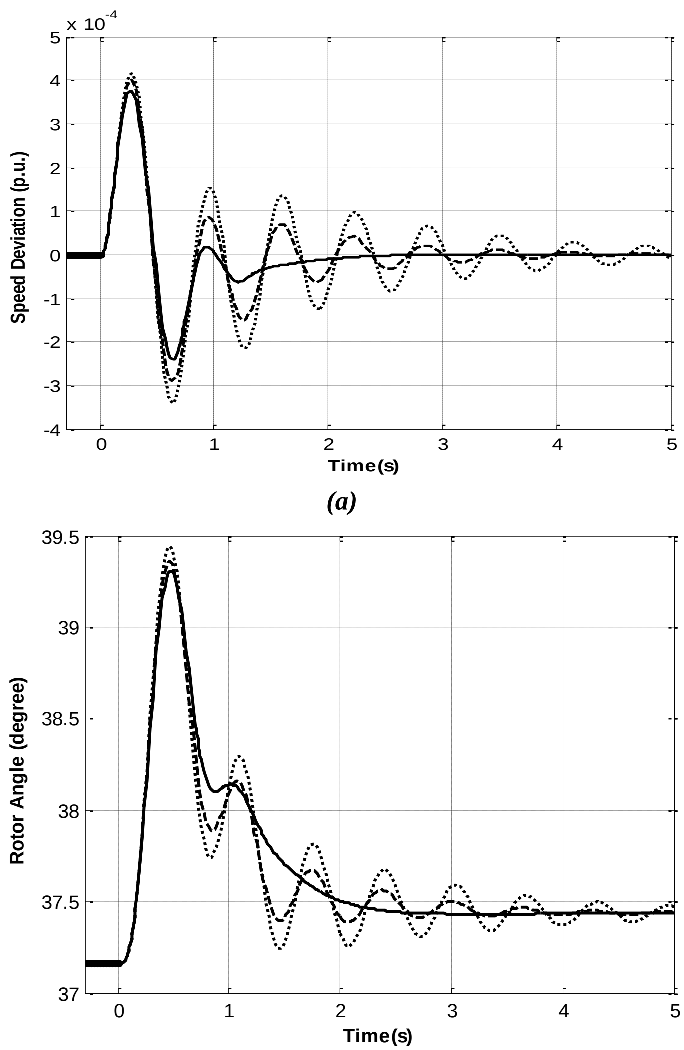
**TABLE 1.** ***Used parameters in simulation of single machine power system connected to infinitive bus.***

| Components | Parameters |
|---|---|
| Conventional power system stabilizer (CPSS) | $K_{PSS}$=5.5, $T_W$=3s, $T_1$=0.6s, $T_2$=0.18s, $T_3$=0.6s, $T_4$=0.18s<br>$U_{Pss,Max}$=0.15<br>$U_{Pss,Min}$= -0.15 |
| Decentralized power system stabilizer (DSPSS) | $K_c$=0.0001, $\Gamma_1$=1.01, $\Gamma_2$=7.23, α=0.11, $K_e$=1, $UPss_{,Max}$=0.15, $U_{Pss,Min}$= -0.15 |

(1) The step change in reference terminal voltage: Under this fault condition, a 0.05 pu step change in the generator's reference terminal voltage was simulated at 0 s. The simulation results, Fig. 3, indicate that the proposed PSS could achieve a better damping effect than doing the CPSSs under power angle oscillations of the generator, the angular speed of the generator, and the output of active power.

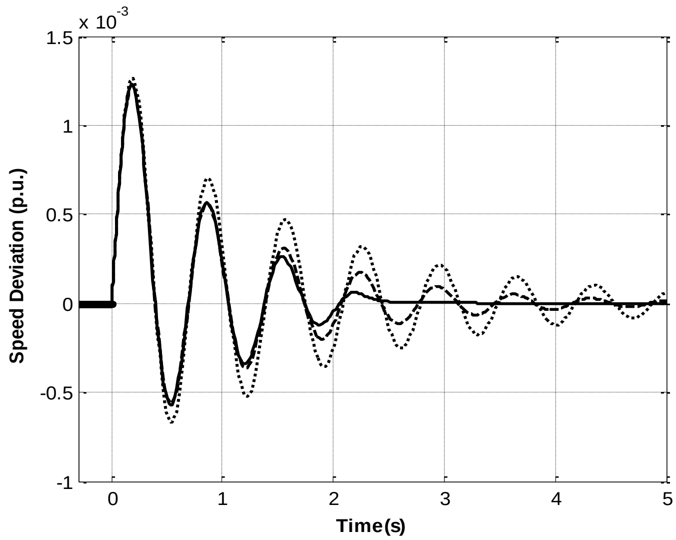
(2) The step change in input mechanical power: Under this fault condition, a 0.05 pu step change in the mechanical power of the generator input was simulated at 0 s. The findings, Fig. 4, illustrate that the proposed decentralized SPSS could exhibit a better damping effect under electromechanical oscillations than doing the CPSS and the system without a PSS.

(3) Three-phase short-circuit fault: Under this condition, a three-phase short-circuit fault could occur at t=0 s in which one of the




*(b)*

***Fig. 3. Simulation results of single machine power system under step change in reference terminal voltage, (a) Speed deviation, (b) Rotor angle [Comparison of system without PSS (dotted line) with CPSS (dashed line) and DSPSS (solid line)].***

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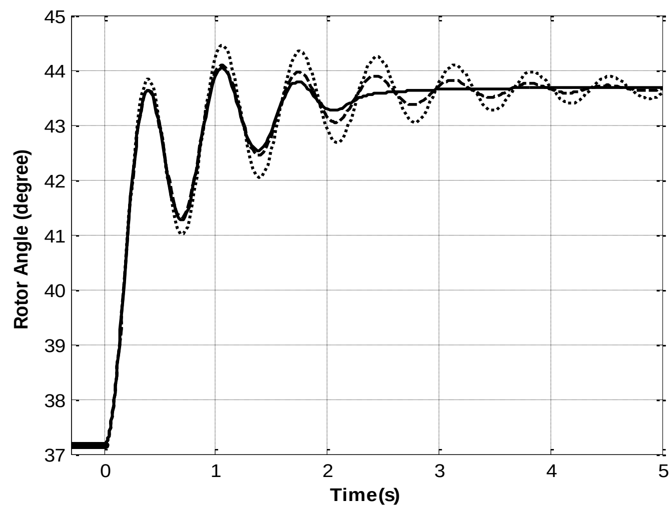



***(b)***

***Fig. 4. Simulation results of single machine power system under step change in input mechanical power, (a) Speed deviation, (b) Rotor angle [Comparison of system without PSS (dotted line) with CPSS (dashed line) and DSPSS (solid line)].***

parallel transmission lines was switched off because of the fault. At t=0.1 s, the fault was cleared, and the line was reconnected. As seen in Fig. 5, the proposed PSS revealed better results than those derived from other PSSs and the former one could realize excellent damping effects under large disturbances and unknown parameters (e.g., parameter changes in the generator or transmission line).

### 6.2. Three-Machine 9-Bus Power System

A single-line diagram of the 3-machine 9-bus power system is shown in Fig. (6-a). In the system, an inductive load was connected to bus 8, and each generator was equipped with an excitation system. In this scenario, system performance under nonlinear loading was evaluated. The parameters of the system were also presented in Table 2 and additional information on the system could be found in [32,33].

Fig. 7 shows the simulation results when the three-phase short-circuit fault occurred in the transmission line located between buses 6 and 9 at t=0 s, and the line was switched off at t=1 s. The decentralized SPSS could bring about more damping effects than those realized with the three other PSSs. The results also show the effect of simultaneously considering the relations between system generators and using the nonlinear control method in the proposed controller design.

### 6.3. Two-Area 4-Machine Power System

A single-line diagram of the 2-area 4-machine power system was illustrated in Fig. (6-b). In this respect, each area was equipped with two 900 MW and 20 KV generators. Each generator was also connected to a 230

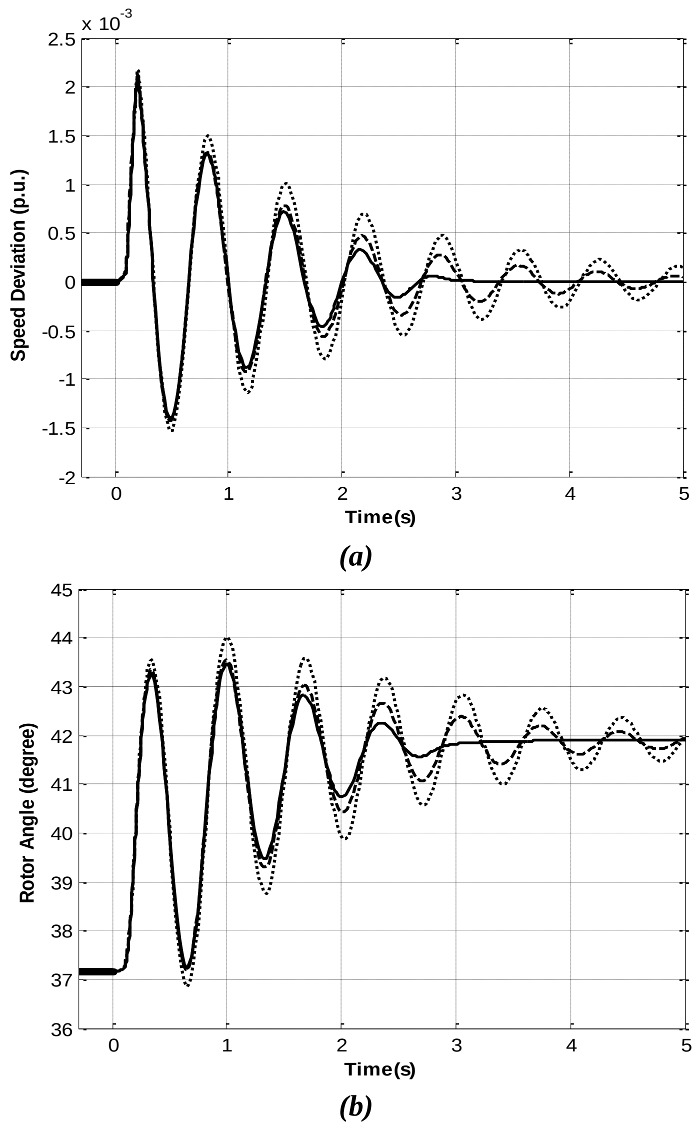
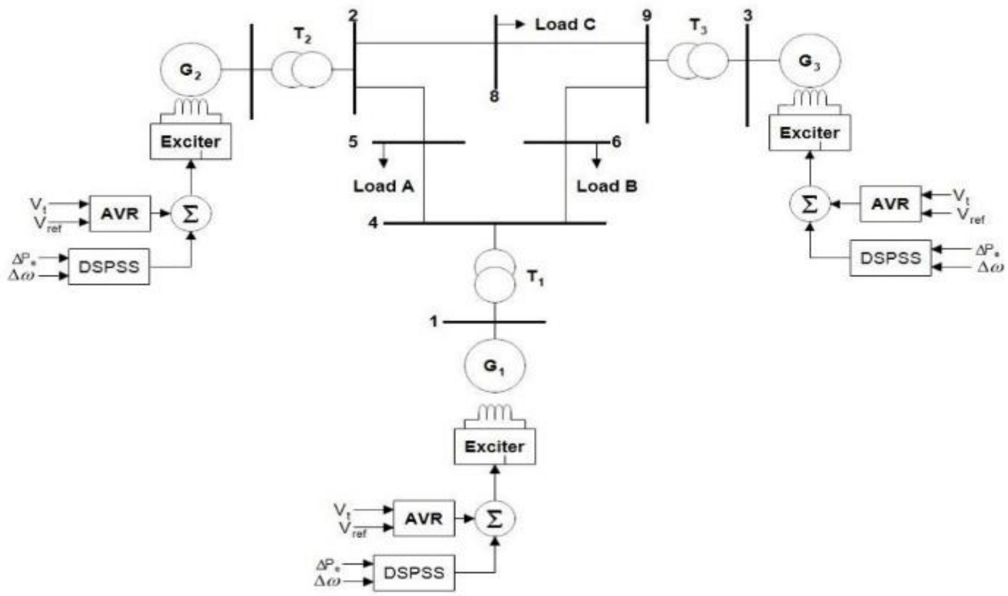



***Fig. 5. Simulation results of single machine power system under three phase short circuit fault, (a) Speed deviation, (b) Rotor angle [Comparison of system without PSS (dotted line) with CPSS (dashed line) and DSPSS (solid line)].***

**Table 2.** ***Used parameters in simulation of three-machine and nine-bus power system.***

| Components | Parameters |
|---|---|
| Δω PSS and $\Delta P_a$ PSS for each generator | $K_{PSS}$=35, $T_W$=3s, $T_1$=0.014s, $T_2$=0.142s, $T_3$=0.014s, $T_4$=0.142s $U_{Pss,Max}$=0.15, $U_{Pss,Min}$= -0.15 |
| Multi band PSS for each generator | $K_{PSS}$=1, $F_L$=0.1.87hz, $K_L$=23, $F_I$=0.92hz, $K_L$=26, $F_H$=11.2hz, $K_H$=145, $V_{LMAX}$=0.1, $V_{IMAX}$=0.15, $V_{HMAX}$=0.15, $V_{SMAX}$=0.15 |
| Synergetic decentralized PSS(DSPSS) for generator1 | $K_c$=9, $\Gamma_{11}$=1.01, $\Gamma_{12}$=16.06, α=0.15, $K_e$=1.5, $U_{PSS,Max}$=0.15, $U_{Pss,Min}$= -0.15 |
| Synergetic decentralized PSS (DSPSS) for generator2 | $K_c$=9.1, $\Gamma_{21}$=4,$\Gamma_{22}$=16.06 ,α=0.15, $K_e$=1.5, $U_{PSS,Max}$=0.15, $U_{Pss,Min}$= 0.15 |
| Synergetic decentralized PSS (DSPSS) for generator3 | $K_c$=7.3, $\Gamma_{31}$=2.88,$\Gamma_{32}$=21.5 ,α=0.015, $K_e$=1.5, $U_{PSS,Max}$=0.15, $U_{Pss,Min}$= -0.15 |

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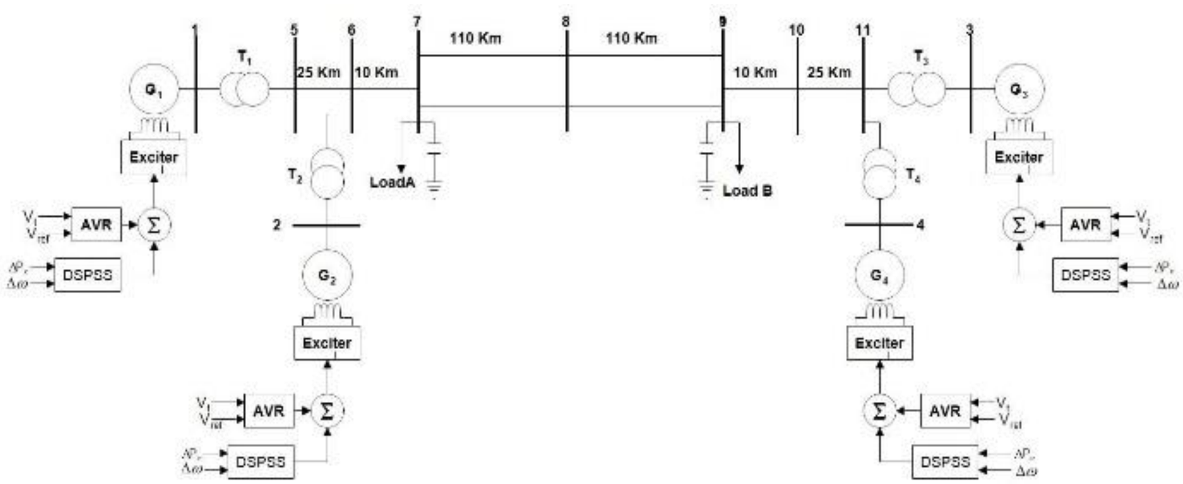


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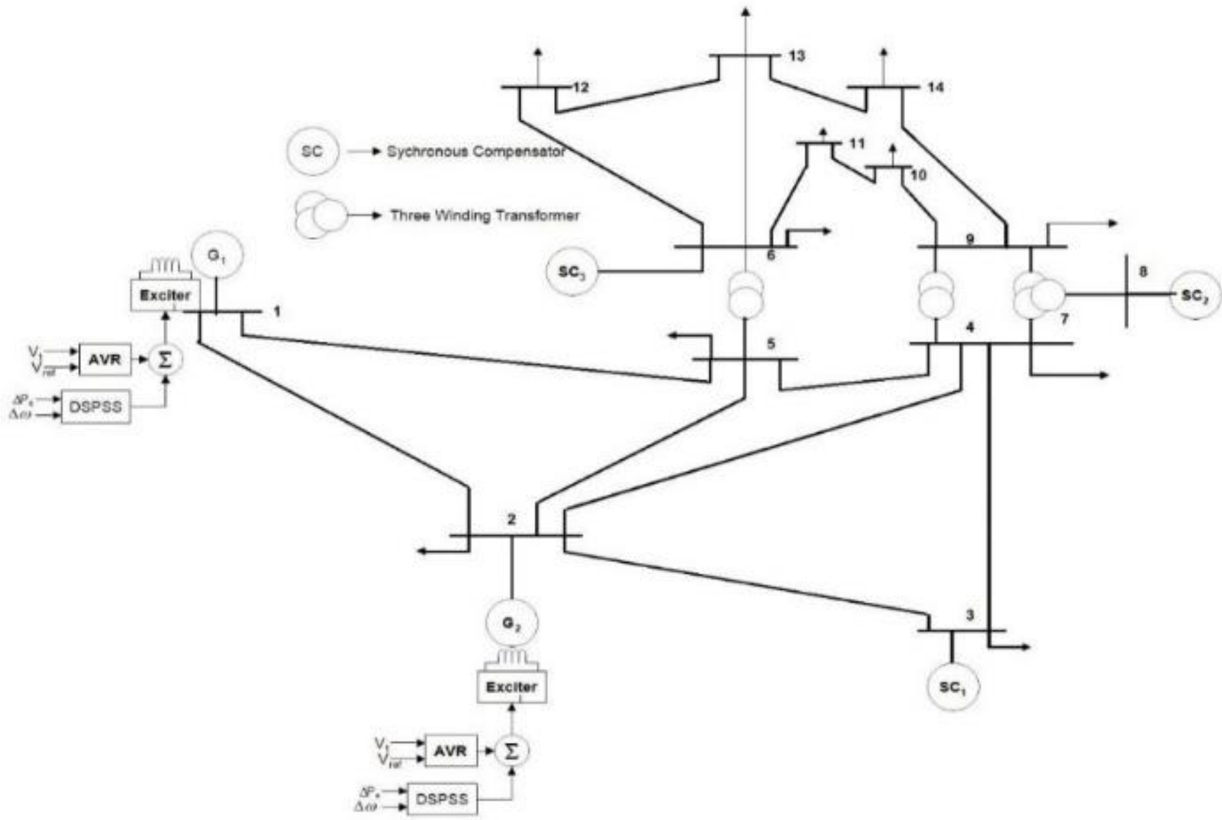



***(c)***

***Fig. 6. Single line diagram of power system, (a) Single line diagram of three-machine and nine-bus power system, (b) Single line diagram of two-area four machine power system, (c) Single line diagram of IEEE 14 bus power system.***

KV transmission line by a transformer, and the volume of power transferred from area 1 to area 2 was 400 MV. These two areas were connected by two 220 km transmission lines, and each generator was equipped with an excitation system. The parameters of the system were listed in Table 3 [34].

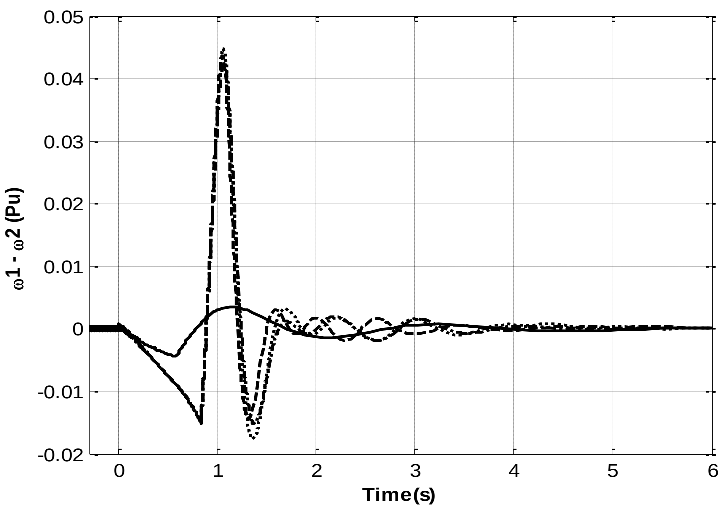
Additional information on this system could be found in [35]. The disturbance imposed on this system was a three-phase short-circuit fault that occurred on one of two 110 km transmission lines located between buses 8 and 9. The fault was also cleared at t=0.2 s. Accordingly, the results (Fig. 8) could verify that the performance of the decentralized SPSS was superior to that of other PSSs. For example, in Fig. 8-C, the effect of the proposed controller on the transition stability and dynamic stability of the system can be seen. According to the results, the Provided decentralized power system stabilizer has shown a greater ability to suppress transient and permanent state oscillations.

### 6.4. IEEE 14-Bus Power System

A single-line diagram of the IEEE 14-bus power system was shown in Fig. (6-c). This system had five synchronous machines, each one equipped with a type-1 IEEE excitation system.

Three of the synchronous machines were used as synchronous compensators for covering reactive power. This system had 11 loads (259 MW and 81.3 MVAR) and its parameters were presented in Table 4 [36]. Within this system, a three-phase short-circuit fault could occur in transmission lines of 1 and 2 at t=0 s. Machines 1 and 2 were similarly used as synchronous generators, whereas the rest of the machines were employed as synchronous compensators. In this work, the decentralized SPSS, a multi-band PSS, and $\Delta\omega$ and $\Delta P_a$ conventional stabilizers were simulated for two synchronous generators.

In this regard, the results (Fig. 9) indicated that the proposed system outperformed other PSSs and posed more noticeable effects on electromechanical oscillations under different disturbances.

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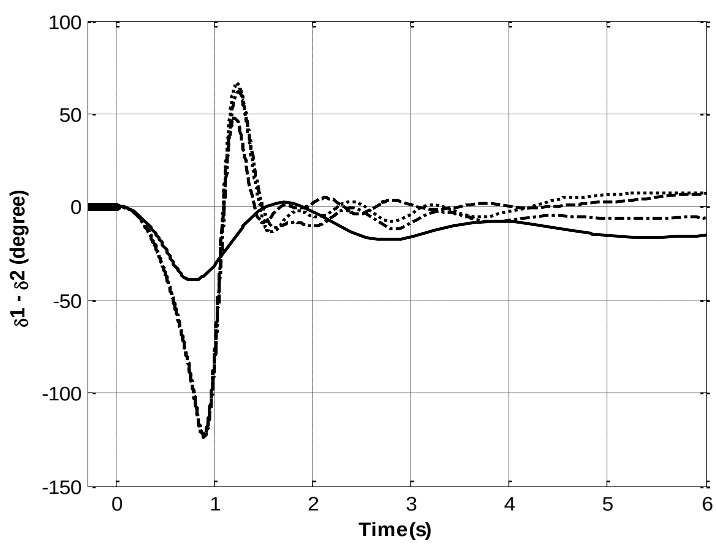


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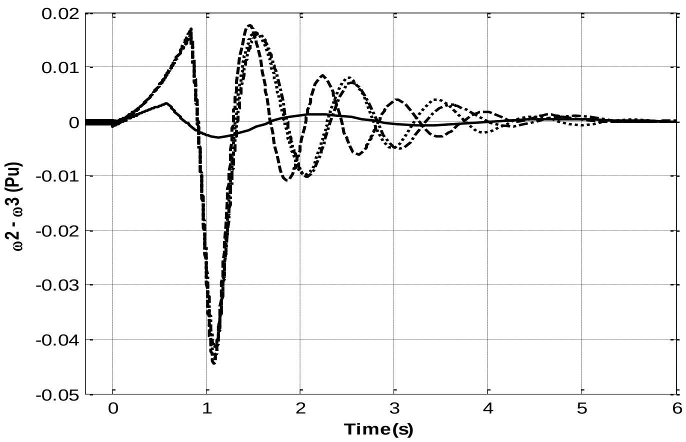


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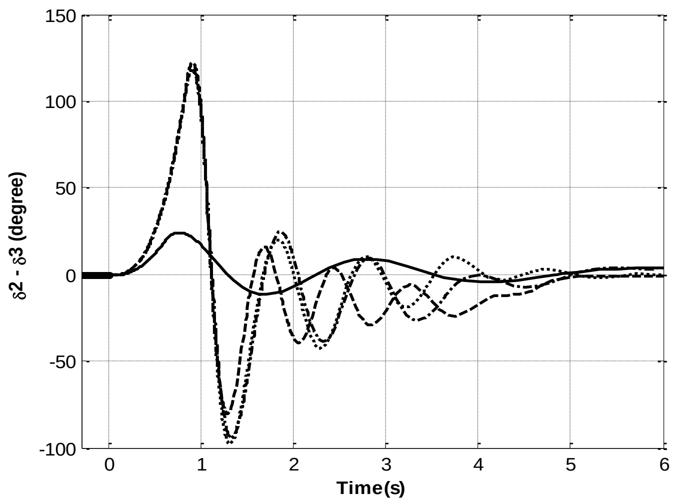
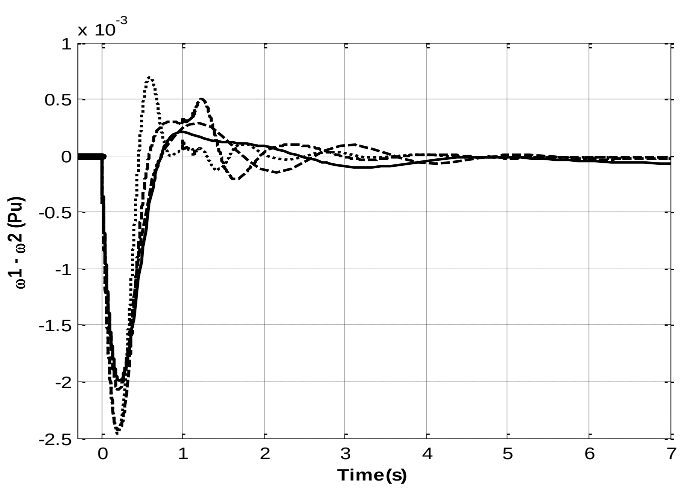


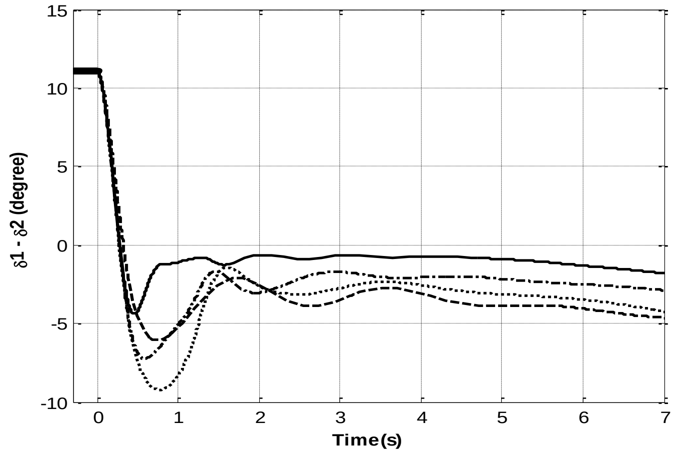

***(d)***

***Fig. 7. Simulation results of three-machine and nine-bus power system, (a) Speed deviation between generators 1, 2, (b) Rotor angle deviation between generators 1, 2, (c) Speed deviation between generators 2, 3, (d) Rotor angle deviation between generators 2, 3. [Comparison of system $\Delta P_a$ PSS (dotted line) with $\Delta\omega$ PSS (dash-dotted line), multi band PSS (dashed line) and DSPSS (solid line)].***

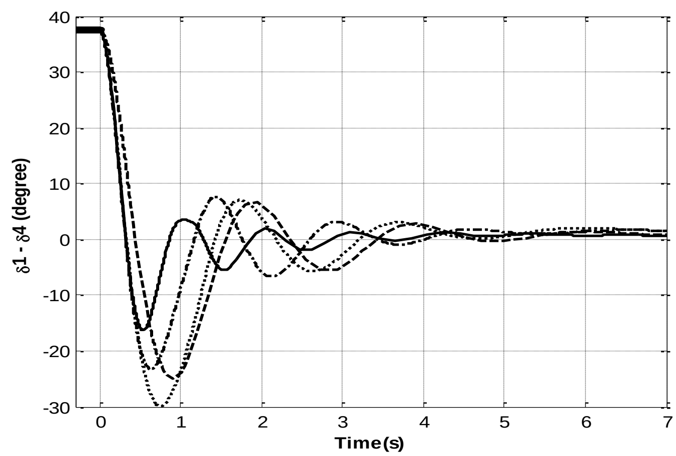



***(a)***

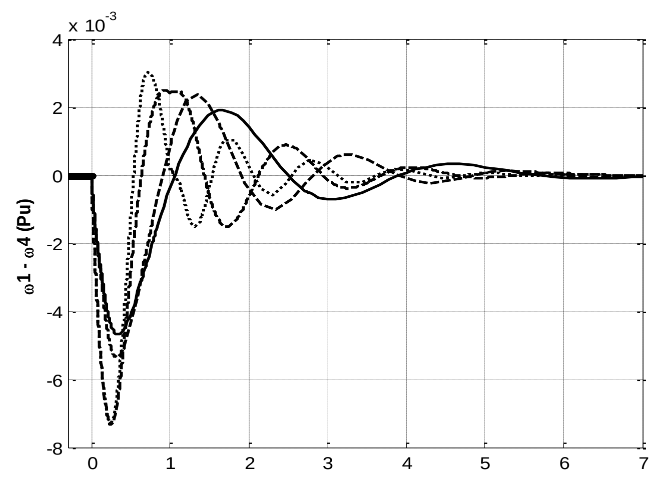
***continued***




***(b)***




***(c)***




***(d)***

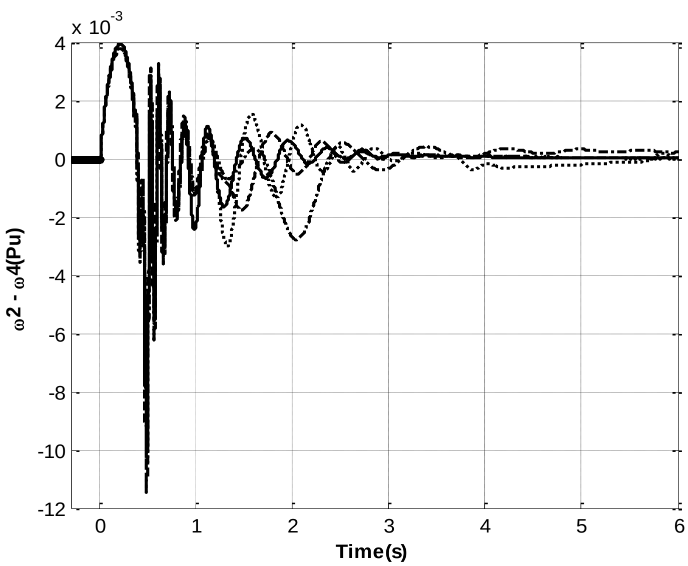
***Fig. 8. Simulation results of 2-area 4-machine power system, (a) Speed deviation between generators 1, 2, (b) Speed deviation between generators 1, 3, (c) Speed deviation between generators 1, 4, (d) Speed deviation between generators 2, 3. (Comparison of system $\Delta P_a$ PSS (dotted line) with $\Delta\omega$ PSS (dash-dotted line), multi band PSS (dashed line) and DSPSS (solid line)).***

**TABLE 3.** ***Used parameters in simulation of two-area four-machine power system.***

| Components | Parameters |
|---|---|
| $\Delta\omega$ PSS and $\Delta P_a$ PSS for each generators | $K_{PSS}$=10, $T_W$=10s, $T_1$=0.08s, $T_2$=0.015s, $T_3$=0.08s, $T_4$=0.015s $U_{Pss,Max}$=0.15, $U_{Pss,Min}$= -0.15 |
| Multi band PSS for each generators | $K_{PSS}$=1, $F_L$=0.21hz, $K_L$=25, $F_I$=0.1hz, $K_L$=22, $F_H$=10.32hz, $K_H$=163, $V_{LMAX}$=0.1, $V_{IMAX}$=0.15, $V_{HMAX}$=0.15, $V_{SMAX}$=0.15 |
| Synergetic decentralized PSS(DSPSS) for generator 1 | $K_c$=19.58, $\Gamma_{11}$=20.02, $\Gamma_{12}$=5.31, $\alpha$=0.921,$K_e$=1.321, $U_{PSS,Max}$=0.15, $U_{Pss,Min}$= -0.15 |
| Synergetic decentralized PSS(DSPSS) for generator 2 | $K_c$=18.03, $\Gamma_{21}$=101.01, $\Gamma_{22}$=0.532, $\alpha$=0. 5, $K_e$=1.5, $U_{PSS,Max}$=0.15, $U_{Pss,Min}$= -0.15 |
| Synergetic decentralized PSS(DSPSS) for generator 3 | $K_c$=20.88, $\Gamma_{31}$=59.8, $\Gamma_{32}$=33.076, $\alpha$=0.8, $K_e$=2.001, $U_{PSS,Max}$=0.15, $U_{Pss,Min}$= -0.15 |
| Synergetic decentralized PSS(DSPSS) for generator 4 | $K_c$=15.07, $\Gamma_{41}$=31, $\Gamma_{42}$=0.1, $\alpha$=0.539, $K_e$=1.342, $U_{PSS,Max}$=0.15, $U_{Pss,Min}$= -0.15 |

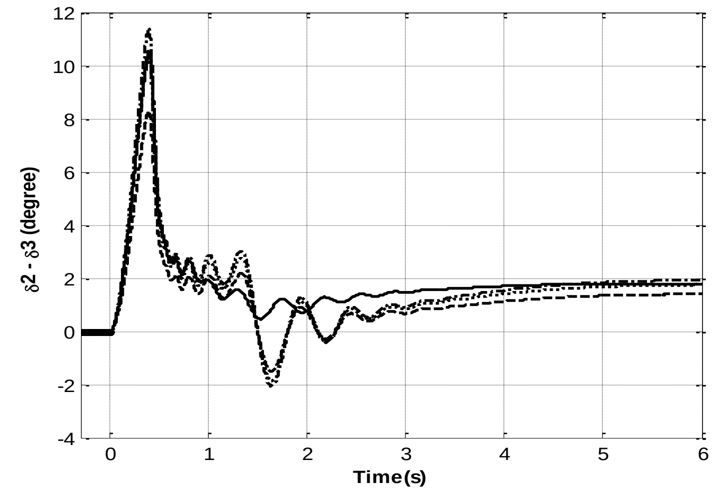
**TABLE 4.** ***Used parameters in simulation of IEEE 14 bus power system.***

| Components | Parameters |
|---|---|
| $\Delta\omega$ PSS and $\Delta P_a$ PSS for each generator | $K_{PSS}$=5, $T_W$=10s, $T_1$=0.38s, $T_2$=0.02s, $T_3$=0.38s, $T_4$=0.02s $U_{Pss,Max}$=0.15, $U_{Pss,Min}$= -0.15 |
| Multi band PSS for each generator | $K_{PSS}$=0.7, $F_L$=0.25hz, $K_L$=18, $F_I$=0.8hz, $K_L$=29, $F_H$=11.9hz, $K_H$=157, $V_{LMAX}$=0.1, $V_{IMAX}$=0.15, $V_{HMAX}$=0.15, $V_{SMAX}$=0.15 |
| Synergetic decentralized PSS(DSPSS) for generator1 | $K_c$=40.19, $\Gamma_{11}$=120, $\Gamma_{12}$=0.885, $\alpha$=0.837, $K_e$=2.32, $U_{PSS,Max}$=0.15, $U_{Pss,Min}$= -0.15 |
| Synergetic decentralized PSS(DSPSS) for generator2 | $K_c$=38.07, $\Gamma_{21}$=16.92, $\Gamma_{22}$=37.77, $\alpha$=0.56, $K_e$=1.502, $U_{PSS,Max}$=0.15, $U_{Pss,Min}$= -0.15 |

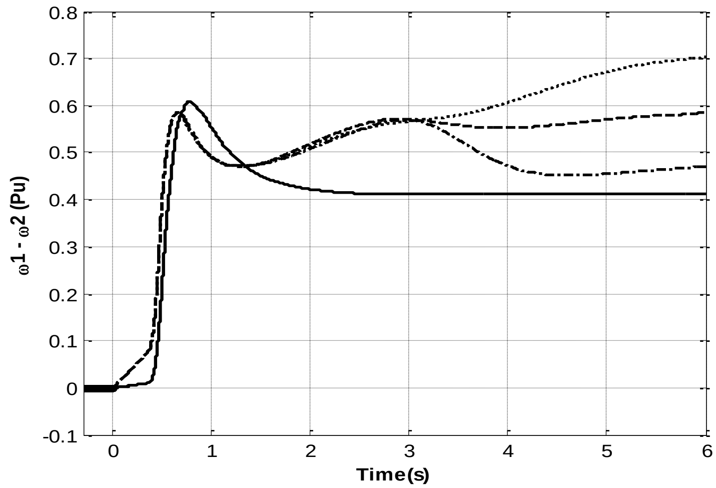


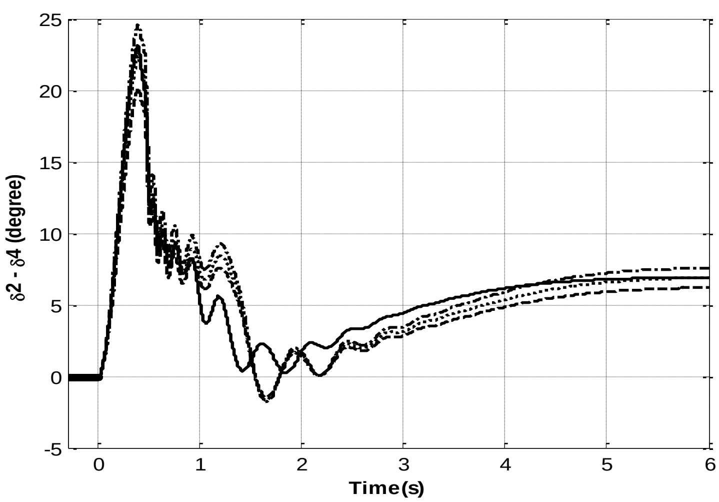

*(a)*

*continued*




***(b)***




***(c)***

***(d)***

***Fig. 9. Simulation results of IEEE 14 bus power system, (a) Speed deviation between G2 and G4, (b) Rotor angle deviation between G2 and G3, (c) Speed deviation between G1 and G2, (d) Rotor angle deviation between G2 and G4.***

In this case, due to the greater number of synchronous generators and also the higher number of relationships between generators to the effect of simultaneously considering the relationship between the generators by their local parameters, the use of the decentralized control method is clearly specified. For example, Fig.9-c shows that the performance of one generator can have a negative effect on other generators, just like a disturbance, while the proposed method can suppress these effects. Additional information on the IEEE 14-bus power system was provided in [37].

## 7. CONCLUSION

In this paper, a nonlinear decentralized method based on synergetic control theory was used to design a PSS. Using the effect of the relation between power system generators and the simultaneous use of decentralized synergistic control, a novel nonlinear stabilizer has been designed. The proposed controller could overcome the problems encountered in linear controllers designed on the basis of simplifications to nonlinear models.

Decentralized synergetic controllers were also simulated on a single-machine power system and three multi-machine power systems (9-bus 3-machine power system, two-area four-machine power system, and IEEE 14-bus power system). The proposed controllers were compared with other PSSs, such as multi-band PSS used in different studies. Moreover, the effects of interconnected machines (coupling term) were simulated using local variables provide significant effects on damping oscillations, especially in multi-machine power systems. the simulation results showed that the proposed controller could be more efficient than other PSSs under damping electromechanical oscillations.

## Nomenclature

$\delta$: rotor angle of the generator (radians)

$\omega$: rotor angular speed of the generator (p.u.)

$E_{fd}$: equivalent electro-motive force (EMF) in the excitation winding (p.u.)

$E'_q$: transient electro-motive force in the quadratic axis of the generator (p.u.),

$f_0$: power system's synchronous frequency (Hz)

H: inertial constant (s)

$I_d$, $I_q$: direct and quadrature-axis components of the generator armature current (p.u)

$P_m$: mechanical power input of the generator shaft (p.u.)

$P_e$: active electrical power delivered by the generator (p.u.)

$T'_{d0}$: direct-axis open-circuit time constant of generator (s)

$X_d$: direct-axis components of the generator synchronous reactance (p.u.)

$X'_d$: direct-axis component of the transient reactance of the generator (p.u.)

## REFERENCES

[1] J. C. Gonzalez-Torres, G. Damm, V. Costan, A. Benchaib and F. Lamnabhi-Lagarrigue, "Transient stability of power systems with embedded VSC-HVDC links: stability margins analysis

and control", IET Generation, Transmission and Distribution, vol. 14, no. 17, pp. 3377-3388, 2020.

[2] S. Lin, Y. Yang, M. Liu, Y. Xie and Y. Lu, "Static voltage stability margin calculation of power systems with high wind power penetration based on the interval optimisation method", IET Renewable Power Generation, vol. 14, no. 10, pp. 1728-1737, 2020.

[3] G. Shahgholian, A. Movahedi, "Power system stabilizer and flexible alternating current transmission systems controller coordinated design using adaptive velocity update relaxation particle swarm optimization algorithm in multi-machine power system", IET Generation, Transmission and Distribution, vol. 10, no. 8, pp. 1860-1868, 2016.

[4] M. Abdollahi, J. I. Candela, J. Rocabert, M. A. Elsaharty and P. Rodriguez, "Novel analytical method for dynamic design of renewable SSG SPC unit to mitigate low-frequency electromechanical oscillations", IEEE Trans. on Power Electronics, vol. 35, no. 7, pp. 7532-7544, 2020.

[5] F. Milano, M. Anghel, "Impact of time delays on power system stability", IEEE Trans. on Circuits and Systems, vol. 59, no. 4, pp. 889-900, 2012.

[6] S. Ghosh, Y. J. Isbeih, M. S. El Moursi, E. F. El-Saadany, "Cross-gramian model reduction approach for tuning power system stabilizers in large power networks", IEEE Trans. on Power Systems, vol. 35, no. 3, pp. 1911-1922, 2020.

[7] S. Fazeli Nejad, G. Shahgholian, M. Moazzami, "Simultaneous design of power system stabilizer and static synchronous compensator controller parameters using bee colony algorithm", Journal of Novel Researches on Electrical Power, vol. 9, no. 1, pp. 1-10, 2020.

[8] A. Kazemi Zahrani, M. Parastegari, "Designing PSS and SVC parameters simultaneously through the improved quantum algorithm in the multi-machine power system", *Journal of Intelligent Procedures in Electrical Technology*, vol. 8, no. 31, 68-75, 2017.

[9] M. Liu, F. Bizzarri, A. M. Brambilla, F. Milano, "On the impact of the dead-band of power system stabilizers and frequency regulation on power system stability", *IEEE Trans. on Power Systems*, vol. 34, no. 5, pp. 3977-3979, 2019.

[10] J. A. O. Lala and C. F. Gallardo, "Adaptive tuning of power system stabilizer using a damping control strategy considering stochastic time delay", IEEE Access, vol. 8, pp. 124254-124264, 2020.

[11] G. Zhang et al., "Deep reinforcement learning-based approach for proportional resonance power system stabilizer to prevent ultra-low-frequency oscillations", IEEE Trans. on Smart Grid, vol. 11, no. 6, pp. 5260-5272, 2020.

[12] M. Farahani, S. Ganjefar, "Intelligent power system stabilizer design using adaptive fuzzy sliding mode controller", Neurocomputing, vol. 226, no. 2, pp. 135-144, 2017.

[13] H. Amiri, G. R. Arab Markadeh, N. Mahdian Dehkordi, F. Blaabjerg, "Fully decentralized robust

backstepping voltage control of photovoltaic systems for DC islanded microgrids based on disturbance observer method", ISA Transactions, vol. 101, pp. 471-481, 2020.

[14] A.R. Tavakoli, A. Seifi, "Adaptive self-tuning PID fuzzy sliding mode control for mitigating power system oscillations", Neurecomputing, vol. 218, pp. 146-153, 2016.

[15] N.N. Islam, M.A. Hannan, H. Shareef, "An application of backtracking search algorithm in designing power system stabilizers for large multi-machine system", Electrical Power System Research, vol. 237, pp. 175-187, 2017.

[16] A. Hamidi, J. Beiza, T. Abedinzade, A. Daghigh, "Improving the dynamic stability of power grids including offshore wind farms and equipped with HVDC transmission system using adaptive neural controller", *Journal of Intelligent Procedures in Electrical Technology*, vol. 11, no. 42, pp. 79-99, 2020.

[17] S. Yang, P. Wang, Y. Tang, "Feedback linearization based current control strategy for modular multilevel converters", IEEE Trans. on Power Electronics, vol. 1, pp. 1-5, 2017.

[18] W. Song, T. Sakao, "A customization-oriented framework for design of sustainable product/service system", Journal of Cleaner Production, vol. 140, no. 3, pp. 1672-1685, 2017.

[19] Z. Bouchama, M. N. Harmas, *"Optimal* robust adaptive fuzzy *synergetic power system stabilizer* design", Electric power *Systems* Research, vol. 83, no. 1, pp. 170-175, 2012.

[20] E. Santi, A. Monti, D. Li, K. Proddutur, R.A. Dougal, "Synergetic control for power electronics applications: A comparison with the sliding mode approach", Journals of Circuits System and Computers, vol. 13, no. 4, pp. 737-760, 2004.

[21] A. Kolesnikov, G. Veselov, A. Monti, F. Ponci, E. Santi, R. Dougal, "Synergetic synthesis of DC–DC boost converter controllers: Theory and experimental analysis", Proceeding of the IEEE/APEC, vol. 1, pp. 409-415, 2002.

[22] J. Zhenhua, R.A. Dougal, "Synergetic control of power converters for pulse current charging of advanced batteries from a fuel cell power source", IEEE Trans. on Power electronics, Vol. 19, No. 4, pp. 1140-1150, 2004.

[23] Z. Jiang, "Design of a nonlinear power system stabilizer using synergetic control theory", Electrical Power System Research, vol. 79, pp. 855-862, 2009.

[24] P. Zhao, W. Yao, J. Wen, L. Jiang, S. Wang, "Improved synergetic excitation control for transient stability enhancement and voltage regulation of power systems", International Journal of Electrical Power and Energy Systems, vol. 68, pp. 44-51, 2015.

[25] Z. Bouchama, M.N. Harmas, "Optimal robust adaptive fuzzy synergetic power system stabilizer design". Electric Power Systems Research, vol. 83, no. 1, pp. 170-175, 2012.

[26] P. Zhao, W. Yao, S. Wang, J. Wen, "Decentralized nonlinear synergetic power system stabilizers design for power system stability enhancement,

International Trans. on Electrical Energy Systems, vol. 24, no. 9, pp. 1356–1368, 2014.

[27] C. Qi et al., "Decentralized DC voltage and power sharing control of the parallel grid converters in multi-terminal dc power integration system", IEEE Trans. on Sustainable Energy, vol. 10, no. 4, pp. 1971-1980, 2019.

[28] A. Fattollahi, “Simultaneous design and simulation of synergetic power system stabilizers and a thyristor-controller series capacitor in multi-machine power systems”, *Journal of Intelligent Procedures in Electrical Technology*, Vol. 8, No. 30, pp. 3-14, 2017.

[29] G. Shahgholian, A. Rajabi, B. Karimi, "Analysis and design of PSS for multi-machine power system based on sliding mode control theory", International Review of Electrical Engineering, vol. 4, no. 2, pp. 2241-2250, 2010.

[30] Zhou, Q., Wu, Ch., Shi, P., “Observer-based adaptive fuzzy tracking control of nonlinear systems with time delay and input saturation", Electrical Power System Research, Vol. 316, June 2017, pp. 49-68.

[31] J. Slotine, W. Li, “Applied nonlinear control”. Prentice-Hall, Englewood Cliffs, Nj, 1991.

[32] T. Fernandes, E.G. Junior, G.L. Luc, “Benchmark models for the analysis and control of small-signal oscillatory dynamics in power systems”. IEEE Trans. on Power Systems, vol. 32, no. 1, pp. 715-722, 2017.

[33] L. Lima, "Task force on benchmark systems for stability controls", IEEE PES, vol. 31, pp. 14, 2014.

[34] M. Bakhshi, M.H. Holakooie, A. Rabiee, "Fuzzy based damping controller for TCSC using local measurements to enhance transient stability of power systems", International Journal of Electrical Power and Energy Systems, vol. 85, pp. 12-21, 2017.

[35] J. Schiffer, F. Dörfler, E. Fridman, "Robustness of distributed averaging control in power systems: Time delays & dynamic communication topology", Automatica, vol. 80, pp. 261-271, 2017.

[36] M. Ouyang, M. Xu, C. Zhang, S. Huang, "Mitigating electric power system vulnerability to worst-case spatially localized attacks", Reliability Engineering and System Safety, vol. 165, pp. 144-154, 2017.

[37] B. V. Patil, L. P. M. I. Sampath, A. Krishnan, F. Y. S. Eddy, "*Decentralized* nonlinear model predictive *control* of a multi-machine power system”, International Journal of Electrical Power and Energy Systems, Vol. 106, pp. 358-372, 2019.