Turkish Journal of Electrical Engineering & Computer Sciences

http://journals.tubitak.gov.tr/elektrik/

Research Article

Turk J Elec Eng & Comp Sci
(2016) 24: 1532 – 1546

doi:10.3906/elk-1311-208

# Modeling, simulation, and optimal design of power system stabilizers using ABC algorithm

**Serdar EKİNCİ***, **Ayşen DEMİRÖREN**
Department of Electrical Engineering, Faculty of Engineering, İstanbul Technical University, İstanbul, Turkey

**Received:** 25.11.2013 • **Accepted/Published Online:** 03.04.2014 • **Final Version:** 23.03.2016

**Abstract:** This paper introduces a methodological system for modeling, simulation, and optimal tuning of the parameters of power system stabilizer (PSS) controllers in a multimachine power system so as to enhance transient stability. The model of a multimachine power system with PSS controllers is developed in MATLAB/Simulink for the simulation design. Simulink is a software instrument related to MATLAB, which is employed for modeling, simulating, and analyzing dynamical systems. The PSS controllers' design problem is expressed as an optimization problem; and the artificial bee colony (ABC) algorithm is utilized so as to examine the optimal PSS controller's parameters. The power system's transient stability performance is enhanced through diminishing a time domain-based objective function, where the oscillatory rotor speed deviation of the generator is obtained. The results of the nonlinear simulations substantiate the efficacy of the proposed modeling and tuning approach for power system stability enhancement. These outcomes likewise indicate that the proposed PSS controllers are operative in damping low frequency oscillations. In addition, comparing the ABC algorithm with the genetic algorithm method shows that better performance is achieved.

**Key words:** Power system stabilizer design, artificial bee colony optimization, power system modeling, MATLAB/Simulink, transient stability

## 1. Introduction

Power systems undergo low-frequency oscillations when they are vulnerable to disturbances. The oscillations can continue and develop to trigger system separation in the case of lack of sufficient damping. To augment the system damping, the generators are fitted out with power system stabilizers (PSSs), which are designed to supply supplementary feedback and stabilize signals in the excitation systems. PSSs prolong the power system stability level through advancing the system damping of the low-frequency oscillations, which are related to the electromechanical modes [1–3].

A number of techniques, such as adaptive control, optimal control, intelligent control, and variable structure control [4–6], are used in the design of PSSs. These existing techniques have numerous disadvantages, since the control law is contingent upon a linearized machine model, as well as the control parameters being arranged for definite nominal operating settings. Likewise, the parameters of controllers are not effective, since the system conditions are modified nonlinearly in the case of large disturbances [7].

Under such limitations, the existing stability techniques are unlikely to be successful in stabilizing the power system efficiency. Accordingly, novel modern control approaches, such as adaptive controllers and $H_\infty$

*Correspondence: ekincis@itu.edu.tr

control systems, have been employed for attaining operating performance superior to that of conventional stabilizers. However, the stabilizers depending upon modern control theory still have firm weaknesses, including completely essential information regarding the power system, high computing time for online parameter identification, and large implementation costs [8].

Therefore, a novel research technique is fundamentally required for the efficient stabilization of power systems. Optimization techniques are considered to function efficiently in the power systems' stabilization because they are extensively employed in a number of real-world problems, including image processing, pattern recognition, classifiers, machine learning, and routing. The field of artificial intelligence (AI) has been regarded as an active research area for the stabilization of power systems as of late. AI is a research field that defines connections between cognitive science and computational theories. The connections are indicated as data structures, problem solving techniques, search methods, and so on [9]. Social insects normally work without supervision. In addition, the social insects' team labor is primarily self-organized; and coordination is triggered by a number of interactions among individuals in the system. Swarm intelligence (SI) [10] is a method representing the collective nature of several social insects. SI systems ordinarily comprise a bunch of self-organized individuals, which interact among individuals in the swarm, as well as individuals interacting with the environment. Although there is no centralized control system for describing the nature of the individuals, interactions among the individuals generally provide the way for the emergence of global behavior.

Hence, SI is utilized for stability optimization, as it can furnish more appropriate methods for stabilizing the power system [11–13]. The artificial bee colony (ABC) algorithm is a representative swarm-based approach optimization, where the search algorithm is spurred by intelligent foraging behavior of a honeybee swarm process [14], and it appears to be a convenient instrument for engineering optimization. It consists of an adjustable and well-balanced mechanism so as to modify the global and local exploration and exploitation abilities in the shortest computation time. Thus, this method is functional in dealing with complex and large search spaces [15]. This paper uses ABC techniques, which have been utilized to improve the power systems' stabilization.

Simulink is an interactive environment for modeling, analyzing, and simulating several dynamic systems. It furnishes users with a graphical user interface for building block diagram models using 'drag and drop' operations [16]. A system is arranged and organized with regard to block diagram representation from a library of standard components. A system situated in block diagram representation is constructed plainly, and the simulation results are viewed swiftly. Simulation algorithms and parameters can be altered amid a simulation with intuitive results, in such a way that it enables the user to have a ready-access learning tool, which simulates a variety of operational real-world problems. Simulink chiefly operates with desired results for studying the impacts of nonlinearity on the behavior of the system; in a way it is also an ultimate research tool.

Simulink has rapidly been used in various research fields and likewise in the study of power systems [17,18]. In this study, we will take a multimachine power system example so as to illustrate the features and extent of a Simulink-based model for transient stability analysis. A self-sufficient model is given with its complete details, which can function as a basic structure for a progressive and comprehensive study.

The rest of this paper is organized as follows. Section 2 presents the modeling of power system, which is a multimachine power system with PSSs. Section 3 describes a short overview of ABC algorithm. The proposed PSS structure and problem formulation are given in Section 4. Simulink models and nonlinear simulation results are introduced in Section 5 and conclusions are presented in Section 6.

## 2. Modeling of two-axis model with fast exciter

In this paper, we use the two-axis model with static exciter for nonlinear time-domain simulations. The mathematical model comprises differential equations with regard to machine and exciter dynamics and the algebraic equations corresponding to the stator and network equations [2]. The differential-algebraic equations for the $m$ machine, $n$ bus system with static exciter are as follows.

### 2.1. Differential equations

The differential equations of the machine and the exciter are given as in [2] where the various symbols are defined.

$$\frac{d\delta_i}{dt} = \omega_s\left(\omega_i - 1\right) = \omega_s \Delta\omega_i \tag{1}$$

$$\begin{aligned} \frac{d\omega_i}{dt} &= \frac{P_{mi}}{M_i} - \frac{P_{ei}}{M_i} - \frac{D_i(\omega_i - 1)}{M_i} \\ &= \frac{P_{mi}}{M_i} - \frac{(E'_{qi} - x'_{di} i_{di}) i_{qi}}{M_i} - \frac{(E'_{di} + x'_{qi} i_{qi}) i_{di}}{M_i} - \frac{D_i(\omega_i - 1)}{M_i} \end{aligned} \tag{2}$$

$$\frac{dE'_{qi}}{dt} = -\frac{E'_{qi}}{T'_{doi}} - \frac{(x_{di} - x'_{di}) i_{di}}{T'_{doi}} + \frac{E_{fdi}}{T'_{doi}} \tag{3}$$

$$\frac{dE'_{di}}{dt} = -\frac{E'_{di}}{T'_{qoi}} + \frac{(x_{qi} - x'_{qi}) i_{qi}}{T'_{qoi}} \tag{4}$$

$$\frac{dE_{fdi}}{dt} = -\frac{E_{fdi}}{T_{Ai}} + \frac{K_{Ai}}{T_{Ai}}\left(V_{ref,i} + V_{PSS,i} - V_i\right) \tag{5}$$

for $i = 1, \ldots, m$

### 2.2. Stator algebraic equations

The stator algebraic equations explain the electrical variables pertaining to the stator windings. The stator algebraic equations are expressed as:

$$E'_{di} - V_i \sin(\delta_i - \theta_i) - r_{si} i_{di} + x'_{qi} i_{qi} = 0 \tag{6}$$

$$E'_{qi} - V_i \cos(\delta_i - \theta_i) - r_{si} i_{qi} - x'_{di} i_{di} = 0 \tag{7}$$

for $i = 1, \ldots, m$

### 2.3. Network equations

The network equations can be expressed in power-balance or current-balance form. In this study, the current-balance form is used and the loads are assumed to be of the constant impedance type. In power system with

$m$ generators, the nodal equation can be formulized as:

$$\begin{bmatrix} \bar{I}_1 \\ \vdots \\ \bar{I}_m \\ 0 \\ \vdots \\ 0 \end{bmatrix} = \left[\bar{Y}'\right] \begin{bmatrix} \bar{V}_1 \\ \vdots \\ \vdots \\ \bar{V}_n \end{bmatrix} \tag{8}$$

$$\bar{I}_i = (i_{di} + j i_{qi})\, e^{j(\delta_i - \pi/2)} \tag{9}$$

for $i = 1, \ldots, m$ where $\bar{I}_1, \ldots, \bar{I}_m$ are the complex injected generator currents at the generator buses. Assume that the modified $\mathbf{\bar{Y}_{bus}}$ represented as $\mathbf{\bar{Y}'}$ can be divided as:

$$\left[\mathbf{\bar{Y}'}\right] = \begin{matrix} \mathbf{m} \\ \mathbf{n-m} \end{matrix} \overset{\begin{matrix}\mathbf{m} & \mathbf{n-m}\end{matrix}}{\left[\begin{array}{c|c} \mathbf{\bar{Y}_1} & \mathbf{\bar{Y}_2} \\ \hline \mathbf{\bar{Y}_3} & \mathbf{\bar{Y}_4} \end{array}\right]} \tag{10}$$

Inasmuch as there are no injections at buses $m+1, ..., n$, we can leave them out in order to obtain:

$$\begin{bmatrix} \bar{I}_1 \\ \vdots \\ \bar{I}_m \end{bmatrix} = \left[\bar{Y}_R\right] \begin{bmatrix} \bar{V}_1 \\ \vdots \\ \bar{V}_m \end{bmatrix} \tag{11}$$

where $\mathbf{\bar{Y}_R} = \left(\mathbf{\bar{Y}_1} - \mathbf{\bar{Y}_2}\mathbf{\bar{Y}_4^{-1}}\mathbf{\bar{Y}_3}\right)$ is the desired reduced matrix. The reduced matrices for every network condition (before fault, during fault, and after fault) are computed on account of the power system under study.

## 3. ABC algorithm

Karaboga and Basturk [19] recently presented an ABC algorithm that simulates the intelligent foraging behavior of honeybee swarms on account of the foraging behavior of honeybees for numerical optimization problems. It is a simple, sturdy, and population-based stochastic optimization algorithm [20].

The foraging bees are categorized into three classes: employed bees, onlookers, and scout bees. The employed bees are those bees that are currently exploiting a food source. They use the food source well and transfer the information regarding the food source to the onlooker bees, which are waiting in the hive to receive information about newly discovered food sources from the employed bees. The bees foraging for new food sources near the hive all the time are called scout bees. Employed bees distribute the information concerning the food sources' whereabouts by dancing in the determined field within the hive. The basis of the dance is commensurate with the food source's nectar content utilized by the dancing bee. The onlooker bees observe the dance and pick a food source in line with the probability proportional to the discovered food source's quality. Hence, food sources with good qualities attract more onlooker bees in comparison with bad food sources. All the employed bees related to a food source leave it and become scout bees at any time that a food source is exploited completely. Scout bees are envisaged as carrying out the duty of exploration, while employed and onlooker bees are envisaged as carrying out the duty of exploitation.

In the ABC algorithm, every food source is considered to be a possible solution to the existing problem, and a food source's nectar quantity signifies the solution's quality symbolized by the fitness value. The number of food sources is identical to the number of employed bees, where every employed bee definitely comes up for each food source.

The algorithm begins by connecting all the employed bees with the arbitrarily produced food sources (solutions). In each time iteration, each employed bee chooses a nearby food source, and then assesses its nectar amount (fitness). The $i$th position of the food source is defined as $X_i = (x_{i1}, x_{i2}, \ldots, x_{id})$ and $fit_i$ denotes the food source's nectar amount situated at $X_i$. Following observation of the employed bees' dancing, an onlooker bee moves to the area of the food source at $X_i$ by the probability $p_i$ represented as

$$p_i = \frac{fit_i}{\sum\limits_{k=1}^{SN} fit_k}, \tag{12}$$

where $SN$ is the overall amount of food sources. The onlooker bee turns up a food source's vicinity in the surrounding area of $X_i$ by using

$$X_i(t+1) = X_i(t) + \delta_{ij} * u, \tag{13}$$

where $\delta_{ij}$ is the size of the neighborhood (patch size) for the $j$th dimension of the $i$th food source formulized as

$$\delta_{ij} = x_{ij} - x_{kj}, \tag{14}$$

where k is a random number $\in (1, 2, \ldots, SN)$ and $k \neq i$, and $u$ is random uniform variate $\in [-1, 1]$.

If its newly obtained fitness value is better than the best fitness value attained as of yet, then the bee approaches the newly discovered food source by leaving the old one; otherwise, it will stay at the previous food source. After all employed bees complete this routine process, they distribute the fitness information among the onlookers, each of which chooses a food source in line with the probability given in Eq. (12). With the scheme, good food sources will be seized by more onlookers than the bad ones. Each bee will forage for the desired food source in the vicinity of the neighborhood for a repeated number of cycles (limit); and if the fitness value is not enhanced, then that bee will transform into scout bee.

Fundamental stages of the algorithm are given as follows [14]:

i) Set the location of the food source.

ii) Each employed bee brings out a new food source around its food source and exploits the better source.

iii) Each onlooker bee chooses a source contingent upon the quality of its solution, brings out a newly discovered food source in a certain food source area, and exploits the better food source.

iv) Define the source to be left and assign its employed bee for scouting new food sources.

v) Recollect the best food source discovered thus far.

vi) Iterate stages ii–v until the stopping criterion is fulfilled.

## 4. The proposed approach

### 4.1. PSS structure

An extensively speed-based conventional lead-lag PSS is employed in this study [2,3]. The transfer function of the $i$th PSS is expressed as

$$V_{PSS,i} = K_i \frac{sT_W}{1+sT_W}\left[\frac{(1+sT_{1i})}{(1+sT_{2i})}\frac{(1+sT_{3i})}{(1+sT_{4i})}\right]\Delta\omega_i, \tag{15}$$

where $\Delta\omega_i$ is the deviation in speed from the synchronous speed at the $i$th machine, and $V_{PSS,i}$ is the PSS output signal of this machine. This sort of stabilizer is composed of a washout filter and a dynamic compensator. The washout filter, which basically is a high-pass filter, is employed to adjust the steady-state offset in the output of the PSS. The value of the time constant $T_W$ is usually not critical and can vary between 0.5 and 20 s [21]. The dynamic compensator is composed of a gain block with gain $K_i$ and two-stage phase compensation block with time constants $T_{1i}$, $T_{2i}$ and $T_{3i}$, $T_{4i}$.

### 4.2. Objective function and PSS tuning

In the event of the above lead-lag structured PSS, the washout time constant is commonly specified. In this paper, washout time constant $T_W = 10$ s is employed. The stabilizer gain $K_i$ and the time constants $T_{1i}$, $T_{2i}$, $T_{3i}$, and $T_{4i}$ are to be defined. It is important to mention that the PSS is designed to minimize the power system oscillations following a large disturbance in order to enhance the power system stability. These oscillations can be seen in the deviations in power angles, rotor speeds, and line powers. Minimization of any one or all of these deviations could be selected as the objective. In this paper, an integral square time of square error of the speed deviations is used as the objective function formulated as

$$J = \sum_{i=2}^{m} \int_{t=0}^{t=t_{sim}} (t\Delta\omega_{i-1})^2 dt \tag{16}$$

where $m$ is the number of machines, $t_{sim}$ is the simulation time, and $\Delta\omega_{i-1}$ is the relative rotor speed of the $i$th generator relative to the first generator, i.e. $\Delta\omega_{i-1} = \Delta\omega_i - \Delta\omega_1$. By virtue of the objective function calculation, the time-domain simulation of the power system model is carried out for the simulation period. It is intended to diminish this objective function so as to enhance the system response with regard to the settling time and overshoots.

The problem restraints are the optimized parameter bounds. Thus, the design problem is represented as the following optimization problem:

Minimize $J$ depending on

$$K_i^{\min} \le K_i \le K_i^{\max} \tag{17}$$

$$T_{1i}^{\min} \le T_{1i} \le T_{1i}^{\max} \tag{18}$$

$$T_{2i}^{\min} \le T_{2i} \le T_{2i}^{\max} \tag{19}$$

$$T_{3i}^{\min} \le T_{3i} \le T_{3i}^{\max} \tag{20}$$

$$T_{4i}^{\min} \leq T_{4i} \leq T_{4i}^{\max} \tag{21}$$

Ordinary ranges of these parameters are $[0.01 - 100]$ for $K_i$ and $[0.01 - 1]$ for $T_{1i}$, $T_{2i}$, $T_{3i}$, and $T_{4i}$ [2]. The proposed approach uses the ABC algorithm in order to work out this optimization problem and seek the optimal set of PSS parameters, $\{K_i, T_{1i}, T_{2i}, T_{3i}, T_{4i};\ \ i = 1, 2, \ldots, n_{PSS}\}$.

## 5. Results and discussion

### 5.1. Test system

We consider the popular Western System Coordinated Council (WSCC) 3-machine 9-bus system depicted in Figure 1. Technicalities of the system data were specified in [1]. The participation factor method [22] and the sensitivity of the PSS effect [23] are employed to ascertain the optimum locations of PSSs. The results of both methods point out that $G_2$ and $G_3$ are the optimum locations for installing PSSs.

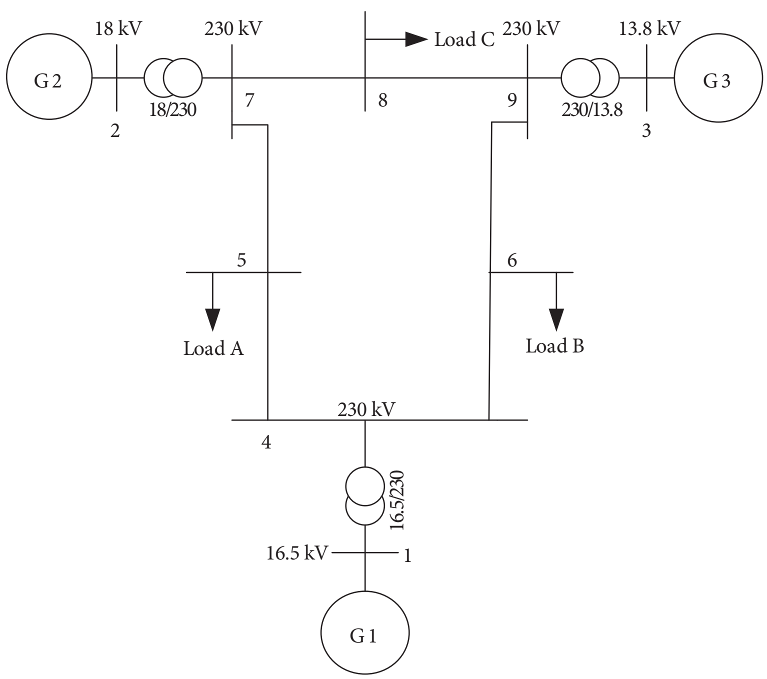


**Figure 1.** WSCC 3-machine, 9-bus system.

### 5.2. Simulink models

The complete 3-generator system, depicted in Figure 1, is embodied with regard to Simulink blocks in a single integral model by using Eqs. (1)–(10) for transient stability study. The Simulink model for computing differential equations and stator algebraic equations is studied and described for all generators, while Figure 2 is depicted for generator 1.

Figure 3 shows the complete block diagram of network equations. Subsystems 1, 2, and 3 are shown in Figure 3 in order to calculate the value of electrical current outputs for different generators, while Figure 4 shows the computation of the current output of generator 1.

The Simulink model for calculation of the stabilizing signal output of PSSs and the objective function output are shown in Figures 5 and 6.

The model also facilitates the choice of simulation parameters, including start and stop times, types of solver, step sizes, tolerance, and output options. The model can be operated either directly or from the MATLAB command line, or from an m-file program. In the this study, the load flow, the fault clearing time, the initial values of parameters, and the changes in the network due to faults are controlled through an m-file program in MATLAB.

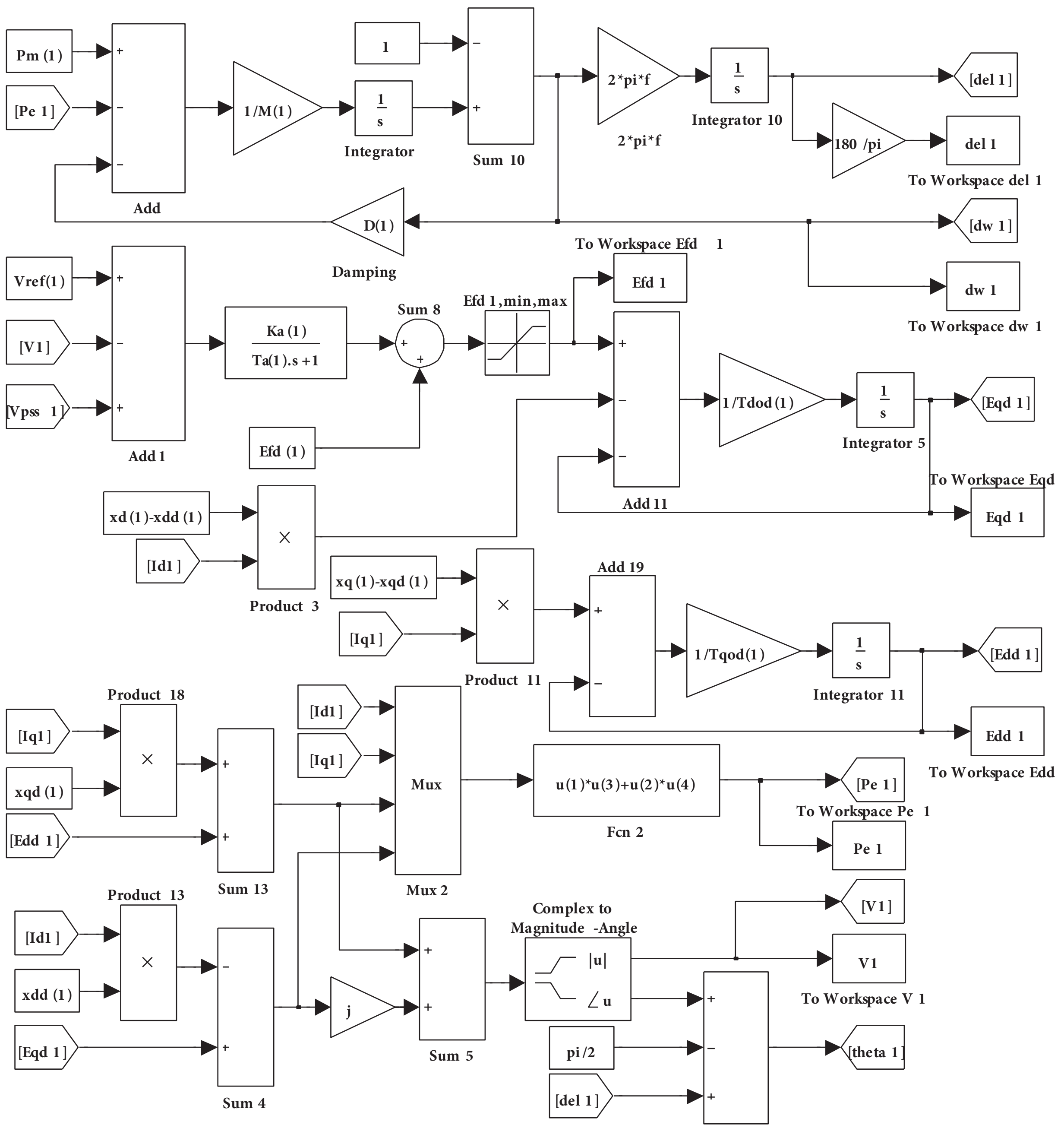


**Figure 2.** Simulink model for calculation of differential equations and stator algebraic equations for generator 1.

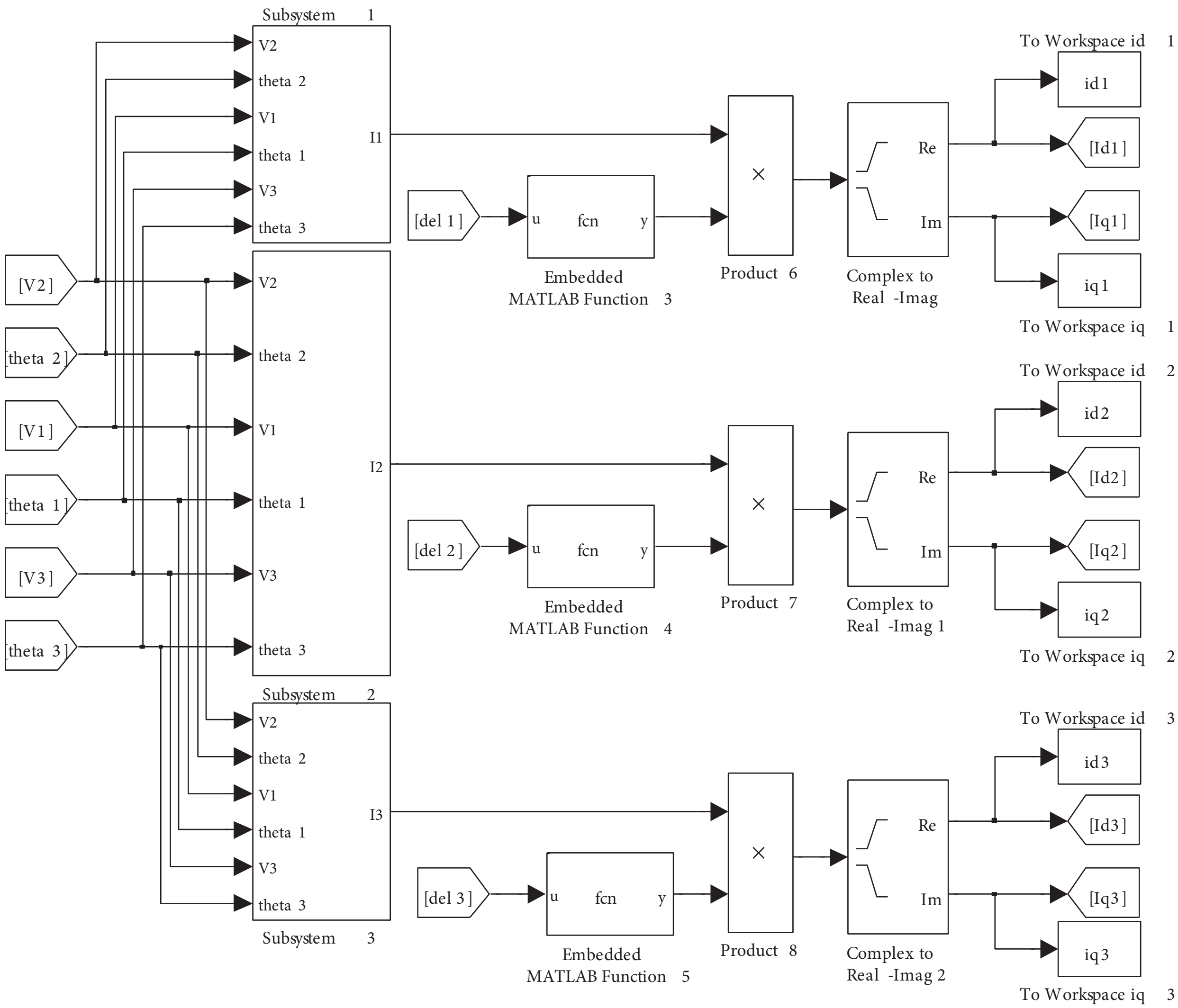


**Figure 3.** Complete block diagram of network equations.

### 5.3. Application of the ABC algorithm

In this study, the optimized parameters are $K_i$, $T_{1i}$, $T_{2i}$, $T_{3i}$, and $T_{4i}$, $i = 2, 3$, and the number of optimized parameters is 10. The ABC algorithm was implemented in MATLAB software so as to resolve the optimization problem and examine the optimal set of stabilizers parameters. The optimization of the PSSs parameters is performed through assessment of the objective function as given in Eq. (16) and the final values of the optimized PSSs parameters using both the proposed ABC algorithm and the genetic algorithm (GA) method (see [24,25] for more details about the problem solution) are shown in Table 1. The convergence rate of the objective function $J$ with the iteration figures is given in Figure 7, from which it is clear that the ABC algorithm seems to perform better compared to the GA. The computation time of the 3-machine 9-bus power system is shown in Table 2. It can be obviously seen that the ABC method takes the least amount of time in its row to finish iterations.

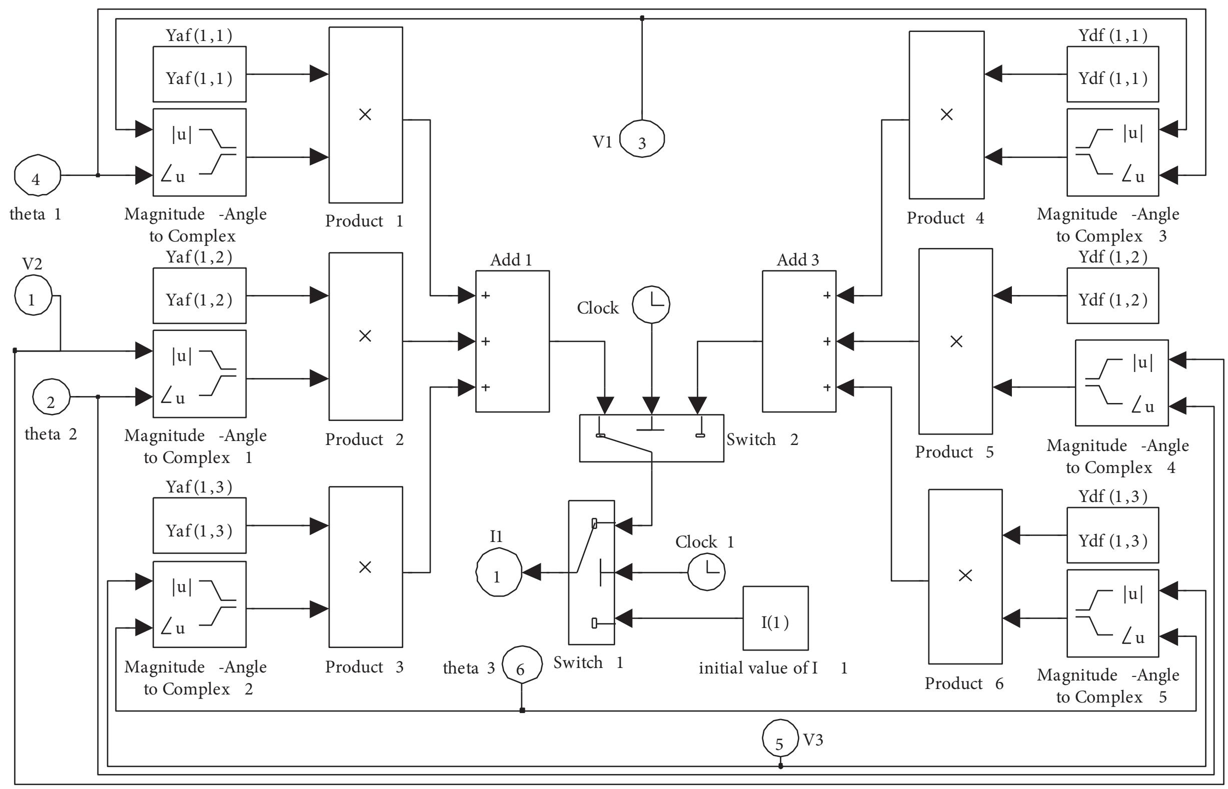


**Figure 4.** Computation of the current output of generator 1.

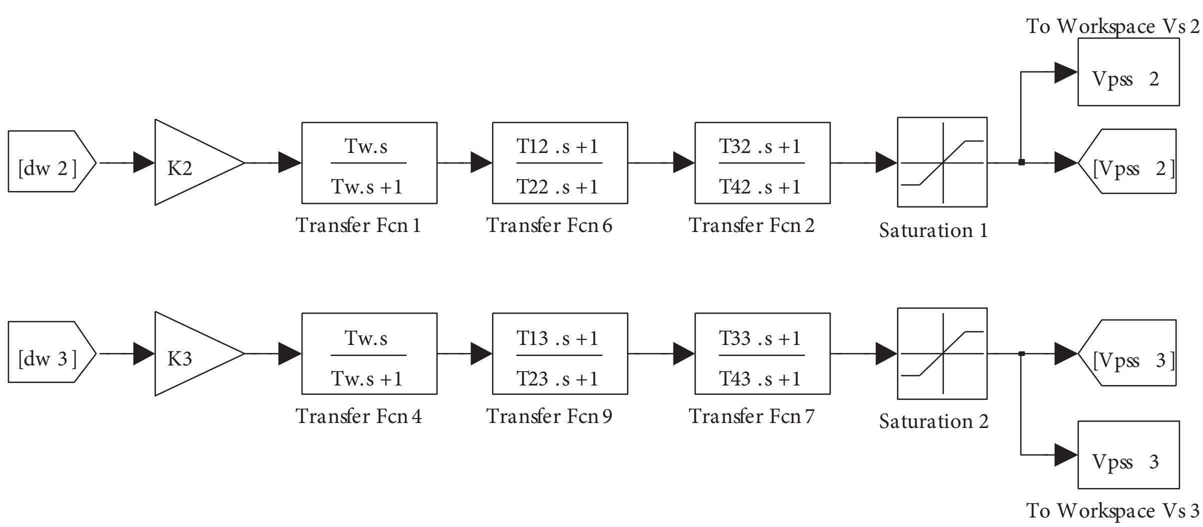


**Figure 5.** SIMULINK model for calculation of the stabilizing signal output of PSSs.

### 5.4. Nonlinear simulation results

In this work, simulation studies are performed for the example power system subjected to a large disturbance in order to show the advantages of modeling the multimachine system with PSSs and tuning their parameters. By applying a 6-cycle 3-phase fault at $t = 1$ s on bus 7 at the end of line 5–7, the performance of the proposed controllers under transient conditions is validated. The fault is removed without line tripping and the original system is restored upon the clearance of the fault.

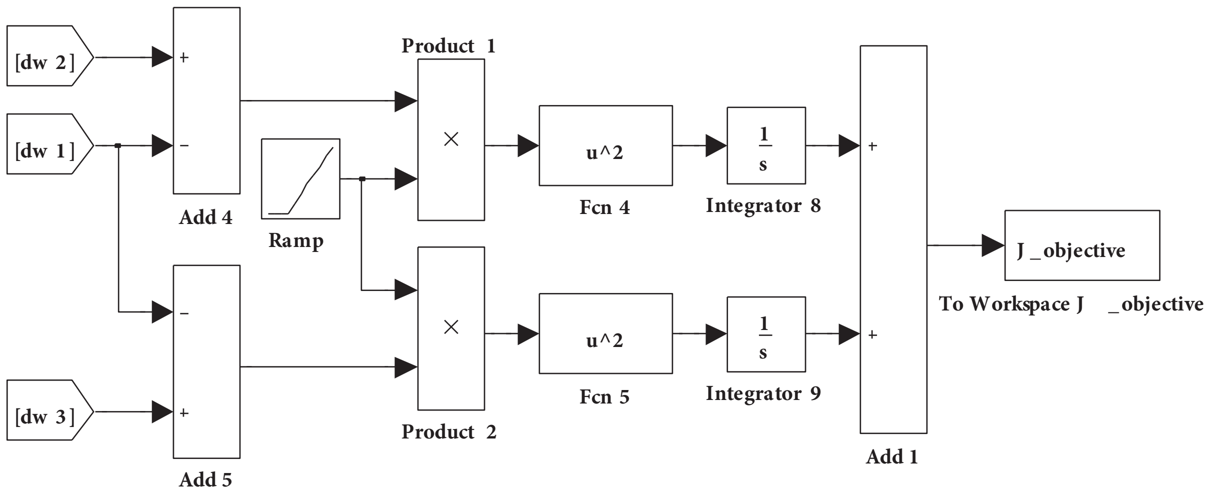


**Figure 6.** SIMULINK model for calculation of the objective function.

**Table 1.** The optimal PSS parameters using ABC and GA algorithms.

| Type of algorithm | Gen. | $K$ | $T_1$ | $T_2$ | $T_3$ | $T_4$ |
|---|---|---|---|---|---|---|
| ABC | $G_2$ | 3.3448 | 0.6516 | 0.0100 | 0.8439 | 0.3623 |
| | $G_3$ | 4.8847 | 0.6372 | 0.0100 | 0.9147 | 1.0000 |
| GA | $G_2$ | 45.6143 | 0.3505 | 0.0725 | 0.3798 | 0.0100 |
| | $G_3$ | 13.1546 | 0.0763 | 0.0100 | 0.6799 | 0.6066 |

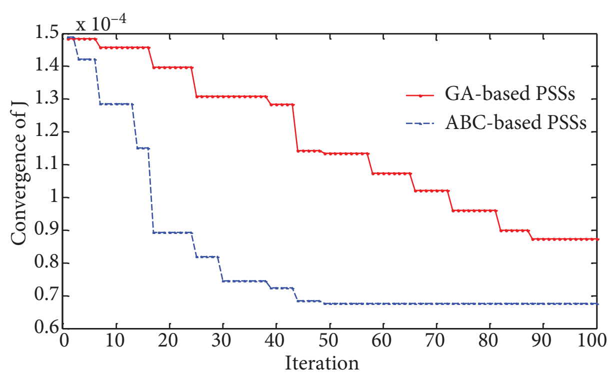


**Figure 7.** Convergence rate of the objective function $J$.

**Table 2.** Computation time for ABC and GA.

| Type of algorithm | ABC | GA |
|---|---|---|
| Time (s) | 3291.85 | 5692.18 |

The system power angle responses of $G_2$ and $G_3$ with respect to $G_1$, $\delta_{21} = \delta_2 - \delta_1$, and $\delta_{31} = \delta_3 - \delta_1$ under this severe disturbance are shown in Figures 8 and 9. The variations of the relative speed deviation of $G_2$ and $G_3$ with respect to $G_1$, $\omega_{21} = \omega_2 - \omega_1$, and $\omega_{31} = \omega_3 - \omega_1$ are depicted in Figures 10 and 11. It is obvious from Figures 8–11 that although the system is stable without a controller, power system oscillations are inadequately damped. Stability of the system is maintained and power system oscillations are effectively suppressed with the application of GA-based PSSs. It is also clear from these figures that, unlike GA-based PSSs, the proposed ABC-based optimized PSSs importantly inhibit the oscillations in the power angles and speeds, and they provide good damping characteristics to low-frequency oscillations through stabilizing the system quicker.

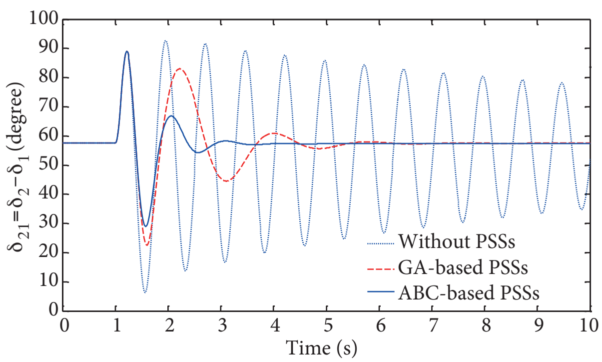


**Figure 8.** Power angle response of $G_2$ with respect to $G_1$.

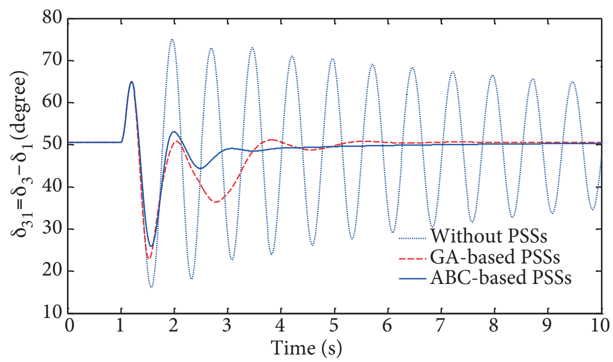


**Figure 9.** Power angle response of $G_3$ with respect to $G_1$.

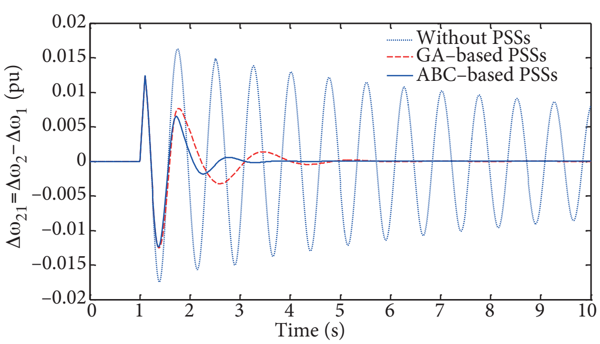


**Figure 10.** Speed deviation response of $G_2$ with respect to $G_1$.

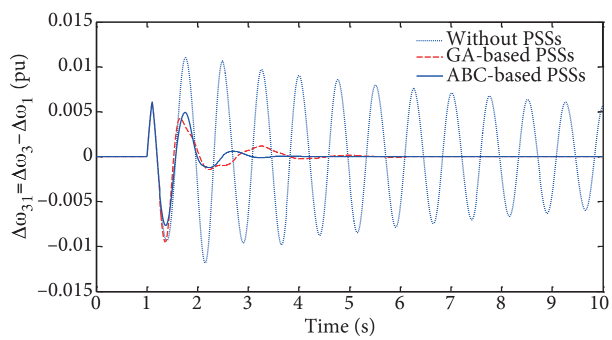


**Figure 11.** Speed deviation response of $G_3$ with respect to $G_1$.

Figures 12–17 show electrical power responses and terminal voltage responses for all generators and respectively all concerning times for the above-mentioned contingency. It is also evident from the figures that the ABC-based PSSs realize good performance and provide superior damping in comparison to the GA-based PSSs.

The nonlinear simulation results indicate the potency of the proposed modeling and tuning approach. As can be seen from Figures 8–17, the proposed PSSs supply good damping characteristics for low-frequency oscillations, as well as significantly improve the power system's dynamic stability under this severe disturbance. Additionally, the figures demonstrate that the proposed ABC-based optimized PSSs yield the desired dynamic performance and outperform the GA-based PSSs through minimizing the transient errors and then swiftly stabilizing the system.

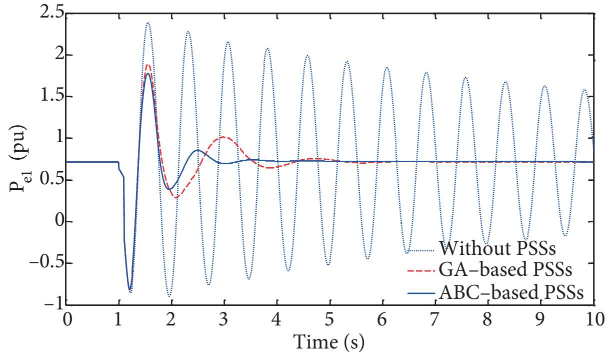


**Figure 12.** Electrical power response of $G_1$.

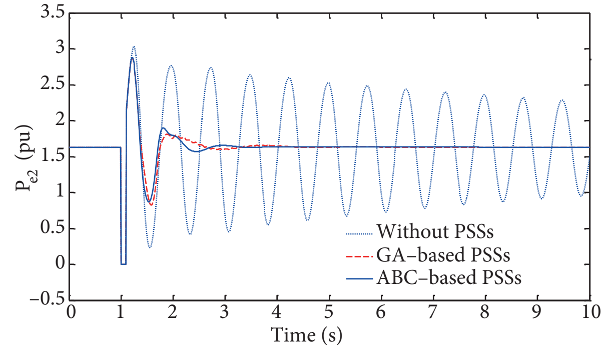


**Figure 13.** Electrical power response of $G_2$.

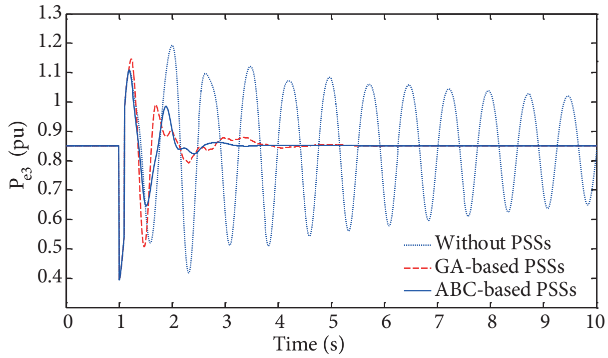


**Figure 14.** Electrical power response of $G_3$.

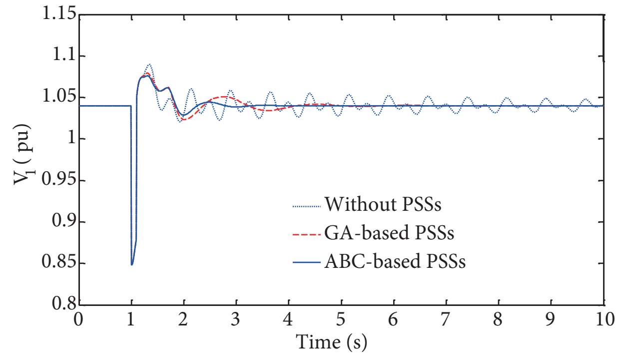


**Figure 15.** Terminal voltage response of $G_1$.

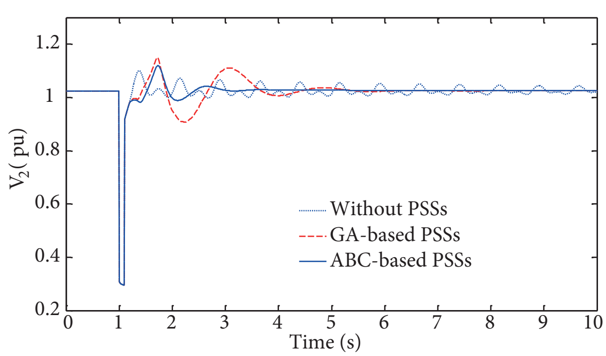


**Figure 16.** Terminal voltage response of $G_2$.

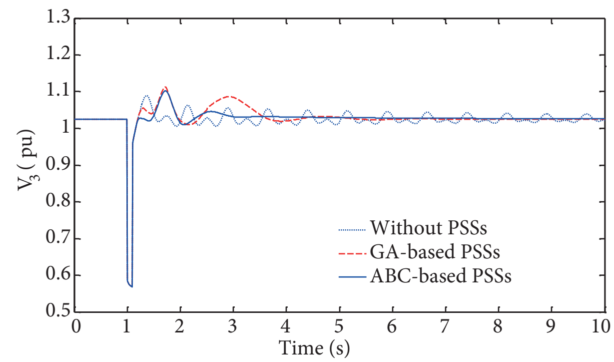


**Figure 17.** Terminal voltage response of $G_3$.

## 6. Conclusion

This paper describes the modeling, simulation, and design of PSSs by employing the ABC optimization technique for transient stability enhancement of a multimachine power system. A comprehensive model for transient stability study of a multimachine power system with PSSs was developed by utilizing MATLAB/Simulink. A Simulink model is user friendly, since it has great interactive capacity and an unrestricted hierarchical model design. Normally, for a transient stability study, the model enables a speedy and exact solution for nonlinear differential-algebraic equations. By means of a proper menu from within Simulink, the user can easily choose or revise the solver type, step sizes, tolerance, simulation period, and output options. For the proposed PSS design problem, a parameter-constrained, time domain-based objective function is designed to enhance the performance of a multimachine power system subjected to a disturbance. Then the ABC algorithm is carried out to examine optimal PSS parameters. The performance of the proposed controllers is tested on the example power system subjected to any severe disturbance. The nonlinear time-domain simulation results indicate the efficacy of the proposed lead-lag type PSSs and their competence to supply good damping of low-frequency oscillations. In addition, the results reveal that the performance of the designed controller is better than the GA-based stabilizer.

## References

[1] Anderson PM, Fouad AA. Power System Control and Stability. Ames, IA, USA: Iowa State University Press, 1977.

[2] Sauer PW, Pai MA. Power System Dynamics and Stability. Upper Saddle River, NJ, USA: Prentice Hall, 1998.

[3] deMello F, Concordia C. Concepts of synchronous machine stability as affected by excitation control. IEEE T Power Ap Syst 1969; 88: 316–329.

[4] Xia D, Heydt GT. Self-tuning controller for generator excitation control. IEEE T Power Ap Syst 1983; 6: 1877–1885.

[5] Cao Y, Jiang L, Cheng S, Chen D, Malik OP, Hope GS. A nonlinear variable structure stabilizer for power system stability. IEEE T Energy Conver 1994; 9: 489–495.

[6] Abido MA, Abdel-Magid YL. A hybrid neuro-fuzzy power system stabilizer for multi-machine power systems. IEEE T Power Syst 1998; 4: 1323–1330.

[7] Arrifano NSD, Oliveira VA, Ramos RA. Design and application of fuzzy PSS for power systems subject to random abrupt variations of the load. In: IEEE American Control Conference; June 30–July 2 2004; Boston, MA, USA. New York, NY, USA: IEEE. pp. 1085–1090.

[8] Hassan LH, Moghavvemi M, Mohamed HAF. Power system stabilization based on artificial intelligent techniques; A review. In: Technical Postgraduates (TECHPOS), 2009 International Conference; 14–15 December 2009; Kuala Lumpur, Malaysia. New York, NY, USA: IEEE. pp. 1–6.

[9] Ravi V, Duraiswamy K. Effective optimization technique for power system stabilization using artificial bee colony. In: Computer Communication and Informatics (ICCCI), 2012 International Conference; 10–12 January 2012; Coimbatore, India. New York, NY, USA: IEEE. pp. 1–6.

[10] Kennedy J, Eberhart RC. Swarm Intelligence. San Francisco, CA, USA: Morgan Kaufmann Publishers, 2001.

[11] Abido MA. Optimal design of power-system stabilizers using particle swarm optimization. IEEE T Energy Conver 2002; 17: 406–413.

[12] Shayeghi H, Shayanfar HA, Safari A, Aghmasheh R. A robust PSSs design using PSO in a multi-machine environment. Energ Convers Manage 2010; 4: 696–702.

[13] Ali ES, Abd-Elazim SM. Coordinated design of PSSs and TCSC via bacterial swarm optimization algorithm in a multimachine power system. Int J Elec Power 2012; 36: 84–92.

[14] Karaboga D, Akay B. A comparative study of artificial bee colony algorithm. Appl Math Comput 2009; 214: 108–132.

[15] Zhang C, Ouyang D, Ning J. An artificial bee colony approach for clustering. Expert Syst Appl 2010; 37: 4761–4767.

[16] The MathWorks Inc. Using Simulink. Version 5. Natick, MA, USA: The MathWorks, 2003.

[17] Dessaint L, Al-Haddad K, Le-Huy H, Sybille G, Brunelle P. A power system tool based on Simulink. IEEE T Ind Electron 1999; 46: 1252–1254.

[18] Aldeen M, Lin L. A new reduced order multi-machine power system stabilizer design. Electr Pow Syst Res 1999; 52: 97–114.

[19] Karaboga D, Basturk B. A powerful and efficient algorithm for numerical function optimization: artificial bee colony (ABC) algorithm. J Global Optim 2007; 39: 459–471.

[20] Omkar SN, Senthilnath J, Khandelwal R, Narayana Naik G, Gopalakrishnan S. Artificial bee colony (ABC) for multi-objective design optimization of composite structures. Appl Soft Comput 2011; 11: 489–499.

[21] Kundur P. Power System Stability and Control. New York, NY, USA: McGraw-Hill, 1994.

[22] Hsu YY, Chen CL. Identification of optimum location for stabilizer applications using participation factors. IEE P-Gener Transm D 1987; 134: 238–244.

[23] Zhou EZ, Malik OP, Hope GS. Theory and method for selection of power system stabilizer location. IEEE T Energy Conver 1991; 6: 170–176.

[24] Coley DA. An Introduction to Genetic Algorithms for Scientists and Engineers. Singapore: World Scientific Press, 1999.

[25] Shayeghi H, Shayanfar HA, Jalilzadeh S, Safari A. TCSC robust damping controller design based on particle swarm optimization for a multi-machine power system. Energ Convers Manage 2010; 51: 1873–1882.