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IMPERIALIST COMPETITIVE ALGORITHM FOR OPTIMAL SIMULTANEOUS COORDINATED TUNING OF DAMPING CONTROLLER

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Abstract- In this paper an evolutionary algorithm named Imperialist Competitive Algorithm (ICA) is employed for simultaneous coordinated tuning of damping controllers for damping the power system low frequency oscillations. ICA is a population-based optimization algorithm inspired by the socio-political process of imperialistic competition. The designing problem is restructured as an optimization problem and a power system stabilizer (PSS) and a supplementary controller for Static Var Compensator (SVC) are designed simultaneously, in 5-area 16-machine system. To show the effectiveness of the designed controllers, the study power system is tested under two conditions: applying a line-to-ground fault at a bus and a three phase fault at a bus. Moreover, the results obtained by the ICA are compared with the previous approaches reported in the literature. The simulation results show that the designed controllers have good capability in damping the power systems low frequency oscillations but the ICA performs better than other algorithms.

Keywords: Imperialist Competitive Algorithm (ICA), Low Frequency Oscillations, PSS, SVC.

I. INTRODUCTION

A broad electromechanical oscillations are inherent phenomena in electric power systems. With the development of extensive power systems, especially with the interconnection of these systems by weak tie-lines, electromechanical oscillations restrict the steady-state power transfer limits and affect operational system economics and security. Therefore, they have become one of the major problems in the power system stability area and have received a great deal of attention. Over the last three decades, there has been extensive research on the stabilization of electromechanical oscillations to enhance system small-signal stability by designing supplemental damping controllers.

To enhance system damping, the generators are equipped with power system stabilizers (PSSs) to damp the generator rotor oscillations by controlling its excitation using auxiliary stabilizing signals. PSSs are supplementary controllers for Flexible AC Transmission System (FACT) devices that augment the power system stability limit and extend the power-transfer capability by enhancing the system damping of low-frequency oscillations in the order of 0.2 to 2.5 Hz [1, 2]. During the past decades, many control strategies applying various techniques based on optimal control, robust control and adaptive control have been proposed and developed by the researchers around the world. The works carried out in [3-8] are examples of such applied techniques. Each of these techniques has their own advantages and disadvantages.

In [4] the optimal control strategies are presented for dealing with low frequency power system oscillations. These controllers are based on state-space approach and require the full data related to the system states, whose measurement or estimation is not simple or might be impossible. Some authors are employed robust control techniques [5, 6] to solve the problem. Although the proposed methods gave good dynamical responses, but robustness in the presence of large modeling uncertainties was not considered and stability of the overall system was not guaranteed. The adaptive control technique are used in [7, 8] to improve power system dynamic stability, but most adaptive controllers are designed on the basis of parameter identification of the system model in real time which results in time consuming and computational burden. Since the 1970s, many meta-heuristic algorithms that combine rules and randomness imitating natural phenomena have been devised to overcome the computational drawbacks of existing numerical algorithms when solving difficult and complex engineering optimization problems.

Recently, there has been a growing interest in meta-heuristic algorithms to find the optimal design of damping controller in a power system by the researches around the world. Evolutionary programming was used to optimal design of PSSs in [9]. The authors in [10] presented an implementation using a genetic algorithm to look for the PSSs parameter. In [11] and [12], the author proposed a solution procedure employing simulated annealing and particle swarm optimization to search for the solution, respectively. Neural network was used in [13], to design PSSs. In [14], fuzzy theory and evolutionary algorithm were used to solve the problem. The authors in [15-17] used different versions of Immune

Algorithm (IA), including binary version of IA (BIA) and real version of IA (RIA) to design PSS or supplementary controller of Static Var Compensator (SVC) to damp oscillations. Furthermore, in [18], the authors suggested a Modified Artificial Immune Network Algorithm (MAINet) and Multi-objective Immune Algorithm (MOIA) to design damping controllers to damp oscillations. In [19, 20], the Shuffled Frog Leaping (SFL) and Artificial Bee Colony (ABC) algorithms are used to find the optimal parameters of PSSs, respectively.

ICA is a population-based optimization algorithm inspired by the socio-political process of imperialistic competition and proven its superior capabilities, such as faster convergence and better global minimum achievement [21]. ICA has been used to solve different kinds of optimization problems, such as PID controller design [22], decentralized PID controller design for MIMO systems [23] and optimal design of power system stabilizers in multi-area power system [24, 25].

In this paper the ability of Imperialist Competitive Algorithm (ICA) investigated for simultaneous coordinated tuning of damping controllers. To illustrate the feasibility and effectiveness of the proposed method, numerical results are presented on a 5-area 16-machine system by designing a PSS for a generator and a supplementary controller for the SVC. For this, the designing problem is restructured as an optimization problem and the ICA is used to solve it. Moreover, the results obtained by the ICA are compared with the MAINet and MOIA approaches reported in the literature.

The paper is organized as follows: to make a proper background, the basic concept of the ICA briefly explained in section II. Section III, described the study system and problem formulation. The design procedures of damping controllers and simulation results in the study system are given in section IV and conclusion is drawn in section V.

II. IMPERIALIST COMPETITIVE ALGORITHM OVERVIEW

A mathematical Imperialist competitive algorithm (ICA) is a new evolutionary optimization algorithm inspired by the socio-political process of imperialistic competition. Compared with the conventional evolutionary optimization algorithms, ICA has proven its superior capabilities, such as faster convergence and better global minimum achievement [21].

Similar to other evolutionary algorithms, this algorithm begins with an initial random population. Each individual of the population is called a *country* and they form an array of variable values. The term *country* in ICA stands for chromosome in GA. In an *n*-dimensional optimization problem, a country is an $1\times n$ array that is defined as:

$$Country = [c_1, c_2, ..., c_n] \quad (1)$$

The related cost of a country is calculated by evaluation of the cost function f_{cost} of the corresponding variables considering the related objective function. Total number of initial countries is set to $N_{country}$. A number of the best countries (countries with the best fitness value) are selected to be the *imperialist* states and the remaining of the initial countries form the colonies of these imperialists. The number of imperialists and their colonies are known as N_{imp} and N_{col} respectively. Based on the imperialists' power, each country is assigned to an empire. To fulfill this aim, the normalized cost (C_n) of an imperialist is defined as:

$$C_n = f_{\cos t}^{(imp,n)} - \max_i (f_{\cos t}^{(imp,i)}) \quad (2)$$

where $f_{\cos t}^{(imp,n)}$ is the cost of the *n*th imperialist. Based on their power or normalized cost, the initial colonies are distributed among empires and for the *n*th empire it will be as follow:

$$NC_n = \text{round}\left(\left| \frac{C_n}{\sum_{i=1}^{N_{imp}} C_i} \right| . N_{col} \right) \quad (3)$$

where NC_n is the initial number of the colonies associated to the *n*th empire which are selected randomly among the colonies. These colonies along with the *n*th imperialist form the *n*th empire.

After creating initial empires, their colonies begin moving toward the relevant imperialist country. This movement is a simple model of assimilation policy that was pursued by some imperialist states [22]. Figure 1 shows this movement in which a colony moves toward the imperialist by a random value that is uniformly distributed between 0 and $\lambda \times d$:

$$\vec{X}_{new} = \vec{X}_{old} + U(0, \lambda \times d) \times \vec{V} \quad (4)$$

where d is the distance between colony and imperialist and λ is a control parameter. $\vec{V}$ is a vector with a unity length that its start point is the previous location of the colony and its direction is toward the imperialist location.

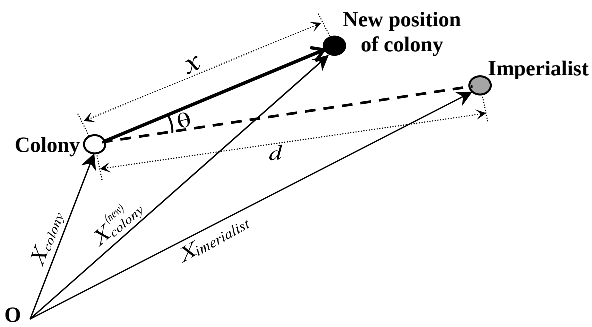

Figure 1. Motion of colonies toward their relevant imperialist

In order to extend the search space around the imperialist, a random amount of deviation, θ is added to the direction of movement as shown in (5):

$$\theta \sim U(-\gamma, \gamma) \quad (5)$$

where γ is an arbitrary number that modifies the random searching area of colonies around the imperialist. In the search based heuristic methods two aspects should be investigated, exploration and exploitation. Exploration deals with searching the solution space while exploitation is able to find optimal solution around the better solutions. For a good performance it is necessary to make a suitable tradeoff between exploration and exploitation.

In ICA, the exploration is controlled by λ and γ. If they are tuned properly, the exploration will be increased and the algorithm avoids the premature convergence. By the above mechanism (Equations (4) and (5)), the diversity of the population is controlled. In other words, the exploration and exploitation of the search space are increased, resulting in avoiding premature convergence and better performance. If this repositioning process produces a colony with better fitness, the imperialist and the colony change their positions and the new location with the lower cost becomes the imperialist.

The power of an imperialist country and its colonies represents the total power of an empire. In this algorithm, the total power of an empire is calculated by the power of imperialist state plus a percentage of the mean power of its colonies as:

$$TC_n = f_{\cos t}^{(imp,n)} + \xi . \frac{\sum_{i=1}^{NC_n} f_{\cos t}^{(col,i)}}{NC_n} \tag{6}$$

where TC_n is the total cost of the nth empire and ζ is a positive number. Similar to (2), the normalized total cost is defined as:

$$NTC_n = TC_n - \max_i (TC_i) \tag{7}$$

where NTC_n is the normalized total cost of the nth empire. Having the normalized total cost, the possession probability of each empire is evaluated by:

$$P_n = \left| \frac{NTC_n}{\sum_{i=1}^{N_{imp}} NTC_i} \right| \tag{8}$$

In imperialistic competition, every empire tries to take possession of colonies of other empires and control them. As a result, a gradually decrease in the power of weaker empires and therefore increase in the power of more powerful ones will happen. This competition is done by picking some (usually one) of the weakest colonies of the weakest empires and making a competition among all empires to possess them (that) colonies. In this competition, each empire will have a likelihood of taking possession of the mentioned colonies, based on their total power. The more powerful an empire, the more likely it will possess these colonies.

Any empire that is not able to succeed in imperialist competition and cannot increase its power (or at least prevent decreasing its power) will be eliminated. The imperialistic competition will gradually result in an increase in the power of great empires and a decrease in the power of weaker ones. The power of weak empires will gradually loose and ultimately they will collapse. In this model implementation where the less powerful empires collapse in the imperialistic competition, the related colonies will be distributed among the other empires. The above procedures cause that all the countries converge to a state in which there exist just one empire in the world and all the other countries are its colonies. The flowchart of the ICA is illustrated in Figure 2. More details can be found in [21-24].

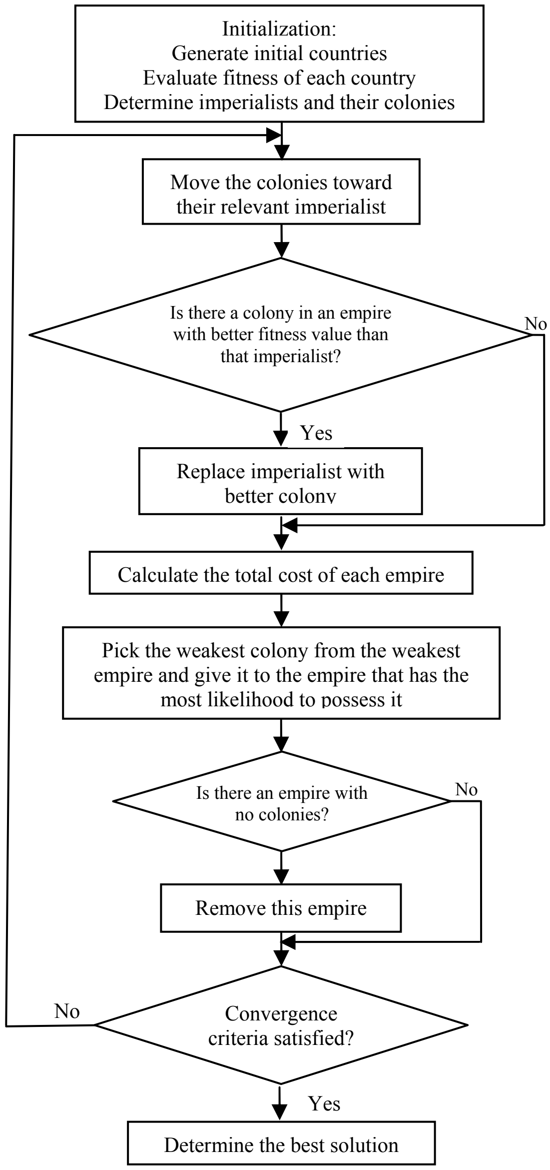

Figure 2. General principle of the ICA

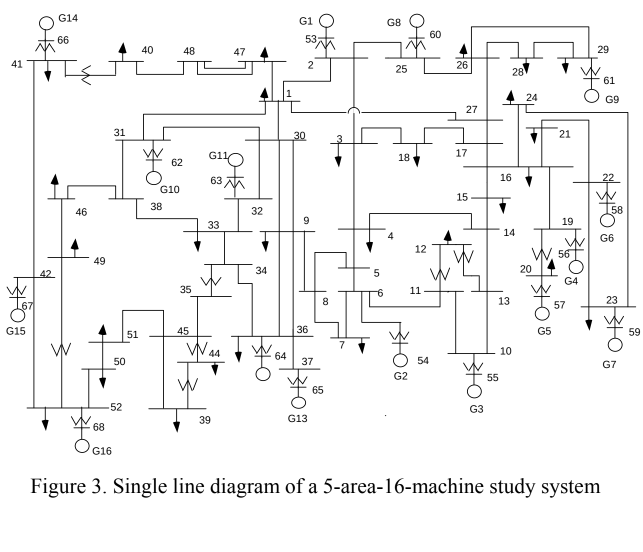

Figure 3. Single line diagram of a 5-area-16-machine study system

III. STUDY SYSTEM AND PROBLEM FORMULATION

A. Study System

A 5-area 16-machine system is considered. This system is illustrated in Figure 3. It consisting of 16 machines and 68 buses for 5 interconnected areas. Area 1 consisted from first nine machines, G1 to G9. Next four machines G10 to G13 represent Area 2 and the last three machines, G14 to G16, are the dynamic equivalents of the three large neighboring areas interconnected to Area 2. The subtransient reactance model for the generators, the first-order simplified model for the excitation systems, and the linear models for the loads and ac network are used. The system data and the concept of the small-signal stability are adopted from [26]. Based on earlier studies in [27], a 546 MVar SVC is placed at bus 1 in the 5-area-16-machine system. The supplementary controller for the SVC and a PSS to be placed in machine 9 are going to be designed.

B. Problem Formulation

The structure shown in Figure 4 is used for both the PSS and the supplementary controller, where the generator speed (GS) is considered as input to the PSS and the input to the supplementary controller is the active power flow in line 1-27.

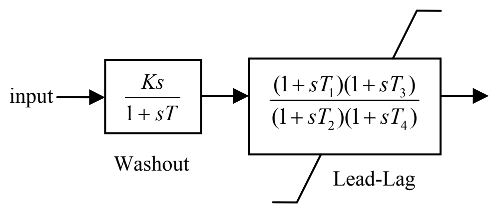

Figure 4. Block diagram for PSS and supplementary controller of SVC

Without damping controllers the study system is unstable. Table 1 shows the damping ratios and electromechanical mode eigenvalues without damping controllers. As can be seen from this table, some of the modes are quite lowly damped and, in some cases, are unstable.

Table 1. Low frequency modes, frequency and damping ratio of the study system without damping controllers

Low frequency modes	Frequency	Damping ratio
-0.4958 ± 7.1190i	1.330	0.064947
-0.5506 ± 6.8714i	1.0936	0.079873
0.1055 ± 3.6544i	0.5816	-0.028857
-0.3357 ± 0.6398i	0.1018	0.464622
-0.3058 ± 0.6643i	0.1057	0.418156
-0.2490 ± 0.6449i	0.1026	0.360190
-0.1957 ± 0. 5545i	0.0882	0.332811
-0.1982 ± 0.5437i	0.0865	0.342492

The control strategy is to choose the best controllers parameters i.e. [k, T, T_1, T_2, T_3, T_4; k, T, T_1, T_2, T_3, T_4] in such a manner that the lightly damped and undamped electromechanical modes of all machines are shifted to a prescribed zone in the left-hand side of s-plane as far as possible. The tuning of the controller parameters for a multi-machine power system is usually formulated as an objective function with constraints consisting of the damping factor and damping ratio. In this paper the suggested approach in [18] is adopted and applied for tuning controller parameters by using ICA.

The parameters to be tuned through the ICA are controller parameters; i.e. [k, T, T_1, T_2, T_3, T_4; k, T, T_1, T_2, T_3, T_4]. In the ICA, each population represents a candidate solution for the problem. Thus, each country is considered as [k, T, T_1, T_2, T_3, T_4; k, T, T_1, T_2, T_3, T_4] which determines the parameters of the controllers. By placing each solution into the study system, related eigenvalues is obtained for the system. For each solution the worst eigenvalue is selected and the corresponding damping ratio (ζ) is calculated.

Now, we define two vectors as follows: $\underline{\xi} = \{\xi_1, \ldots, \xi_N\}$ and $\underline{\sigma} = \{\sigma_1, \ldots, \sigma_N\}$ as those elements are the damping ratio of the worst eigenvalue for each solution and the real parts of the eigenvalues with the damping ratios less than 0.36, respectively. With these two vectors the following objective functions are considered:

$$f_1 = \min_{i \in \{1,\ldots,n\}} (\xi_i) \quad (9)$$

$$f_2 = \min_{i \in \{1,\ldots,n\}} (-\sigma_i) \quad (10)$$

Thus, the optimization problem can be formulated as maximize $\{f_1, f_2\}$. According to these objectives function, the controllers are designed so that the damping ratio of the close-loop system is increased as well as shifting the eigenvalues of the close-loop system to the left hand side of S-plane [28]. In other words, this fitness function will place the system closed-loop eigenvalues in the D-shape sector characterized by $\sigma_i < \sigma_0$ and $\xi_i > \xi_0$ as shown in Figure 5.

To implement the ICA a weighted-sum-approach is used for (9) and (10). The weighted-sum-approach considers the above two objective to a single objective function. Therefore to restrict the system closed-loop eigenvalues in the D-shape sector illustrated in Figure 5, the following objective function is defined:

$$\max F = f_1 + f_2 \quad (11)$$

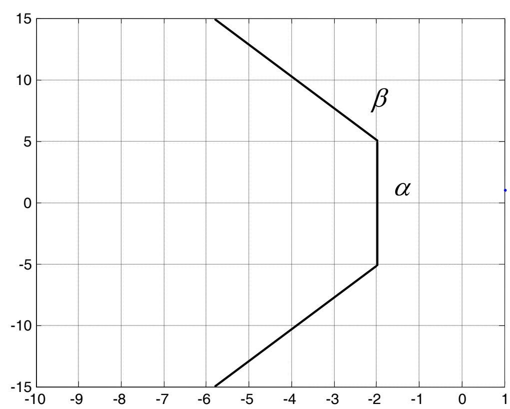

Figure 5. A D-shape sector in the s-plane

IV. DESIGN OF POWER SYSTEM STABILIZER AND SUPPLEMENTARY CONTROLLER FOR SVC

The goal of the optimization is to find the best optimal values for the parameters of PSS and supplementary controller. Thus each country represents a candidate solution for PSS and supplementary controller parameters i.e; $[K,T,T_1,T_2,T_3,T_4;K,T,T_1,T_2,T_3,T_4]$. The principle of the ICA applied in this paper is as given in Figure 2. According to the fitness function defined in (11), the PSS and supplementary controller are designed simultaneously so that the damping ratio of the close-loop system is increased as well as the eigenvalues of the close-loop system are shifted to the left-hand side. The boundary of D-shape sector for eigenvalues (see Figure 5) is chosen as $\alpha_0 = -0.16$ and $\xi_0 = 0.049$, [18, 28]. Also, the design problem can be formulated as the constrained optimization problem, where the constraints are the bounds on the damping controllers parameter. The bounds on the PSS parameters are as follows:

$$\begin{cases} 1 \le K \le 50 \\ 1 \le T \le 10 \\ 0 \le T_i \le 2 \ , \ i = 1,2,3,4 \end{cases} \qquad (12)$$

The bounds on the SVC supplementary controller parameters are the same as the bounds on PSS parameters, except the gain:

$$1 \le K \le 50 \qquad (13)$$

The first step to implement the ICA is generating the initial population (*N* countries), therefore, a set of countries are generated randomly where *N* is set to be 100. The numbers of imperialist states is set to be 5 and thus, 15 colonies will be existed. Since the ICA parameters have significant effect on the quality of the solutions, first the parameters in (4) and (5) must be tuned. These parameters control the exploration and exploitation of the algorithm. Based on the author's previous experience and empirical studies on a number of optimization problems [21-24], the best range of variation is 0.5-2.5 for λ and 0.3-1 (Radian) for γ. In this work, many experiments are performed by changing the range of variation for the coefficients (λ between 0.5-2.5 and γ from 0.3-1 radian) which is found that a value of about 2 for λ and about 0.5 (Radian) for γ result in good convergence of countries to the global minimum.

In ICA, during each generation, the countries are evaluated with some measure of fitness, which is calculated from the objective function defined in (11) subject to (12) and (13), searching for the country associated with F_{best}. Then the 15 first best countries are chosen as imperialist states. In the current problem, the best country is the one that has minimum fitness. Based on Figure 2 the imperialistic competition processes continue until the last iteration is met. In this paper, the number of iteration is set to be 100, which is the stopping criteria used in other methods available in the literature.

To find the best value for the controller parameters, K,T,T_1,T_2,T_3,T_4; the algorithm is run for 10 independent runs under different random seeds. The results obtained from ICA, for K,T,T_1,T_2,T_3,T_4 are shown in Table 2. The other rows of the table show the obtained results by MAINet and MOIA reported in [18].

Table 2. The results obtained by ICA, MAINet and MOIA

Algorithm	*PSSs*	*K*	*T*	T_1	T_2	T_3	T_4
ICA	PSS	33.60	5.838	1.638	0.552	1.735	0.508
	Supp-Controller	10.39	5.665	0.007	0.903	0.115	1.285
MAINet [18]	PSS	18.10	1.833	1.778	1.195	1.737	1.23
	Supp-Controller	27.75	8.862	0.58	1.56	0.03	0.35
MOIA [18]	PSS	25.32	2.3	0.177	0.252	1.238	0.38
	Supp-Controller	29.76	7.35	0.367	0.874	0.93	0.07

Also, Table 3 shows the system close-loop eigenvalue with minimum damping ratio for designed damping controllers by ICA, MAINet and MOIA. It shows that the ICA can move the worst eigenvalue to D-shape sector.

Table 3. The system closed-loop eigenvalues with minimum damping ratio for designed PSS and supplementary controller

	Low frequency mode	Frequency	Damping ratio
Without PSSs	0.01 ± 7.48i	1.2	-0.0013
ICA	-0.185 ± 3.78i	0.601	0.048
MAINet	-0.149 ± 3.31i	0.529	0.045
MOIA	-0.161 ± 3.28i	0.521	0.0493

The obtained PSS and supplementary controller by ICA and those obtained by MAINet and MOIA, are placed in the considered study power system (Figure 3). To show the effectiveness of the designed controller, a time-domain analysis is performed. A line-to-ground fault is applied in one of the tie lines at bus 26. The fault persisted for 70.0 ms. The behavior of the system was evaluated for 20 s. The voltage magnitude at fault bus and machine angles, δ, with respect to a particular machine (machine 13), were computed over the simulation period and shown in Figures 6-9, respectively. These figures show that ICA provides a good damping for the study system. To show the robustness of the designed controllers, a three-phase fault is applied in one of the tie circuits at bus 26. The dynamic behavior of the system was evaluated for 20 s. The voltage magnitude at fault bus and the machine angles, δ, were computed over the simulation period and shown in Figures 10-13, respectively. Again, these responses are similar to the responses in Figures 6-8 for a line-to-ground fault, showing the robustness of the designed controllers.

VI. CONCLUSIONS

In this paper new metaheuristic technique, Imperialist Competitive Algorithm (ICA) is used to design coordinated damping controllers, where the design problem is formulated as an optimization problem. For this, the parameters of the controller are determined by ICA using an eigenvalue-based objective function. To show the effectiveness and robustness of the designed controller, a line-to-ground fault and three phase fault are applied at a bus. The simulation results show the superiority and capability of designed controller by ICA in comparison with those designed by MAINet and MOIA approaches in improving stability of the system.

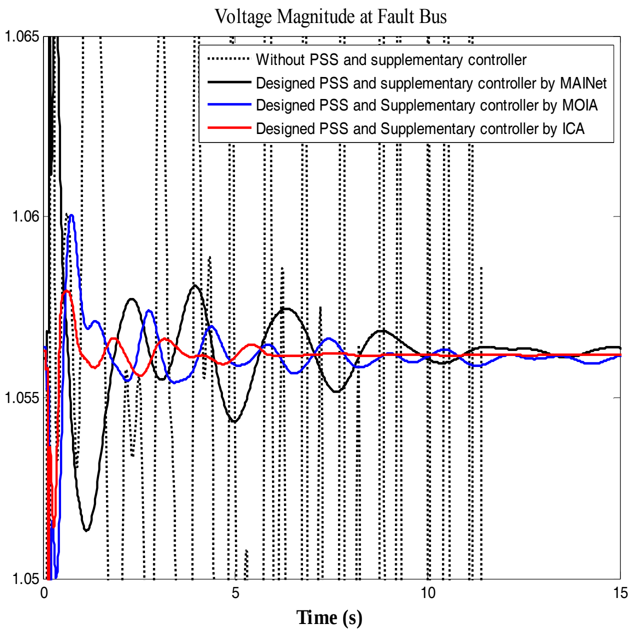

Figure 6. The response of the system to a line-to- ground fault at bus 3

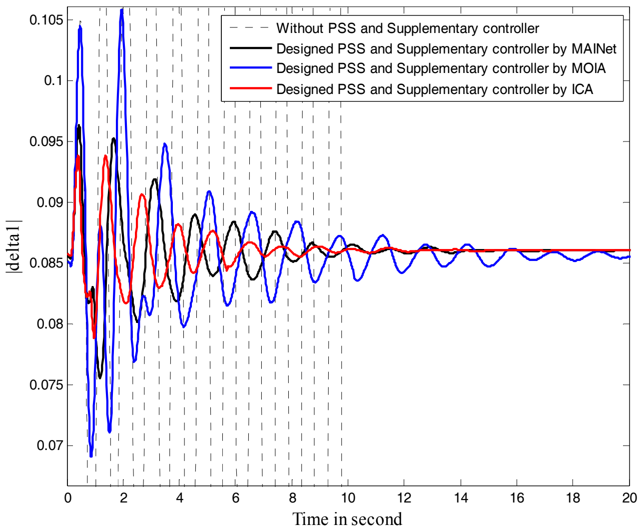

Figure 7. The response of generator 1 to a line–to-ground fault

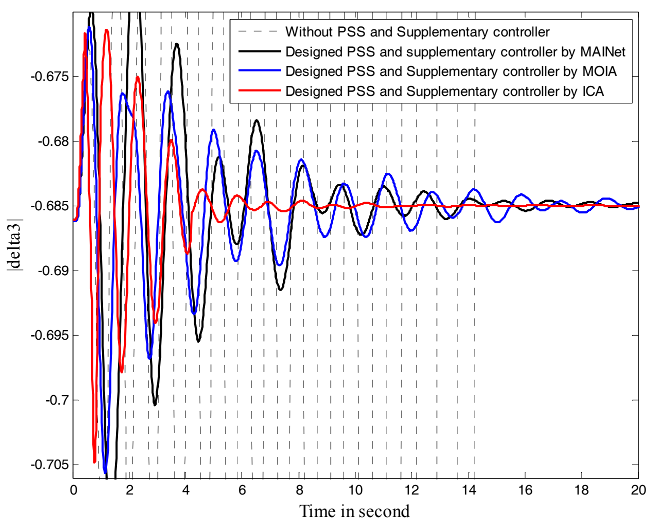

Figure 8. The response of generator 3 to a line-to-ground fault

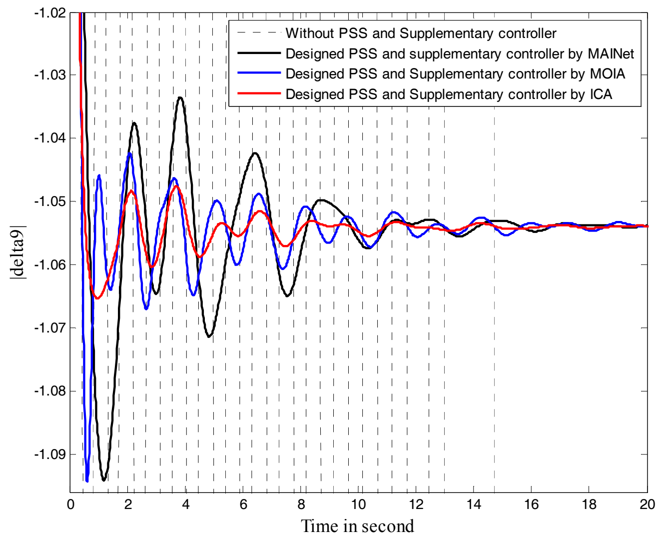

Figure 9. The response of generator 9 to a line-to-ground fault

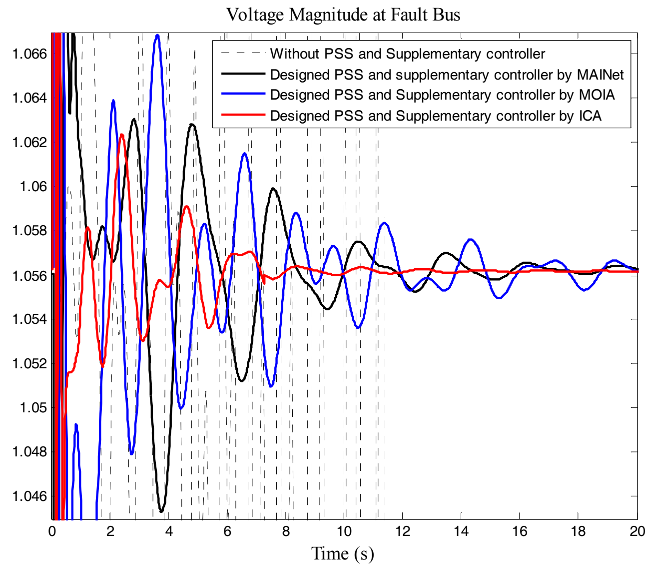

Figure 10. The response of the system to a three-phase fault at bus 3

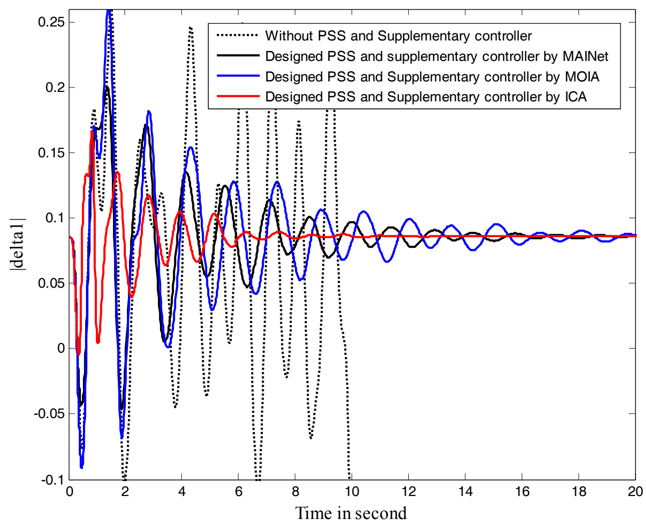

Figure 11. The response of generator 1 to a three-phase fault at bus 26

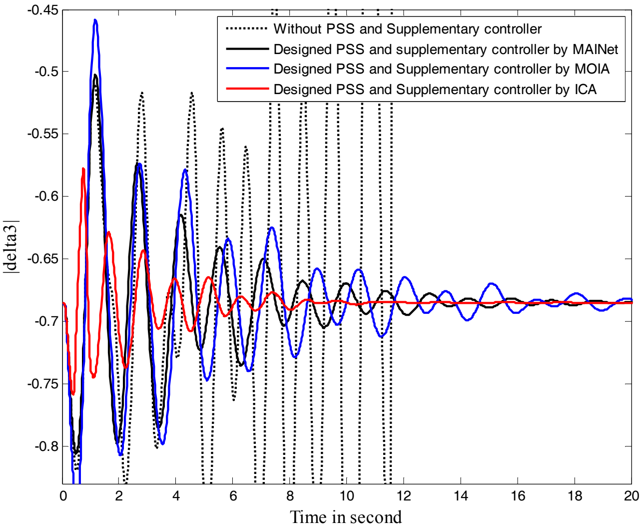

Figure 12. The response of generator 3 to a three-phase fault at bus 26

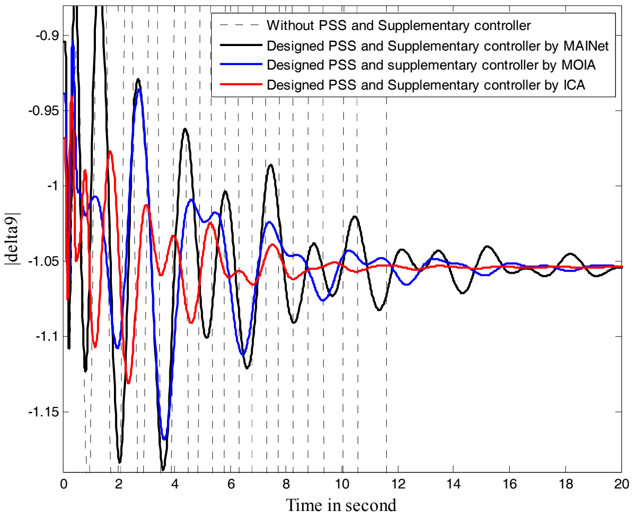

Figure 13. The response of generator 9 to a three-phase fault at bus 26

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