

## Design of optimal multi-objective-based facts component with proportional-integral-derivative controller using swarm optimization approach

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### Abstract

*This study proposes a multi-objective-based swarm intelligence method to improve angle stability. An optimization operation with single objective function only improves the performance of one perspective and ignores the other. The combination of two objective functions which derived from real and imaginary components of eigenvalue are able to provide better performance beyond the optimization capabilities of single objective function. Tested using MATLAB, the simulation is performed using a single machine attached to the infinite bus (SMIB) system equipped with static var compensator (SVC) that attached with PID controller (SVC-PID). The objective of this experiment is to explore the excellent parameters in SVC-PID to produce a more stable system. In addition to the comparison of objective functions, this study also compares particle swarm optimization (PSO) capabilities with evolutionary programming (EP) and artificial immune system (AIS) techniques.*

### Keywords

*Single machine, Static var compensator, Particle swarm optimization, Multi objective function.*

## 1. Introduction

The development of a country depends strongly on the efficiency of its power system. Enhancement of power system stability is very important in maintaining the efficiency of the power system and economy of the country. Angle stability improvement is an important key to consider in maintaining the efficiency of power system as reported in [1–3].

Power systems require very precise control and high flexibility to ensure good system performance. This issue can be realized with the use of Flexible Alternate Current Transmission Systems (FACTS) components. Through shunt and network compensation, FACTS components are able to increase the power network capabilities in terms of controllability and stability.

Among the commonly used FACTS components are static synchronous series compensator (SSSC) [4], thyristor-controlled series capacitor (TCSC) [5], static synchronous compensator (STATCOM) [6] and static VAR compensator (SVC) [7–9].

In one hand, STATCOM and SVC are FACTS devices that provide shunt compensation to transmission lines. On the other hand, SSSC and TCSC provide series compensation to the reactance of the lines that the FACTS components are connected. Among FACTS components, SVC is often the top choice because it provides high accuracy and fast response. This gives SVC the ability to better control the steady state and transient voltage compared to classic shunt compensation. Facts components are also often paired with various controllers to facilitate the system stabilization. Among them are lead-and-lag (LL) [10–12], proportional-and-integral (PI) [13–15] and

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proportional-and-integral-and-derivative (PID) [16–18].

The variables found on the FACTS component and controller need to be tuned to produce the best stability controls. It is very difficult to find the appropriate value if there is more than one variable on one FACTS-and-controller unit. Here, optimization techniques are introduced to find the best tuning for the selected variables. Optimization techniques have become increasingly important and popular in different engineering applications. Some algorithms, such as Gravitational Search Algorithm [19], Firefly [20], Whale Optimization Algorithm [21, 22], Ant Colony Optimization [23], Flower Pollination Algorithm [24, 25], Moth Flame Optimization [26, 27], Bat Algorithm [28, 29], evolutionary programming [30, 31] and Artificial Immune System [32] have gained attention because of their efficiency. These algorithms are inspired from nature with the characteristic of the investigated biological system. These methods are swarm-intelligence based, making them easier to implement and obtain better outcomes. In this paper, swarm-based optimization technique called Particle Swarm Optimization technique [33–35] is chosen.

The objective of this study is to propose a multi-objective-based swarm intelligence method to improve angle stability. During the optimal tuning search process using optimization technique, an appropriate objective function is selected as standard. In this study, the increase in the value of the objective function is in line with the increase in tuning towards

the optimal value and this will result in a more stable system. However, the use of one objective function only improves performance in one perspective and weakens performance in the other. To ensure an improvement in more than one performance, multi objective functions are introduced. In this study, two objective functions are combined to produce a multi objective function (MO).

The remainder of this paper is divided into five sections. Section 2 presents the basic calculation of single-machine-infinite-bus (SMIB) system. Section 3 explain the formulation for multi objective functions. Section 4 provides the explanation of PSO, EP and AIS optimization methods. The results and discussions were explained in Section 5. The conclusions were presented in Section 6.

### 2.Single-machine-infinite-bus system

In this study, SVC was connected with PID controller (SVC-PID) to improve stability for single-machine-infinite-bus (SMIB) system. The for the SMIB-SVC-PID system is shown in *Figure 1* based on Phillips-Heffron block diagram model.

Inside the SVC-PID block, there are SVC and PID elements. Circuit constant,  $K_V$  and time constant,  $T_V$  are constants that found inside SVC element. Meanwhile, there are three PID element involved: proportional gain,  $K_p$ , integral gain,  $K_I$  and derivative gain,  $K_D$ .

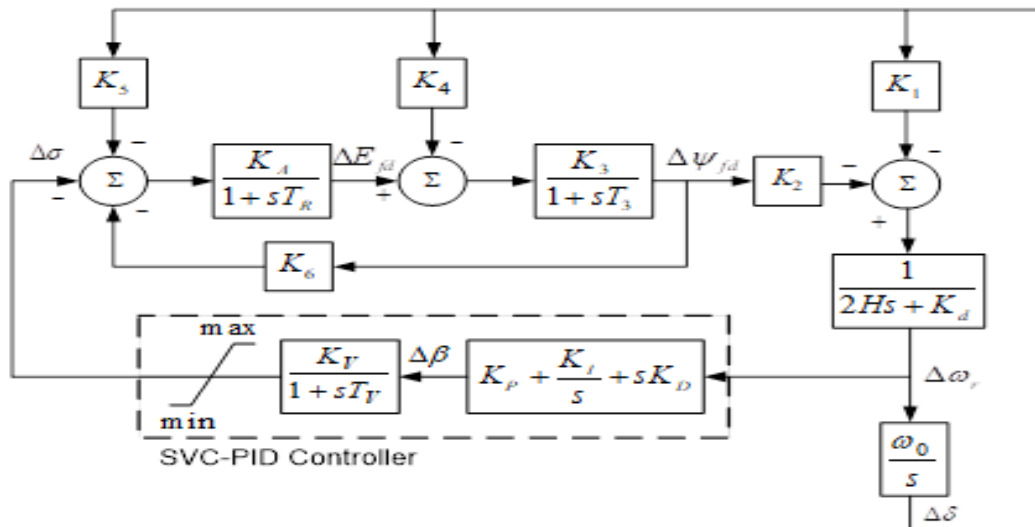


Figure 1 The single-machine-infinite-bus system (Phillips-Heffron perspective)

From Figure 1, the following equations can be derived:

$$\Delta\omega/\Delta t = \Delta T_m - K_1\Delta\delta - K_d\Delta\omega_r - K_2\Delta E_q/2H \tag{1}$$

$$\Delta\delta/\Delta t = \omega_0\Delta\omega_r \tag{2}$$

$$\Delta E_q/\Delta t = -(K_3K_4\Delta\delta + \Delta E_q - K_3\Delta v_f)/T_K \tag{3}$$

$$\begin{aligned} \Delta v_f/\Delta t \\ = -(K_RK_5\Delta\delta + K_RK_6\Delta E_q + \Delta v_f + K_R\Delta\sigma)/T_R \end{aligned} \tag{4}$$

$$\Delta\sigma/\Delta t = K_V\Delta\beta - \Delta\sigma/T_V \tag{5}$$

$$\begin{aligned} \Delta E_q/\Delta t \\ = (K_DK_d/(4H^2) - K_p/(2H))(K_1\Delta\delta + K_d\Delta\omega_r \\ + K_2\Delta E_q) + (K_1 - K_DK_1\omega_0/(2H))\Delta\omega_r \\ + K_2K_D(K_3K_4\Delta\delta + \Delta E_q - K_3\Delta v_f)/(2HT_K) \end{aligned} \tag{6}$$

### 3.Multi-objective functions

The concept of multiple objective functions has been introduced in finding the optimal value of a parameter in a system using optimization techniques. Typically, only a single objective function is used at a time. However, this method only focuses on improving performance capabilities based on only one objective. By using more than one objective function, performance improvement will be seen in more than one perspective, and this is seen as a more comprehensive approach.

In the field of power system stability, performance is often measured based on damping ratio and damping factor. Both of these indicators have a separate impact on the eigenvalue value of a system. In the damping ratio approach, the minimum value of all damping ratio, called the minimum damping ratio  $\xi_{min}$  is used as an indicator. This value is obtained based on the actual and imaginary parts of each eigenvalue.  $\xi_{min}$  can be calculated using the following equation:

$$\xi_{min} = \min\left(-\sigma_i/\sqrt{\sigma_i^2 + \omega_i^2}\right) \tag{7}$$

Here,  $\omega_i$  and  $\sigma_i$  are the imaginary and real part of the  $i^{th}$  eigenvalue, respectively. The correlation of the eigenvalue sectors, pre-optimized and post-optimized  $\xi_{min}$ , on the real-imaginary plane are shown in figure below. As for damping factor, the maximum value of damping factor, or maximum damping factor  $\sigma_{max}$  is used.  $\sigma_{max}$  can be calculated as following:

$$\sigma_{max} = \max(\sigma_i) \tag{8}$$

Figure 3 shows the correlation of the eigenvalue sectors, pre-optimized and post-optimized  $\sigma_{max}$  on the real-imaginary plane.

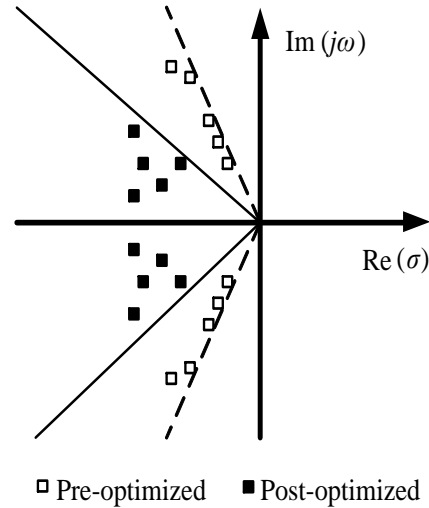


Figure 2 Correlation of eigenvalue sectors (pre-optimized and post-optimized  $\xi_{min}$ )

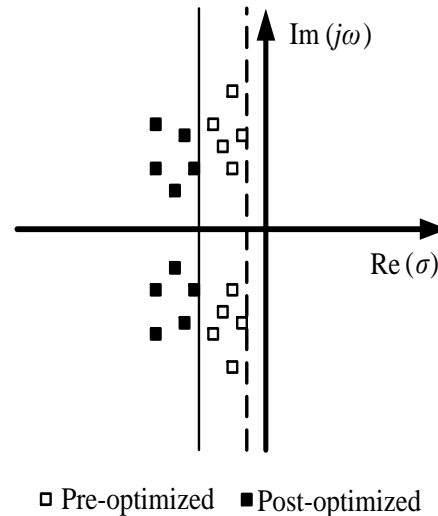
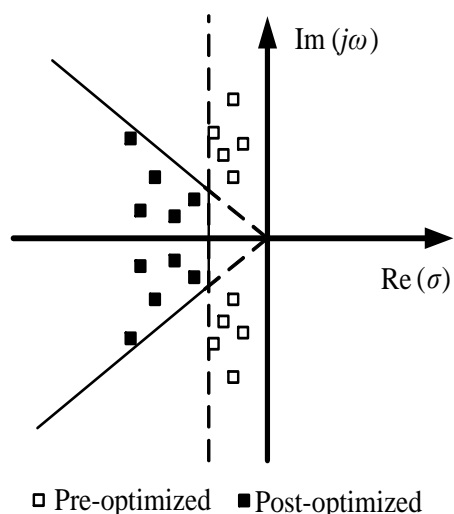


Figure 3 Correlation of eigenvalue sectors (pre-optimized and post-optimized  $\sigma_{max}$ )

If we compare the position of the eigenvalue before and after the implementation of the  $\xi_{min}$  in Figure 2, the eigenvalue sectors will be found to change place, which approaching the real-axis of the real-imaginary plane. Meanwhile, in Figure 3, if the eigenvalue position is compared before and after  $\sigma_{max}$  implementation, the eigenvalue area will be found

moving away from the imaginary-axis of the real-imaginary plane.

With the implementation of multi objective functions (MO) based on both  $\xi_{min}$  and  $\sigma_{max}$ , eigenvalue sectors will approach and move away respectively, from the real-axis and the imaginary-axis of the real-imaginary plane at the same time. The correlation of the eigenvalue sectors, pre-optimized and post-optimized MO on the real-imaginary plane is shown in *Figure 4*. This eigenvalue scattering pattern for post-implementation of MO is almost like a wedge-shaped, tapering from left to right of the complex s-plane.



**Figure 4** Correlation of eigenvalue sectors (pre-optimized and post-optimized MO)

$J_{mo}$  (which is referring to MO) is designated as follows:

$$J_{MO} = K_1 \cdot \xi_{min} + K_2 \cdot \sigma_{max} \quad (0 \leq \alpha_1, \alpha_2 \leq 1) \quad (9)$$

$K_1$  and  $K_2$  are constants that respectively linked to  $\xi_{min}$  and  $\sigma_{max}$ . These constants are applied to tune the combination of both  $\xi_{min}$  and  $\sigma_{max}$  in certain ratio.  $J_{mo}$  can be formulated as:

Maximize ( $J_{mo}$ )

Following limitations have to be followed for SMIB system attached with SVC-PID:

$$\begin{aligned} K_P^{max} &\leq K_P \leq K_P^{min} \\ K_I^{max} &\leq K_I \leq K_I^{min} \\ K_D^{max} &\leq K_D \leq K_D^{min} \end{aligned}$$

#### 4. The optimization techniques

The field of optimization is closely related to science and engineering. Optimization of a design is about minimizing production costs or maximizing production performance. In power systems, the optimal evaluation of parameters for FACTS components is critical to improving system stability. Among the commonly used optimization techniques, there are algorithms inspired by animal herds such as Moth Flame Optimization, Whale Optimization Algorithm and Ant Colony Optimization. This concept is characterized by the ability of these animals foraging in groups. Meanwhile, Genetic Algorithm, Artificial Immune System and Evolutionary Programming are among the optimization approaches inspired by organic systems. The concept adopted by this method is evolution in the face of extinction or when fighting disease. In this study, Particle Swarm Optimization was selected to optimize parameter values on SMIB-SVC-PID.

##### 4.1 Particle swarm optimization (PSO)

R. Eberhart and J. Kennedy were pioneers of PSO technique in 1995. Inspired by the concept of flocking of birds and herding of fish when looking for food, the advantage of PSO is that it has two search features: local and global. With the right balance of these two features has made the PSO successfully find the optimal value at a fast rate. In PSO, the velocity  $v_k$  and position  $p_k$  for  $k^{th}$  particle at  $m^{th}$  iteration is updated according to the following equations:

$$v_{k,m} = \omega \cdot v_{k,m-1} + d_1 \cdot \begin{pmatrix} pb_{k,m-1} \\ -pb_{k,m-1} \end{pmatrix} + d_2 \cdot \begin{pmatrix} pg_{m-1} \\ -pg_{m-1} \end{pmatrix} \quad (10)$$

$$p_{k,m} = v_{k,m} + p_{k,m-1} \quad (11)$$

Here,  $\omega$  is the inertia weight.  $d_1$  and  $d_2$  are the acceleration coefficients.  $pb_{k,m}$  is the personal best position for the  $k^{th}$  particle at  $m^{th}$  iteration.  $pg_m$  is the global best position at  $m^{th}$  iteration. The value of  $d_1$  and  $d_2$  are adjusted manually to achieve better convergence. In this paper, the value of both  $d_1$  and  $d_2$  are random number between (0,1). The flow chart for PSO is illustrated in *Figure 5*. A complete explanation of PSO can be found at [35].

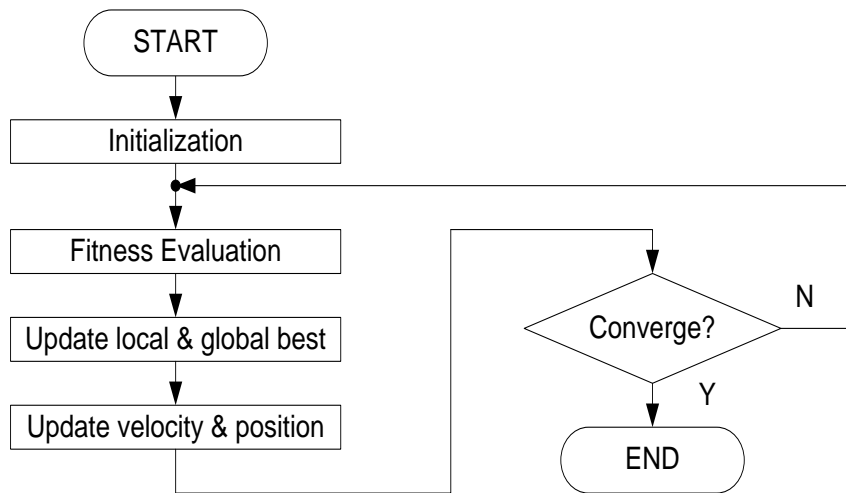


Figure 5 Flowchart for PSO

**4.2 Evolutionary programming (EP)**

EP was developed by Lawrence J. Fogel in 1960. With the concept of the life evolution, every offspring in the EP will go through mutations and selections to find the best offspring among them. The process of mutation of parents to produce offspring is according to the following equation:

$$q_{k,m} = q_{k,m-1} + \gamma \cdot \left( \frac{J_{k,m-1}}{J^m} \right) \cdot \begin{pmatrix} q_{k,m-1}^{max} \\ -q_{k,m-1}^{min} \end{pmatrix} \quad (12)$$

Here,  $q_{k,m}$  and  $J_{k,m}$  are the  $k^{th}$  offspring and the  $k^{th}$  objective function at  $m^{th}$  iteration, respectively.  $q^{max}$  and  $q^{min}$  are the maximum and minimum value of offspring, respectively.  $J^m$  is the latest maximum value of  $J$ .  $\gamma$  which is the search factor, which are random number (0,1). The flow chart for EP is illustrated in Figure 6. Details of EP are described in [31].

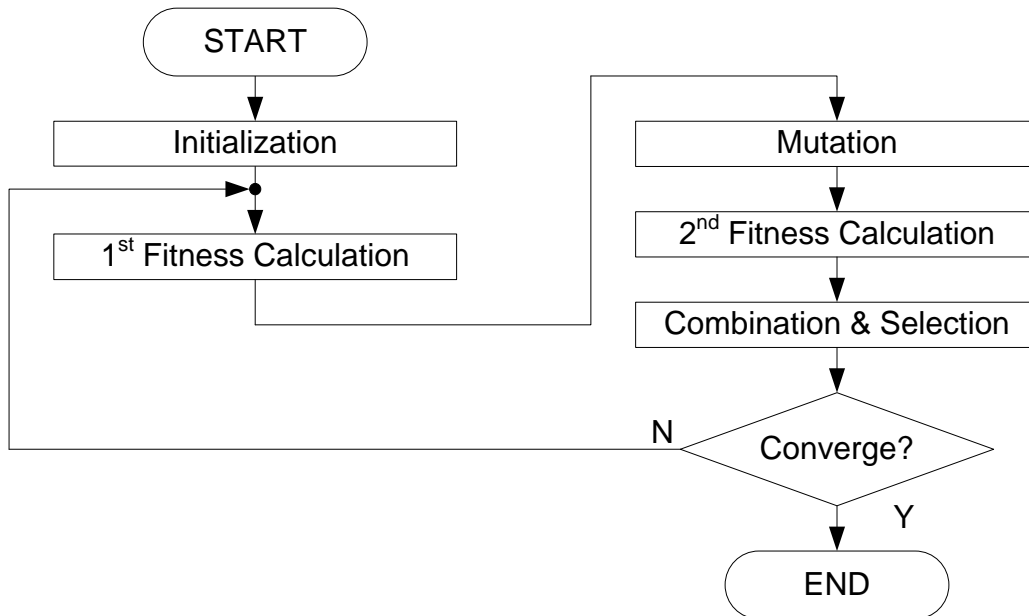
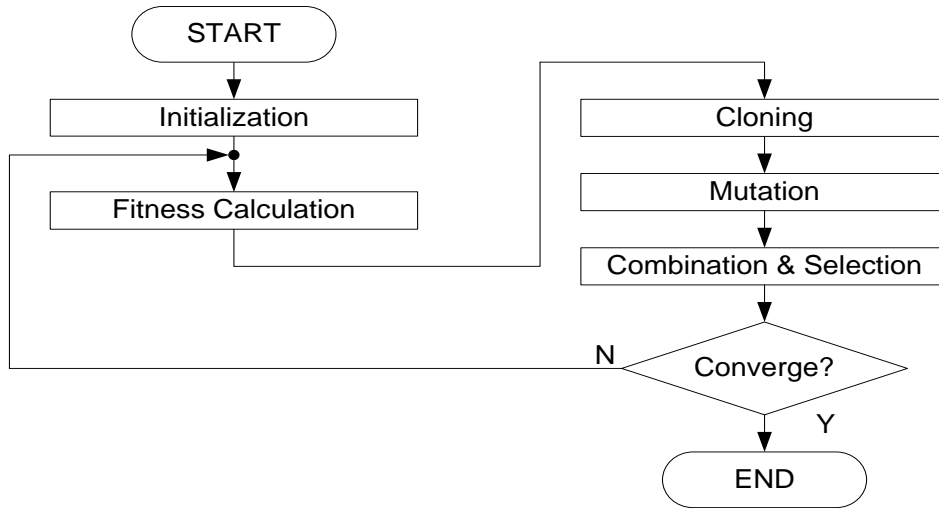


Figure 6 Flowchart for EP

### 4.3 Artificial immune system (AIS)

The AIS algorithm is based on the concept of the human immune system. The characteristics of AIS are almost similar to EP, but there is one difference: cloning. The mutation process in AIS is similar to EP

and also uses equation (12). The flow chart for AIS is illustrated in *Figure 7*. A complete explanation of AIS can be found at [32].



**Figure 7** Flowchart for AIS

### 5. Results and discussion

This section presents the results and discussions of the multi-objective approach for oscillation stability enhancement in SMIB system using various optimization techniques. Three series of cases using MO,  $\zeta_{min}$  and  $\sigma_{max}$  approaches to SMIB system are simulated. All cases were conducted with SVC-PID controller (SMIB-SVC-PID) in MATLAB environment. In this paper, there are seven system conditions were compared as follows:

- (a) System tuned with MO PSO (PSO-MO)
- (b) System tuned by MO EP (EP-MO)
- (c) System tuned by EP with  $\zeta_{min}$  (EP-Zt)
- (d) System tuned by EP with  $\sigma_{max}$  (EP-Sg)
- (e) System tuned with MO AIS (AIS-MO)
- (f) System tuned by AIS with  $\zeta_{min}$  (AIS-Zt)
- (g) System tuned by AIS with  $\sigma_{max}$  (AIS-Sg).

Three cases (Cases A, B and C) with different loading conditions are simulated as tabulated in *Table 1*. All parameter values for SMIB-SVC-PID can be found in [12].

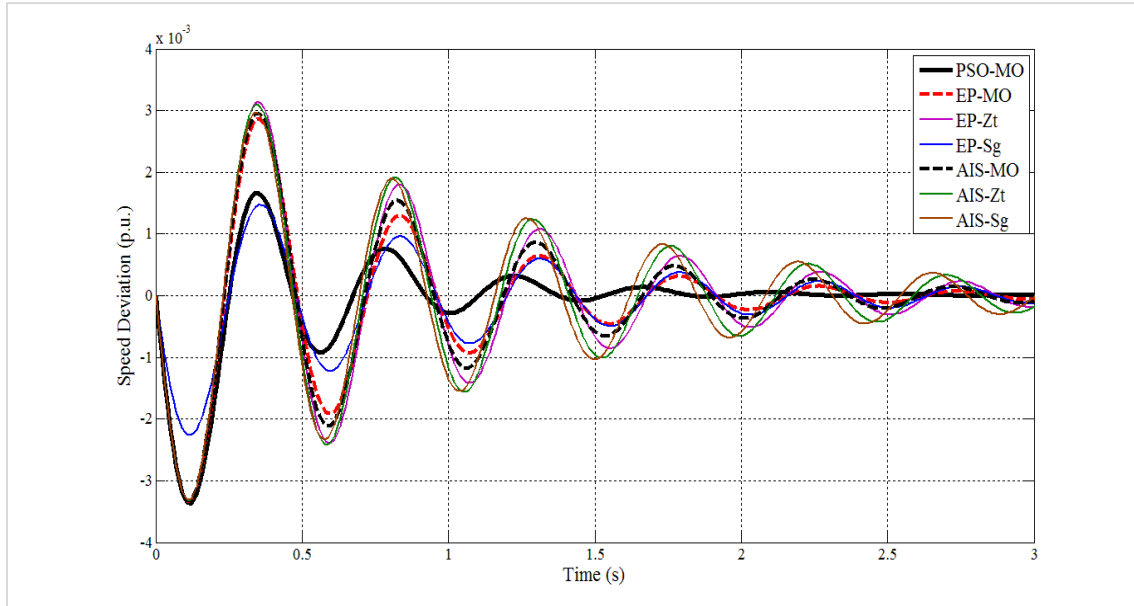
*Figures 8 (a), 8 (b) and 8 (c)* show the speed response, angle-speed plane and the eigenvalues

sectors for Case A, respectively. For speed deviation response, PSO-MO shows the smoothest response and smallest swing compared to other conditions. The system was damped within 2.5 seconds after the simulation is started. EP-MO is at the second place was followed by EP-Zt, EP-Sg and all three series of AIS system. AIS-Sg is at the last position which shows the biggest oscillation of all seven techniques. Except PSO-MO, other techniques take damping time longer than 3 seconds. From this result, for the same optimization technique, the result of the system using MO as objective function is capable to improve better damping capability compared to system with  $\zeta_{min}$  and  $\sigma_{max}$ .

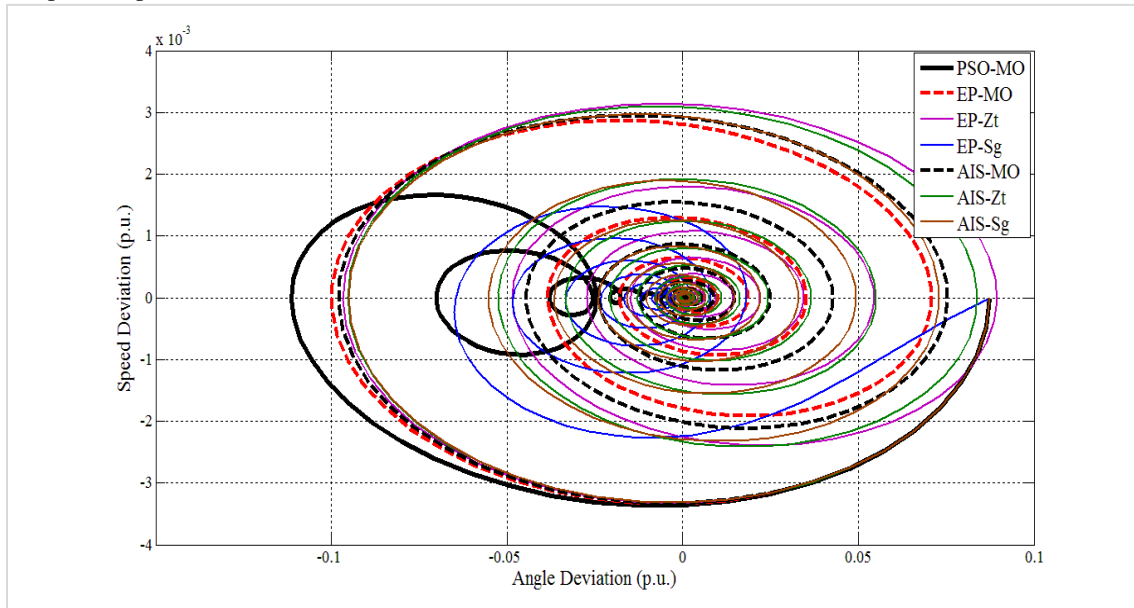
From the result of the phase plane as shown in *Figure 8 (b)*, all approaches give almost the same number of cycles, in the range of 5-6 cycles. Among them, PSO-MO produces phase plan with half the size of other cycle sizes. This result obviously shows that the suggested approach is the best technique to tackle the damping problem compared to the other seven methods.

**Table 1** Active & reactive power (Case A, B & C)

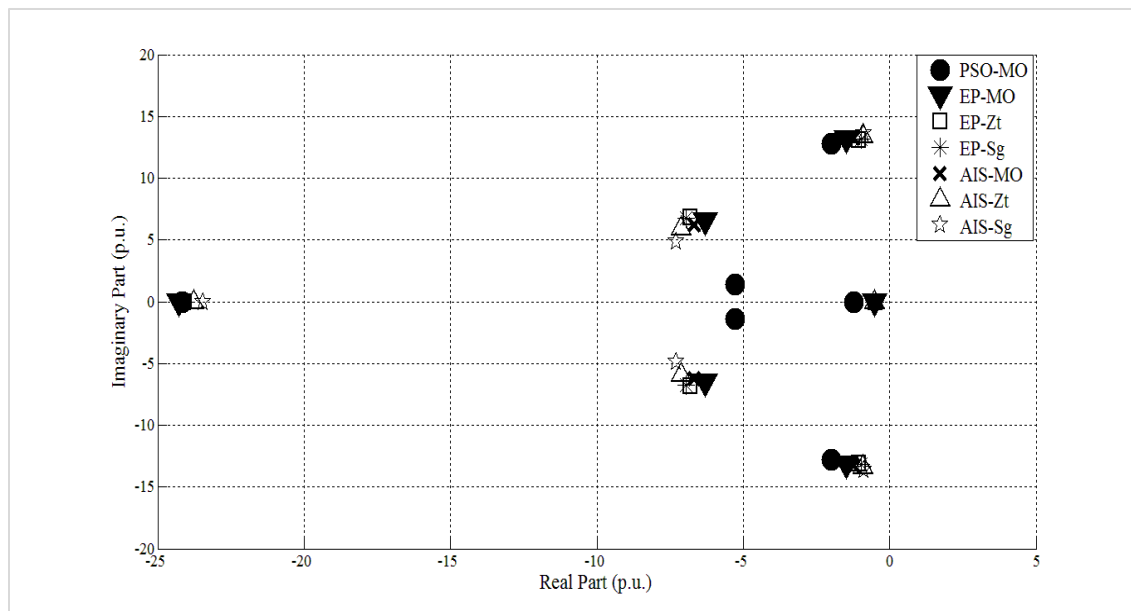
Case	A	B	C
Active power (p.u.)	0.5	0.8	-0.15
Reactive power (p.u.)	-0.35	0.2	0.25



(a) Speed response



(b) Angle-speed plane



(c) Eigenvalues

**Figure 8** Speed response, angle-speed plane and eigenvalue sectors for Case A

Figure 8 (c) shows the eigenvalues sectors for Case A. Overall, all approaches are succeeded to shift the eigenvalue location to the left side of phase plan, signs that all systems are in stable condition. Here, PSO-MO manages to allocate most of the eigenvalue location far to the left side compared to the other six techniques. Except for PSO-MO, the other five techniques mapped one of their eigenvalues at the nearest location to the origin. The coordinates, which are almost at the same location between -0.5595 to -0.4748 on real axis, are considered as less stable condition, compared to PSO-MO which at -1.2164 on real axis. The result of PSO-MO also shows that the eigenvalues sector is shifted to the nearest location towards the real-axis of the real-imaginary plane. Meanwhile, several eigenvalues of all the three AIS systems are located at the most far position from the real axis, justify that these three techniques are the

worst among the rest. As a result, PSO-MO is verified as the best solution for SMIB system stability enhancement.

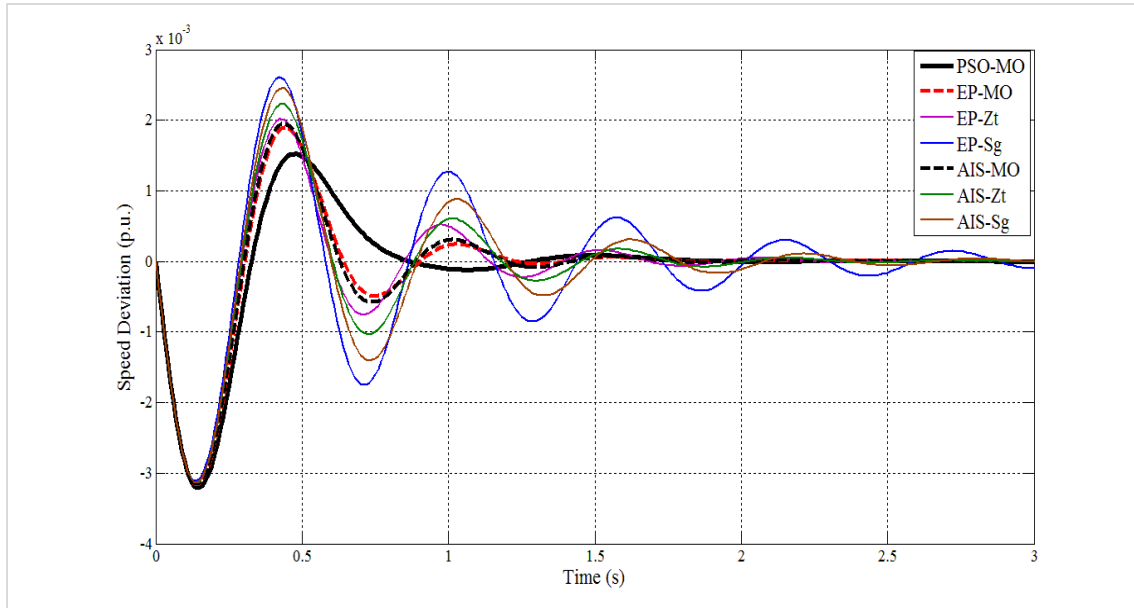
Table 2 tabulates the PID parameters for SMIB-SVC-PID which tuned by all seven conditions for Case A.

The speed response, angle-speed plane and the eigenvalues sectors for Case B are shown in Figure 9 (a), 9 (b) and 9 (c), respectively. The PSO-MO system shows the best performance in terms of give the fastest damping and the smallest swing among seven conditions. EP-MO and AIS-MO are at the second and the third place, respectively. In this case, EP-Sg system shows the worst performance as the speed deviation is not damped completely even the simulation time exceeds 3 seconds.

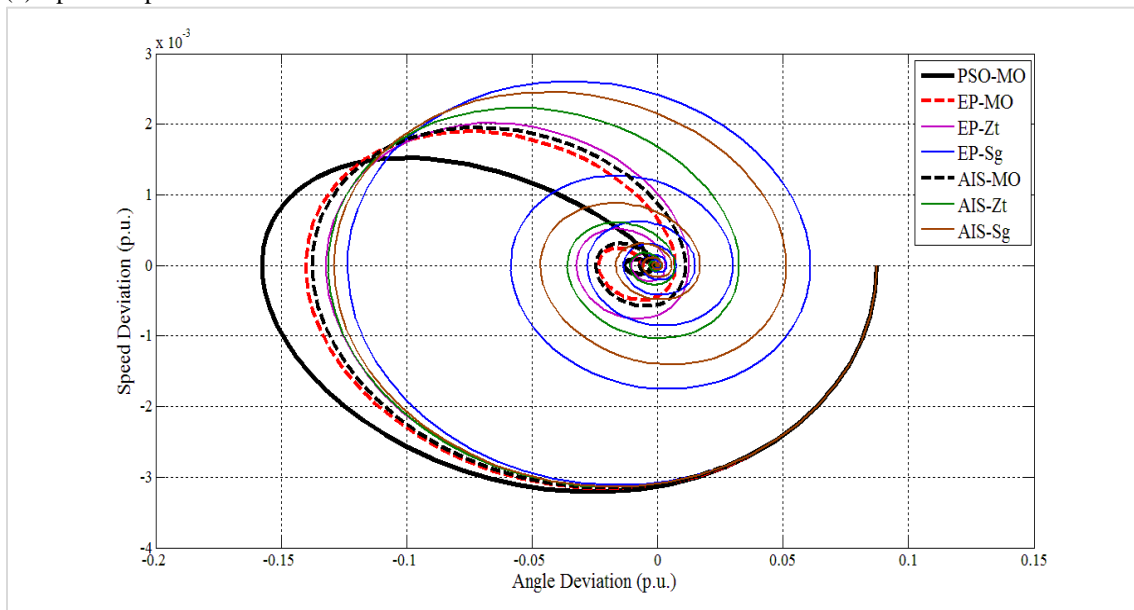
**Table 2** Comparison of PSO, EP & AIS (Case A)

Type	SVC-PID Parameters		
	$K_P$	$K_I$	$K_D$
PSO-MO	0.9091	-0.0091	0.2859
EP-MO	0.7312	0.0092	0.2911
EP-Zt	0.6312	0.0292	0.2875
EP-Sg	0.6010	0.0170	0.3112
AIS-MO	0.6524	0.0119	0.2934
AIS-Zt	0.5524	0.0190	0.2928
AIS-Sg	0.5043	0.0028	0.2931

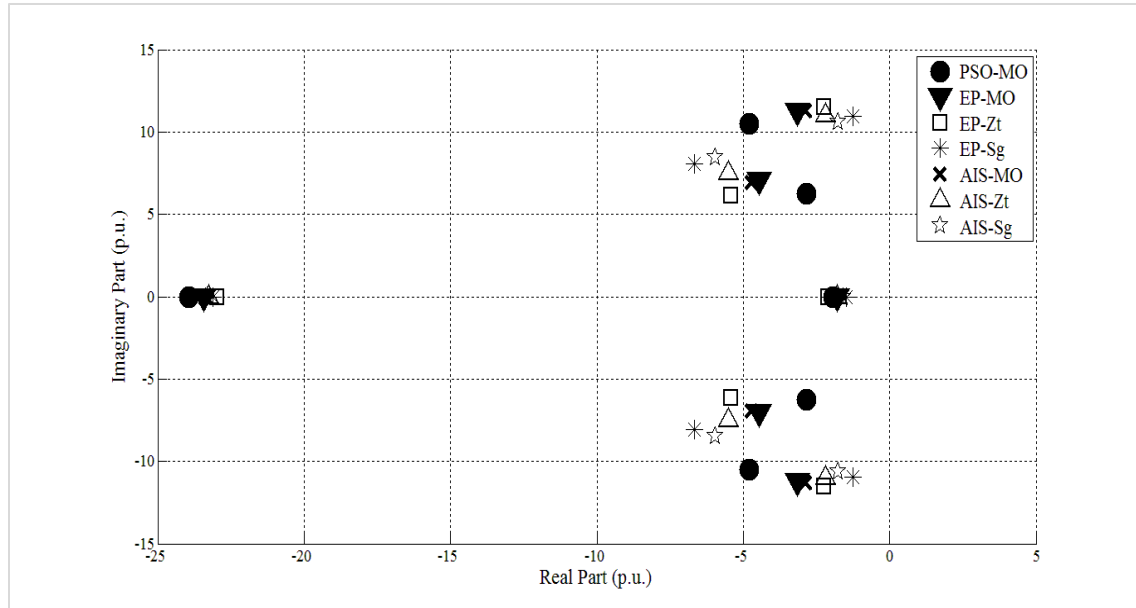




(a) Speed response



(b) Angle-speed plane



(c) Eigenvalues

**Figure 9** Speed response, angle-speed plane and eigenvalue sectors for Case B

For the phase plane response for Case B as shown in *Figure 9 (b)*, PSO-MO, EP-MO and AIS-MO system stopped oscillate in just 2 cycles, with PSO-MO gives the smallest circle size compared to other approach. In other hand, both EP-Sg and AIS-Sg system oscillate over more than 5 cycles.

*Figure 9 (c)* shows the eigenvalues sectors for Case B. From the result, the eigenvalues location of the proposed system is located at the most far to the left-hand side, and at the nearest positions towards the real axis of the plane. It follows by EP-MO and AIS-MO for second and third best eigenvalue region. Compared to other systems, the eigenvalue location of EP-Sg and AIS-Sg are scattered at the nearest position from the imaginary-axis of the plane. This indicates that all three MO based approaches are more capable in improving the stability condition of

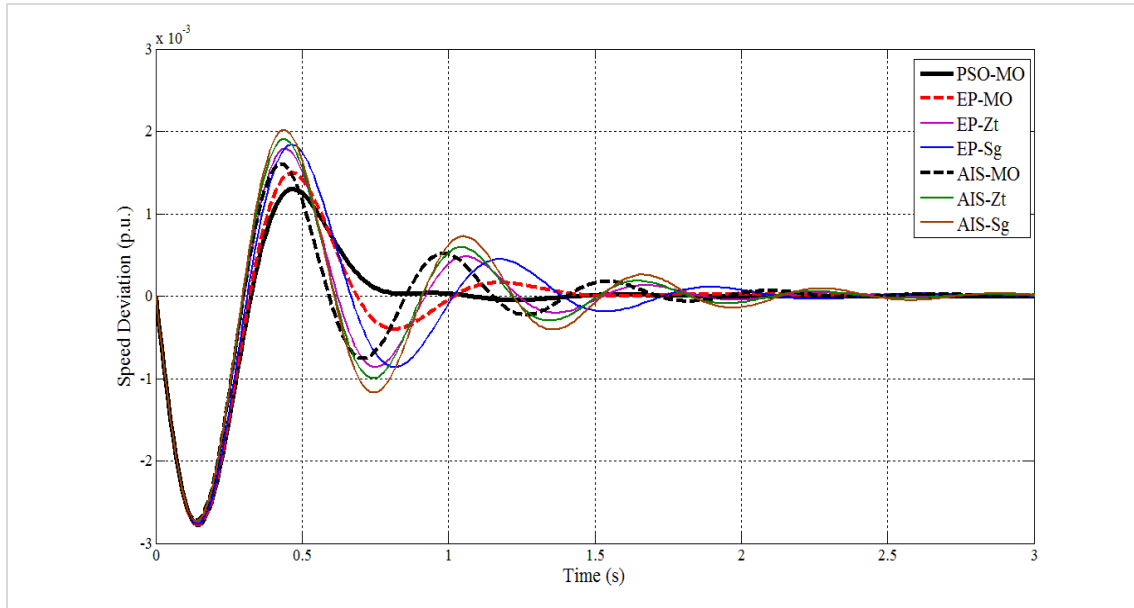
SMIB system compared to  $\zeta_{min}$  and  $\sigma_{max}$  based systems. *Table 3* tabulates the PID parameters that optimized by all seven systems for Case B.

The results of Case C are shown in *Figure 10*. In Case C, almost similar results to Case A and Case B are received. All three cases approve that all three MO based systems outperformed  $\zeta_{min}$  and  $\sigma_{max}$  system in terms improving the stability of SMIB system with the smallest oscillation and the fastest damping. Among MO based approaches, PSO-MO shows the most prominent results compared to EP-MO and AIS-MO.

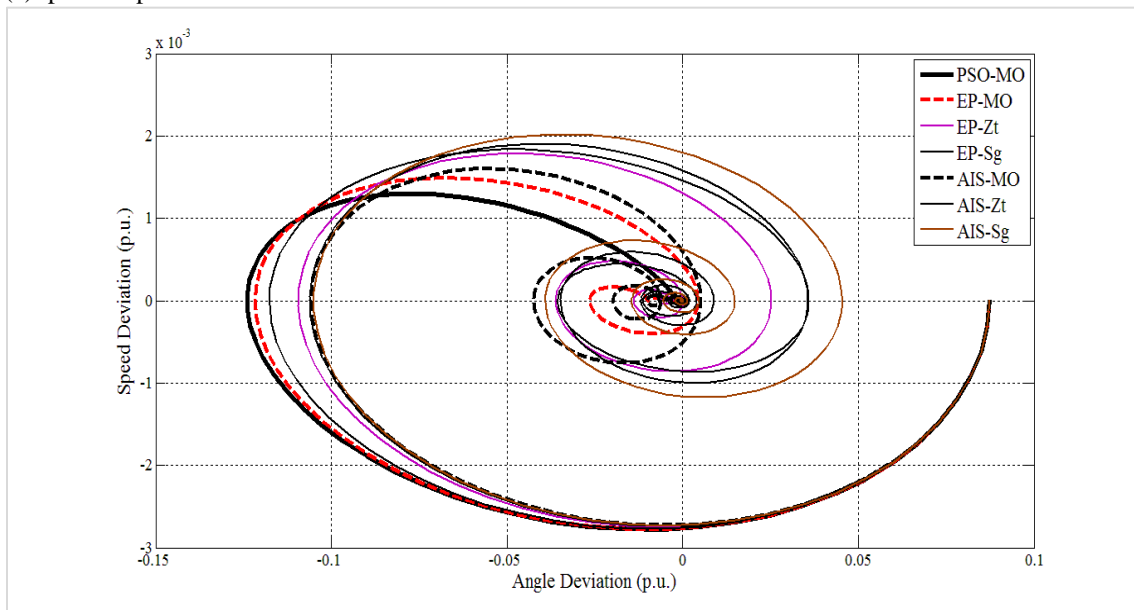
*Table 4* tabulates the value of optimized PID parameters for SVC-PID by all seven systems for Case C.

**Table 3** Comparison of PSO, EP & AIS (Case B)

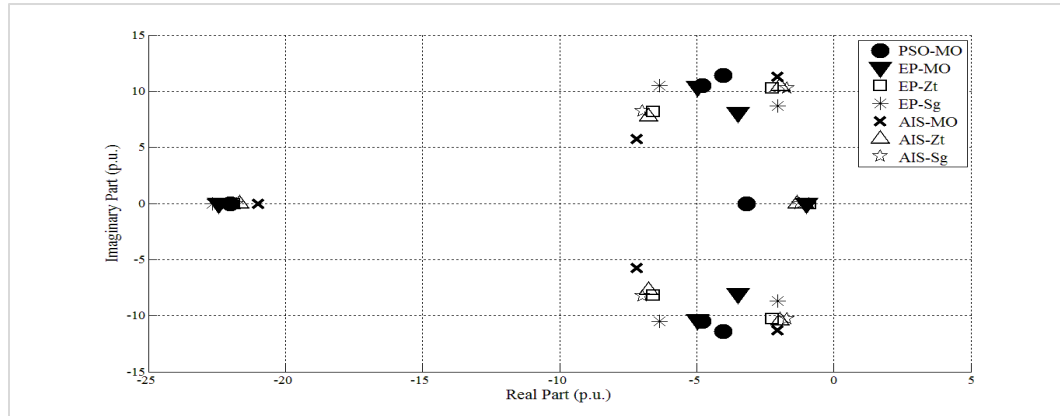
Type	SVC-PID Parameters		
	$K_p$	$K_I$	$K_D$
PSO-MO	0.7450	-0.1091	0.2350
EP-MO	0.6154	-0.0829	0.2564
EP-Zt	0.5312	-0.0692	0.2911
EP-Sg	0.4910	-0.0421	0.2931
AIS-MO	0.5946	-0.0752	0.2759
AIS-Zt	0.5429	-0.0589	0.2934
AIS-Sg	0.5533	-0.0511	0.3010



(a)Speed response



(b)Angle-speed plane



(c) Eigenvalues

**Figure 10** Speed response, angle-speed plane and eigenvalue sectors for Case C

**Table 4** Comparison of PSO, EP & AIS (Case C)

Type	SVC-PID Parameters		
	$K_p$	$K_I$	$K_D$
PSO-MO	0.7946	-0.0875	0.3759
EP-MO	0.8062	-0.1388	0.1986
EP-Zt	0.6053	-0.1006	0.1999
EP-Sg	0.8143	-0.0915	0.2109
AIS-MO	0.4489	-0.1325	0.1906
AIS-Zt	0.5524	-0.0588	0.2913
AIS-Sg	0.5643	-0.0439	0.3123

### 6. Conclusion and future work

This study proposes a multi-objective (MO) based swarm intelligence technique to improve angle stability. This multi-objective function is able to provide better performance beyond the optimization capabilities of one objective function. The weakness of single indicator (either  $\xi_{min}$  or  $\sigma_{max}$ ) as objective function compared to MO is proved in all three cases tested in MATLAB. Also from the cases simulated, PSO-MO technique is more prominent in searching the preferable PID parameters compared to EP and AIS method that use either MO or  $\xi_{min}$  or  $\sigma_{max}$  approach. For future studies, this proposed technique can be introduced to multi-machine systems to determine the impact on the stability of the power system.

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#### Conflicts of interest

The authors have no conflicts of interest to declare.

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