Optimization based Design of Dual Input PSS for Improving Small Signal Stability of Power System with RESs

by Awan Uji Krismanto

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Abstract: This paper proposes a method to enhance the small signal stability performance of power system considering high RESs penetration. A hybrid differential evolution-particle swarm optimization (DE-PSO) is used to design and tune DIPSS parameters. Eigenvalue, damping performance, and time domain simulation are thoroughly investigated to analyze the system performance using DIPSS based on hybrid DE-PSO and find how much RESs penetration level can be considered. From the simulation results, it is found that by utilizing DIPSS based on hybrid DE-PSO can enhance the small signal stability performance of power system with significant penetration of RESs.

Keywords: Dual input power system stabilizer, metaheuristic algorithm, power system stability, renewable energy sources

1. Introduction

The majority of the world population believes that climate change is the most serious challenges in the 21st century. To prevent the climate change due to the global warming reducing fossil fuel application on electricity sector is crucial. Hence, deployment of Renewable Energy Sources (RESs) for generating electricity is one of the solutions to reducing global warming contribution by electricity sector, which is considered as the major sector of GHG in many developed and developing countries.

Among numerous type of RESs, wind and PV are the most promising resources as they are free, abundance, and its delivery at no cost. RES uses relatively new technologies for converting natural energy to electrical energy. Electrical energy from the RES is highly intermittent. The biggest challenge is how to integrate intermittent renewable energy technologies into the existing system and make the entire power grid secured and reliable [1]. Another major issue with these technologies is the application of power electronic components for energy conversion. These components could potentially contribute to the system instability especially small signal stability as the entire RESs comes with different dynamic characteristic [2, 3].

The significant impact of wind energy conversion (WECS) and PV in small signal stability has been reported in previous research [2-5]. It is noticeable that integrating WECS potentially enhance and deteriorate the small signal stability performance of the power system. Furthermore, integration of large-scale PV plant into existing grid might potentially decreasing the damping performance of the system. Hence additional controller such as power system stabilizer can be used as alternative solutions to add damping and improve the small signal stability [6].
However, with increasing number of new renewable types of power plants, the complexity level of the system is gradually increasing. Some of the oscillation modes are not only electromechanical from traditional synchronous machine but also others modes from newly introduced wind and PV power plants. Therefore, conventional PSS is not sufficient to ensure

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stable operation of the power system with high penetration of RES based power generation. To enhance the system oscillatory stability performance, a dual input power system stabilizer (DIPSS) can be considered to address the problem created by the RES. However, having a continuously increasing proportion of RESs would make the system more complicated and vulnerable to instability. As a consequence, it is difficult to obtain the optimum gain setting of DIPSS considering various operational challenges and conditions using the conventional method. Therefore, the nature-inspired algorithm can be used to design and tune the DIPPS parameter as they proven to get better results and easy implementation.

There are numerous types of nature inspired-algorithm developed and deployed in the last few decades. Those types are firefly algorithm, ant colony optimization, harmony search algorithm, particle swarm optimization and differential evolution [7]. Among them particle swarm (PSO) and differential evolution (DE) are becoming more popular due to a simple concept, easy implementation, fast calculation, efficient memory utilization than other algorithms [8, 9].

The application of those algorithms is to design and tune the parameter of PSS as reported in [10-12]. However, very scant attention has been paid to consider high penetration of PV and WECS as well as the dynamic behaviour of PV and WECS for designing PSS. It is reported that PSO has disadvantages on the process such as tend to convergence in local optima. Moreover, DE is also has shortcoming in the mutation process [13, 14]. Hence, the main contribution of this paper can be stated as follows:

1. Investigation of the impact of synchronous generator displacement with large-scale PV plant and WECS on damping performance of low frequency oscillation.
2. Designing of a dual input of PSS considering displacement of synchronous generator with large-scale PV plant and WECS.
3. Utilization of a hybrid DE-PSO to design dual input PSS for overcoming the disadvantages of PSO and DE in individually using them.
4. Examination of RESs penetration due to dual input PSS based on hybrid DE-PSO in power system.

The rest of the paper is organized as follows: Section II provides, a dynamic model of large-scale PV plant, WECS, DIPSS, power system and fundamental theory of small signal stability. Section III briefly explain PSO, DE, hybrid DE-PSO and designing DIPSS based on hybrid DE-PSO. Eigenvalue analysis, and time domain simulation are presented in section IV. Section V highlights the contributions, conclusions and future direction of the research.

2. Fundamental Theory

A. PV Plant Model

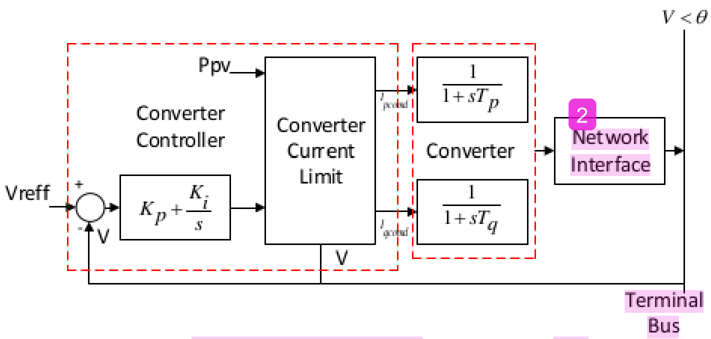


Figure 1. Dynamic model of large-scale PV.

B. Wind Energy Conversion System Model

This research considers WECS based on permanent magnet synchronous generator (PMSG). It system consists of wind turbine, rotor, and grid side converter as well as the controller and

PMSG. Small signal model of WECS can be presented by a mathematical equation as given by (1)-(5) [17]. The detailed model of WECS based on PMSG can be found in [17]. While Figure. 2 illustrates the electrical scheme of WECS based on PMSG.

$$\frac{d\omega_g}{dt} = \frac{\tau_e - \tau_{w\_g}}{J_{eq}} - \frac{B_m}{J_{eq}}\omega_g \tag{1}$$

$$\frac{di_d}{dt} = \frac{1}{L_{ds}+L_{is}}\left(-R_s i_d + \omega_e\left(L_{qs} + L_{is}\right)i_q + u_d\right) \tag{2}$$

$$\frac{di_q}{dt} = \frac{1}{L_{qs}+L_{is}}\left(-R_s i_q + \omega_e\left[\left(L_{ds} + L_{is}\right)i_q + \psi_f\right] + u_d\right) \tag{3}$$

$$\omega_e = p\omega_g \tag{4}$$

$$\tau_e = 1.5p\left(\left(L_{ds} + L_{is}\right)i_d i_q + i_q \psi_f\right) \tag{5}$$

Where ω_g is mechanical angular speed of generator and B_m corresponds to damping coefficient. τ_{w_g} represents aerodynamic torque. While τ_e, and J_{eq} are electromechanical torque and equivalent inertia, respectively. Generator parameters corresponding to stator resistance (R_s), leakage inductances (L_{id},L_{iq}), generator inductances (L_d,L_q), electrical rotating speed (ω_e), magnetic flux (ψ_f) and number of poles (p) are considered in this model. The sub-index g in this model represents the parameter of generator side [17].

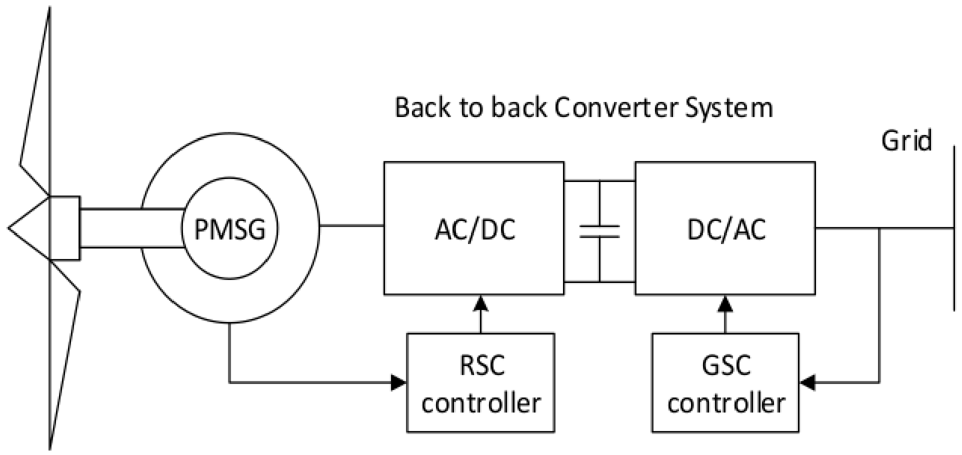


Figure 2. Electrical scheme of WECS based on PMSG.

C. Dual Input Power System Stabilizer

Power system stabilizer (PSS) is an additional control device to enhance the stability by modulating a generator excitation system output of a synchronous generator, to provide damping [18]. PSS provides additional electrical torque based on rotor speed deviation. The input of PSS is typically rotor speed deviation, while the output is additional control signal to the exciter. The exciter then controls the magnetic field density of the machine to modulate and control the terminal voltage of synchronous machine. This magnetic field density will be proportional to the value of the electrical torque from the machine. Electric torque then used to damp the oscillation by matching with the mechanical torque. With increasing number of new renewable types of power plant, the complexity level of the system is gradually increasing. Furthermore, large-scale PV and WECS also introduce another mode that could contribute to the oscillatory condition of the systems. Therefore, dual input power system stabilizer (DIPSS) can be another solution to address the problem created by various sources. Figure. 3 shows the block diagram of DIPSS that use in this paper [18, 19].

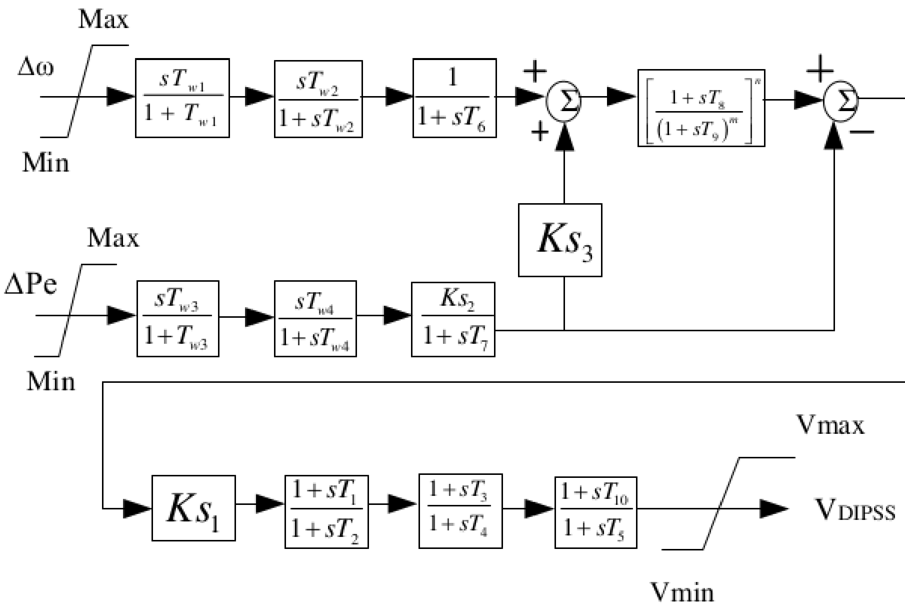


Figure 3. Block diagram of DIPSS.

The advantages of DIPSS are enhancing damping by combining two signals from rotor speed (mechanical signal) and electrical power of the machine (electrical signal). By considering those two signals, DIPSS can provide more detail and precise damping signal to the excitation system. Furthermore, by employing two different input signals, DIPSS can handle problems coming from more than one modes. This signal can be derived from the shaft motion that causes excessive modulation generator excitation system, it can also come from torsional oscillation resulting from electrical torque changes [18, 19]. Each input signal is fed to the washout and transducer circuit. Washout circuit provides continuous condition at the output of stabilizer while the transducer is used to convert the input signal into a voltage signal.

D. Small signal stability

Low-frequency oscillation can be classified as a local and global mode [20]. The local mode has a frequency around 0.7 to 2 Hz [20]. While the inter-area mode is associated with the generator in one area oscillates against another machine from another area, has a frequency range around 0.1 to 0.7 Hz [20]. Furthermore, increasing penetration of RESs also contributes in low-frequency oscillation. As reported in [21] the mechanical oscillation of wind power system has the frequency around 0.5 Hz.

Low-frequency oscillation can be examined by monitoring system eigenvalues of the reduced system state matrix. The eigenvalues will reflect various modes in the system, including oscillatory and non-oscillatory. State space representation of the system can be determined using (8) [22].

$$\begin{bmatrix} \Delta\dot{x} \\ 0 \end{bmatrix} = \begin{bmatrix} A & B & \\ C & D_{11} & D_{12} \\ & D_{21} & J_{LF} \end{bmatrix} = \begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} + E[\Delta u] \quad (6)$$

Where Δx is a vector of state variables. Δy represents a vector of algebraic variables. Δu corresponded to the input vector. J_{LF} is the load-flow Jacobian. *A* and *B* are plant and control or input matrix respectively. While output and feedforward matrix are denoted by *C* and *D*, respectively. Furthermore, the reduced system state matrix of the entire system can be defined using (9) [22].

$$A_{sys} = \left(A - B \left[\begin{pmatrix} D_{11} & D_{12} \\ D_{21} & J_{LF} \end{pmatrix}^{-1} \right] C \right) \quad (7)$$

The eigenvalue of the system matrix carries information about the stability of the system. Complex eigenvalue indicates frequency oscillation (*f*) and damping ratio (ξ) which can be described as given in (10), (11), and (12) [20].

$$\lambda_i = \sigma_i \pm j\omega_i \quad (8)$$

$$f_i = \frac{\omega_i}{2\pi} \quad (9)$$

$$\xi = \frac{-\sigma_i}{\sqrt{-\sigma_i^2 + -\omega_i^2}} \quad (10)$$

Design of DIPSS using Hybrid DE-PSO

A. Particle Swarm Optimization

PSO is an optimization algorithm inspired by the behavior of animals in search of food. PSO was introduced by Kennedy and Eberhart in 1995. In PSO, particles can be assumed as birds living socially, where each of member of the group has a dependence on each other [23]. There are several key advantages of PSO for solving global optimization problems such as derive-free techniques, easy in concept and coding compared to other optimization method. Moreover, PSO has limited number of parameter and can generated high quality solutions within shorter time compared to the other metaheuristic method [24]. Due to the those advantages, there are a lot of application of PSO in power and energy sector as reported in [25]. In those paper, the PSO is used to optimize the battery energy storage sizing in Microgrid system. Moreover, PSO can be used for designing frequency control in AC Microgrid system as reported in [26]. Although PSO has provided satisfactory result on optimization problems, they also has major drawback. PSO tend to get convergence on the local optima. This condition makes the PSO has a hard time to get the best results in the optimization process. Moreover, PSO also has problems of dependency on parameters and initial condition [24].

B. Differential Evolution

Differential evolution (DE) is an algorithm introduced by Storn and Prince in 1995. The special characteristic of DE is the utilization of differential mutation-based operations in the deployment of candidate solution in a given population. This algorithm has 5 important steps, namely, Initialization, mutation, recombination, crossover, and selection [27, 28].

The application of DE in power system sector has increased significantly over the decade. As reported in [29], DE can be used to design the framework of directional relay in meshed network. Moreover, DE also can be used to design robust power system stabilize to mitigate oscillatory condition on multi-machine power systems as reported in [30].

DE has advantages and disadvantages on the process. The advantages of DE are ease of use and has efficient memory compared to the other metaheuristic algorithm. DE also has advantages on the lower complexity of the coding as well as less computational effort compared to the other optimization method [27]. Furthermore, DE is also has a frailty in terms of slowing down the convergence when the algorithm has enter the global optima region due to one of the DE process called mutation process [27].

C. Hybrid Differential Evolution Particle Swarm Optimization

The basic program of hybrid DE-PS optimization technique uses an algorithm from PSO. To enhance the convergence speed, the process from DE is combined into PSO algorithm process. Technically this process can minimize the search function space. The initial process of the hybrid DE-PSO algorithm begins with the initialization of the PSO parameter which includes the number of particles, the upper and lower search limits, as well as several other PSO parameters. Then each particle is distributed in a solution space. Randomly dispersed particles begin to move their movement based on information from the particle with the best position. Fitness function of each particle is evaluated, where the best value of the movement of each particle and the best value of the swarm. In the next process, the DE method is taking place [31].

In the second iterations, The DE selects some of the fitness particles before the particles in the swarm continue the searching process of the solution. DE performs the process of particle selection by involving mutation, recombination, and evaluation steps. After passing through the DE process, the particles will be more accumulated or focused on the smaller search space so that this can speed up the discovery of the best solution. Furthermore, the particles on the swarm perform the same procedure as the PSO algorithm in general [31].

The oscillation of the rotor speed in the machine reflects the electromechanical oscillation of the system. Hence, the objective function for hybrid DE-PSO can be determined using (17) [32].

$$E = \sum\left[\left(\int_0^{t1} t|\Delta\omega_1(t,X)|dt\right) + \left(\int_0^{t1} t|\Delta\omega_2(t,X)|dt\right) + \ldots\left(\int_0^{t1} t|\Delta\omega_n(t,X)|dt\right)\right] \quad (11)$$

where $\Delta\omega(t,X)$ is the oscillatory condition of generator rotor speed. X consists of DIPSS parameters while $t1$ is the time frame of the simulation. The objective function in this research is to minimize the value of E subject to minimum and maximum values of individual parameter of DIPSS. The flow diagram for designing DIPSS using hybrid DE-PSO is illustrated in Figure. 4. This objective function is focused on reducing the error on rotor speed deviation. By setting the DIPSS parameter based on the minimum error deviation of the rotor speed, the small signal stability performance of the power system can be enhanced. However, over the other objective functions, the main advantage of this objective function is the simplicity.

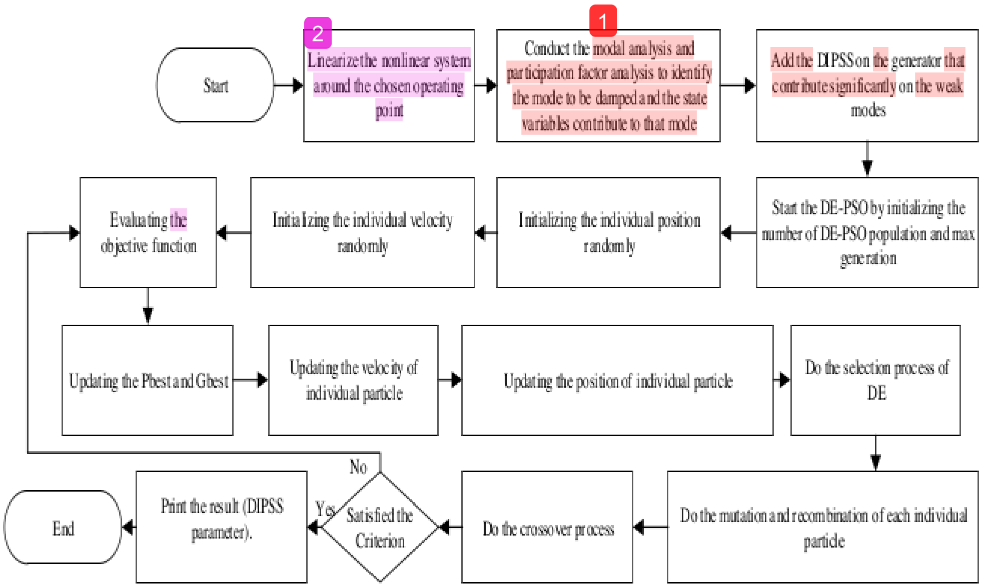


Figure 4. The flow diagram for designing DIPSS using hybrid DE-PSO.

4. Results and Simulations

Several case studies are reported in this paper to investigate the impact of the optimizing DIPSS using hybrid DE-PSO on the low-frequency oscillation of power system considering high penetration of RESs. Case studies are carried on MATLAB/SIMULINK analytical tool. The 4 machine 12 buses power system is selected as a test system. A modification is made to the system by replacing one synchronous generator in area 1 with 350 MW aggregated PV plant. Moreover, 350 MW aggregated WECS is also connected at bus 6 as shown in Figure 5.

The modified system consists of three synchronous machines, one WECS, one PV plant. It is assumed that WECS and PV are operated at maximum power point condition. The WECS is modeled by eleventh order model consisting of the wind turbine drive train (first order model), permanent magnet synchronous generator (second order model), rotor and grid side converter including the associated controller (tenth order model). The synchronous generator in the system is presented by ninth order model with fast exciter and governor. The PV in this paper modeled into sixth order model (second order from inverter dynamic, fourth order from reactive power controller and inverter controller).

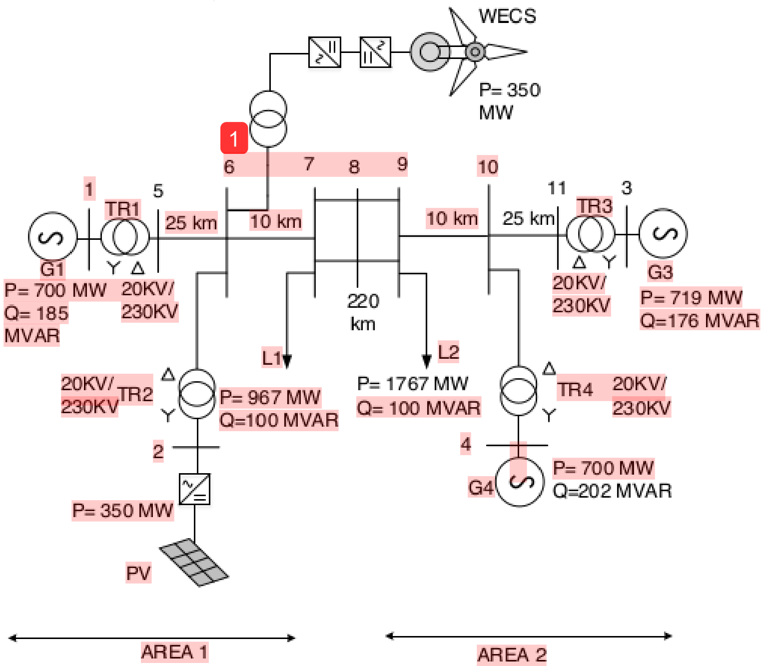


Figure 5. Test system.

In this paper, the DIPSS is installed in the G1 and G3. Furthermore, hybrid DE-PSO technique is used to tune the DIPSS parameter. Figure. 6 shows the convergence graph comparison of the different optimization method. The blue line corresponded to the convergence graph of PSO, while the red line related to the convergence graph of DE. Moreover, the black one corresponded to the hybrid DE-PSO convergence graph. It is monitored that the fitness function (objective function) of the system using hybrid DE-PSO is the smallest one. Hence, the smallest error of rotor speed is obtained by using hybrid DE-PSO. Table 1 illustrates the DIPSS parameter under different optimization method. It is observed that only two parameters of DIPSS has different value from different optimization approach. It is noticeable that gain constant of DIPSS in G1 and G3 played important role on the system dynamic performance.

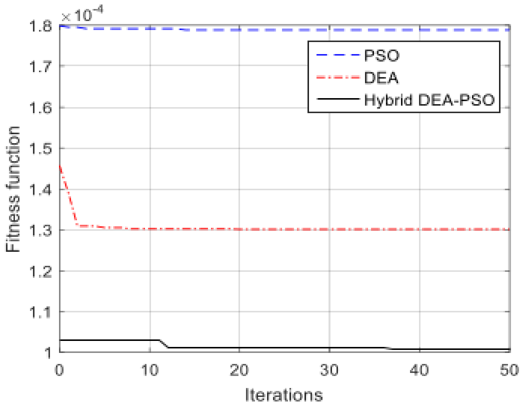


Figure 6. Convergence graph of PSO, DE and Hybrid DE-PSO.

Table 1. DIPSS parameter under different optimization method.

Cases	PSO	DE	Hybrid DE PSO
Ks1G1	194.787	196.556	200
T1G1	100	100	100
T2G1	20	20	20
T3G1	0.1	0.1	0.1
T4G1	0.01	0.01	0.01
T10G1	0.6	0.6	0.6
T5G1	15	15	15
Ks1G3	172.668	161.65	150.152
T1G3	0.5	0.5	0.5
T2G3	1	1	1
T3G3	0.5	0.5	0.5
T4G3	1	1	1
T10G3	1	1	1
T5G3	2.5	2.5	2.5

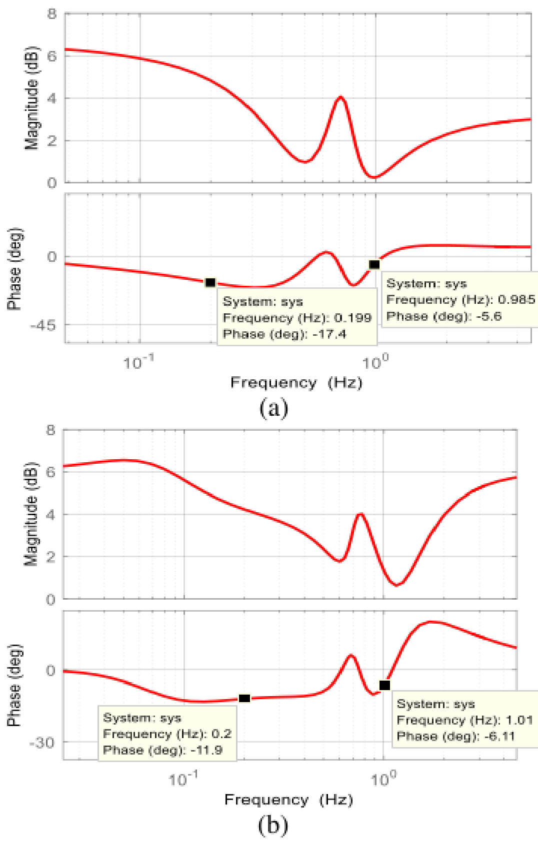


Figure 7. Bode plot of V_t/V_r transfer function: a. Generator 1, b. Generator 3.

To investigate the tuned DIPSS performance in the frequency domain, the bode diagram of V_t/V_r transfer function is performed. Figure 7a-7b illustrates the bode diagram of V_t/V_r transfer function of G1 and G3. Based on the Western Electricity Coordination Council (WECC) new standard (2016 standard), PSS shall be set to provide compensated V_t/V_r frequency response such that the phase will not exceed ±30 degrees through the frequency range from 0.2 Hz to 1 Hz [33]. From Figure. 7a-7b, it is observed that between the frequency ranges from 0.2 Hz to 1 Hz, the phase of V_t/V_r is under ±30 degrees for G1 and G3. Hence it can be stated that the tuning methods can meet the WECC new criterion.

A. Case study 1

In the first case study, observation of eigenvalue and damping of the electromechanical mode is carried out. Table 2 shows the comparison of damping performance of electromechanical mode (EM) due to integration of PV and WECS. It is found that replacing one synchronous generator with large-scale PV and WECS making the damping of local mode of area 1 and inter-area mode deteriorated. This could have happened due to the different dynamic characteristic of RESs. It is also monitored that the damping of local mode of area 2 relatively same with the base case scenario. It is suggested that the proximity of RESs integration has a significant influence on the system dynamic. Moreover, Figure. 8 illustrates the rotor speed oscillatory condition due to displacement of synchronous generator with RESs. The time domain simulation is performed by giving 0.05 step input of load (small perturbation). It is noticeable that system with RESs experience higher overshoot than the system without RESs. Hence the time domain simulation in Figure. 8 corroborates the damping values in Table 2.

Table 2. Electromechanical damping due to the RESs integration.

Scenarios	Local mode 1	Local mode 2	Inter-area
Base cases	0.0480	0.0485	0.0260
With PV	0.0416	0.0485	0.0165
With WECS	0.0430	0.0486	0.0170
With PV+WECS	0.0429	0.0486	0.0105

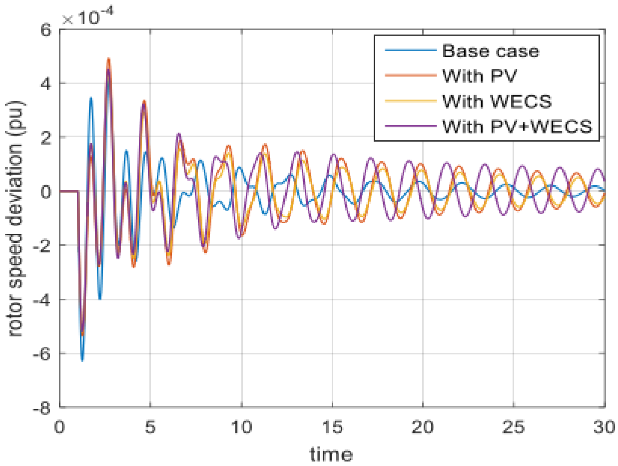


Figure 8. Rotor speed oscillatory condition due to RESs integration.

A comparison of eigenvalue under different scenarios are performed to investigate the effectiveness of the proposed controlled method. Table. 3 shows the eigenvalue of the electromechanical mode under different controller scenarios. It is noticeable that by using the proposed method (DIPSS based on hybrid DE-PSO) the system is more stable indicated by more negative value of the real parts.

Table 3. Eigenvalue comparison of different controller scenarios.

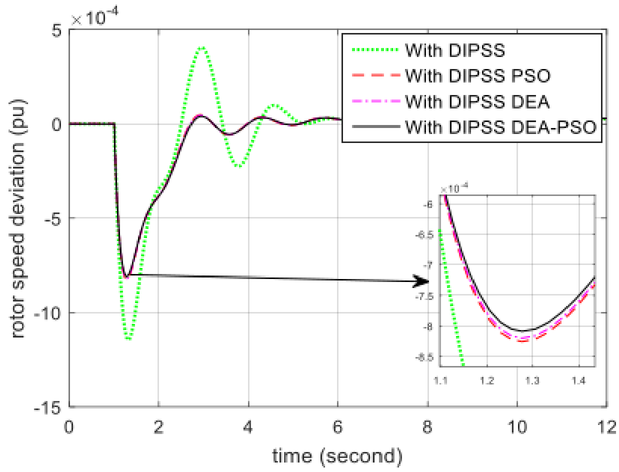
Scenarios	Local mode 1	Local mode 2	Inter-area
With PSS	-1.65+8.59i	-0.34+7.03i	-0.18+3.5i
With DIPSS	-1.05+2.91i	-1.14+7.48i	-0.66+4.65i
DIPSS PSO	-3.24+1.71i	-5.49+5.36i	-0.64+4.56i
DIPSS DE	-3.23+1.65i	-5.14+5.59i	-0.65+4.56i
DIPSS Hybrid DE-PSO	-3.36+1.52i	-4.78+5.78i	-0.81+4.58i

The damping performance of different scenario is illustrated in Table 4. It is observed that the system with DIPSS based on hybrid DE-PSO could enhance the damping performance of the system significantly from (the damping become 92%) for local mode area 1. While damping performance in local mode area 2 enhances from significantly and become 63%. Furthermore, the damping performance of inter-area mode increase up to 17% even one synchronous generator has been replaced by RESs. This condition could happen due to precise signals damping provided by DIPSS tune with hybrid DE-PSO to the excitation of the synchronous generator.

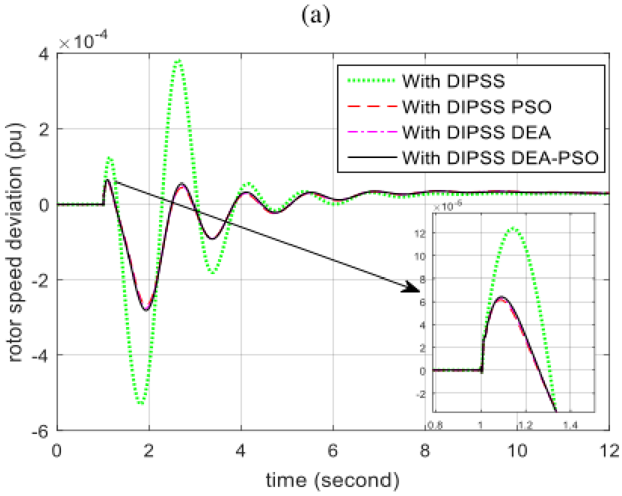
Table 4. Damping comparison of the cases.

Scenarios	Local mode 1	Local mode 2	Inter-area
With PSS	0.1856	0.0486	0.0335
With DIPSS	0.3264	0.1579	0.1221
DIPSS PSO	0.8733	0.7109	0.1321
DIPSS DE	0.8954	0.6843	0.1380
DIPSS Hybrid DE-PSO	0.9105	0.6362	0.1733

To validate and verify the eigenvalue analysis, time domain simulation is carried out. To observe the dynamic response, a small perturbation is made in the system by giving 0.05 pu step input of load. Figures. 9a-9c illustrate the oscillatory condition of rotor speed generator 1, generator 3, and generator 4. The system dynamic behavior with conventional DIPSS is presented by a green line, while red and pink line corresponds to the system with DIPSS tuned by PSO and DE. Moreover, the dynamic response of the system with DIPSS based on hybrid DE-PSO is presented in black lines. It is observed that system with conventional DIPSS experienced higher rotor speed oscillation than a system with DIPSS tuned by PSO, DE, and hybrid DE-PSO. It is noticeable that for rotor speed generator 3 the system with DIPSS based on PSO has shown a better response than a system with DIPSS based on DE and hybrid DE-PSO. However, for a dynamic response on generator 1 and generator 4, the best system performance is identified when the proposed tuning method (hybrid DE-PSO) is employed to the DIPSS, indicated by the smallest overshoot and fastest settling time compared to another scenario.



(a)



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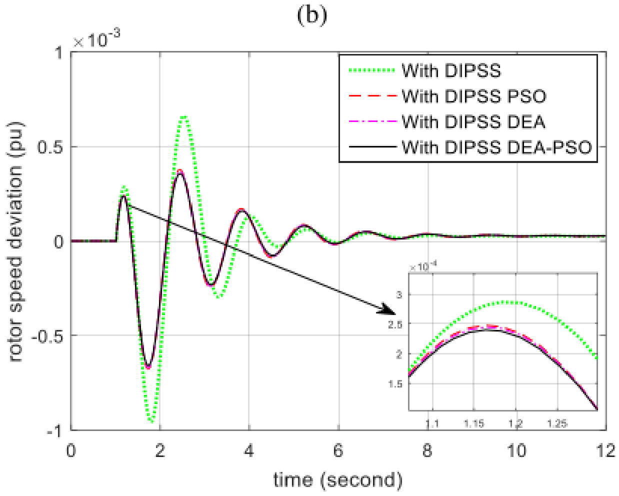
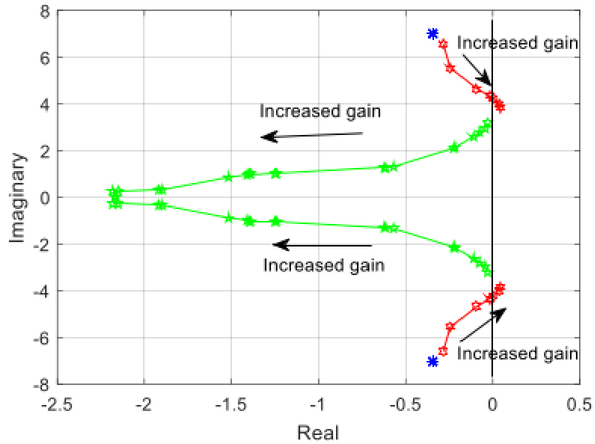


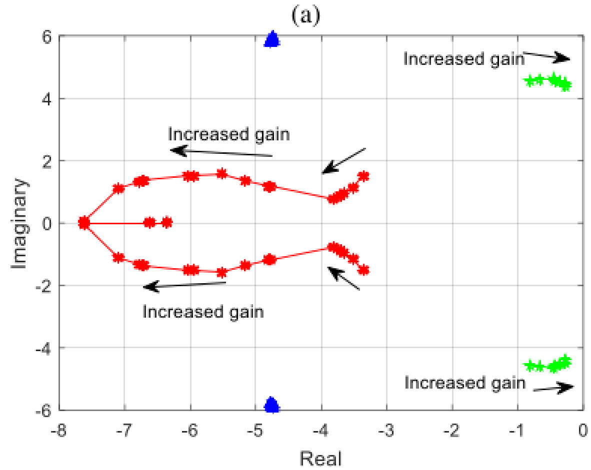
(c)

Figure 9. The oscillatory condition of different cases: a. Generator 1 rotor speed pu, b. Generator 3 rotor speed pu, c. Generator 4 rotor speed pu.

For testing the dynamic performance of the EM mode in complex plane, a root locus analysis is performed. Figure. 10a illustrates the root locus plot of the modified system (system without DIPSS and RESs displaced the synchronous generator in area 1). The red colour indicates the local mode area 1 movement due to the increased gain. While the blue and green colours indicated the local mode area 2 and inter-area mode, respectively.
It is found that by increasing the gain of the system local mode area 1 eigenvalue is move towards right half plane. It is also found that in certain point of gain the eigenvalue of local mode area 1 become unstable (real parts of eigenvalue become positive). In contrast, when root locus analysis is tested on the system with proposed method (DIPSS based on hybrid DE-PSO) the eigenvalue of local mode area 1 is move toward left half plane. Furthermore, in certain point the mode become only real part (damping 100% and no oscillation) as shown in Figure. 10b. It is also observed that by using the proposed control method all of the eigenvalue of EM mode is on the left half plane when gain is increased from 0 to infinite. Moreover, the eigenvalue of local mode area 2 remains in the position.



(a)



(b)

Figure 10. The eigenvalue locus of: a. Generator 1 rotor speed pu,
b. Generator 3 rotor speed pu.

B. Case study 2

The second case study focused on the analysing the controller performance. To assess the performance of the proposed controller, five different operating conditions are used. The operating conditions used for the performance analysis are given in Table 5. The damping performance of the system for these operating conditions is illustrated in Table 6. It should be noted that the base condition in Table 7 referred to the nominal operating condition for which

the DIPSS is designed. It is observed from Table 6 that the damping performance in local mode 1, local mode 2 and inter-area is above 0.05 under different operating conditions.
It is also found that under stressed condition (OC6), the damping performance in local mode 1, local mode 2, and inter-area mode is relative high (0.8798 for local mode area 1, 0.5315 for local mode area 2, and 0.0986 for inter-area mode) and meet the minimum criterion of damping performance (above 0.05). Hence, it can be concluded that the proposed controller is robust enough against different operating conditions as well as the stressed operating condition that could be emerged in the test system.

Table 5. Operating condition for the test system.

Operating condition	Changed system topologies from base case
OC1	G3 output is 539 MW
OC2	G4 output is 525 MW
OC3	Load demand in area 1 is 1208.75 MW
OC4	Load demand in area 2 is 2208.75 MW
OC5	G3 and G4 output are 674 and 656.25 MW also load demand in bus area 1 and 2 are 1027 and 1877 MW
OC6	G3 and G4 output are decreased until 50% from the total generating capacity as well as load demand in area 1 and 2 are increased up to 50% from the total load demand

Table 6. Damping comparison for different operating conditions.

Scenarios	Local 1	Local 2	Inter-Area
Base condition	0.9105	0.6362	0.1733
OC1	0.9354	0.5844	0.1562
OC2	0.9389	0.6442	0.1320
OC3	0.9505	0.6403	0.1535
OC4	0.9402	0.6319	0.1561
OC5	0.9454	0.6295	0.1485
OC6	0.8798	0.5315	0.0986

C. Case study 3

In the third case study, investigation of damping performance of the system with the proposed method under different loading conditions. The light load operating condition is performed by decreasing the load of the system to 25% of the total load. While the heavy load operating condition is performed by increasing the load of the system to 50% more than the base case load. Furthermore, it should be note that the medium load operating condition is the modified system in this paper.

Table 7 illustrates the damping performance of the system with proposed method under different loading condition. It is found the damping performance of the system with the proposed method is still above the minimum standard. Hence, it can be stated that the proposed method is robust enough against different loading scenarios.

Table 7. Damping comparison for different operating conditions.

Scenarios	Local 1	Local 2	Inter-Area
Light	0.7810	0.6308	0.1355
Medium	0.9105	0.6362	0.1733
Heavy	0.7777	0.6380	0.1413

D. Case study 4

In the fourth study case, the performance of the proposed controller method is assessed using IAE, ISE and ITAE criterion. All of the rotor speed of conventional generator are assessed by using this criterion. The purpose of this assessment is to check the error of system nonlinear response. Tables 8, 9 and 10 are shown the comparison of IAE, ISE and ITAE criterion of G1, G3 and G4 under different scenarios. In this three criterion, the less the value the better the performance. It is noticeable that except in the G3, the proposed method (DIPSS based on DE-PSO) has the most minimum value for all three criterion compared to other scenarios.

Table 8. ITAE, IAE, ISE criterion comparison for G1

Case	With DIPSS	With DIPSS PSO	With DIPSS DE	With DIPSS DE-PSO
ITAE	0.004145	0.003105	0.003102	0.003096
IAE	0.001409	0.0009793	0.0009774	0.0009732
ISE	0.0000007553	0.0000004136	0.0000004107	0.000000446

Table 9. ITAE, IAE, ISE criterion comparison for G3

Case	With DIPSS	With DIPSS PSO	With DIPSS DE	With DIPSS DE-PSO
ITAE	0.003073	0.002457	0.002466	0.002474
IAE	0.0008276	0.0004858	0.0004931	0.0005001
ISE	0.0000002113	0.00000004928	0.00000005148	0.0000000535

Table 10. ITAE, IAE, ISE criterion comparison for G4

Case	With DIPSS	With DIPSS PSO	With DIPSS DE	With DIPSS DE-PSO
ITAE	0.004073	0.003557	0.003505	0.003447
IAE	0.001266	0.0009785	0.0009623	0.0009432
ISE	0.00000005798	0.0000002731	0.0000002655	0.0000002546

E. Case study 5

The fifth study case is analyzed on how much penetration level of RESs could be integrated into the system with DIPSS based on hybrid DE-PSO. The penetration of RESs is varied from 0% to 70% of the total system generation. This case study focused on the influence of the penetration level of RESs with damping performance of the system. Figure. 11 shows the damping performance of inter-area due to increasing penetration of RESs.

It is monitored that the damping performance of local mode area 1 and inter-area mode deteriorated significantly when RESs penetration level increased. This condition could emerge due to the different dynamic characteristic of RESs. It is also monitored, that the increasing penetration level of RESs did not have a significant influence on the damping performance of local mode area 2. This could happen due to the proximity of RESs. It is observed that a system with conventional DIPSS could only increase the RESs penetration level until 65%, after that percentage the damping performance of inter-area is less than 5%. While a system with proposed tuning method (hybrid DE-PSO) could increase the penetration level of RESs up to 70% of the total system generation.

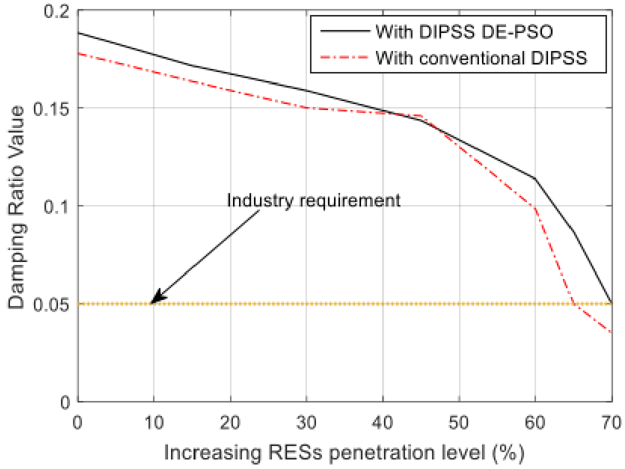


Figure 11. Damping performance of inter-area mode due to the increasing RESs penetration level.

5. Conclusions

This paper proposed a method to enhance the small signal stability performance of power system considering high penetration of RESs using intelligent DIPSS. The DIPSS is designed with the helped of hybrid DE-PSO. From the investigated study cases, it is found that replacing one synchronous generator with large-scale PV and WECS resulting in deterioration of system damping performance due to the different dynamic characteristic of the RESs. It is monitored that the eigenvalue of local mode area 2 remains in its position due to the proximity of RESs integration. It is also investigated that adding PSS and DIPSS in G1 and G3 could enhance the damping performance of the system even one synchronous generator has been replaced by RESs. Furthermore, the best performance is monitored in a system with DIPSS tuned by hybrid DE-PSO indicated by, more negative real part of the eigenvalue, high value of damping ratio, smallest overshoot and fastest settling time. Moreover, by using the proposed tuning method (hybrid DE-PSO) the penetration level of RESs could be increased until 70% of the total generating capacity.

Further research is required to analyze the impact of replacing more than 1 synchronous with large-scale PV and WECS in small signal stability performance of the power system. Designing DIPSS using another new metaheuristic algorithm such as social spider algorithm, grey wolf algorithm, and whale algorithm can be considered. Utilizing another type of PSS such as multi-band power system stabilizer can be considered to handle the oscillatory condition emerges in a different mode. Furthermore, adding additional devices such as battery energy storage (BES) and designing coordinated controller between BES and DIPSS could be the solution to accommodate more RESs in the system.

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