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Optimal Design of Power System Stabilizer and Energy Storage Using Particle Swarm Optimization Under Load Shedding Condition

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Abstract- Changes in the load on the electric power system suddenly cause dynamic disturbances. The disturbance causes the stability of the generator to be disturbed, because the generator does not respond to the disturbance quickly. This causes oscillations in the generator in the form of oscillations of frequency and rotor angle. Additional control equipment that can increase the stability of a generator is the Power System Stabilizer (PSS) and Energy Storage (Superconducting Magnetic Energy Storage (SMES) and Capacitive Energy Storage (CES). To get maximum results, proper PSS, SMES and CES settings are needed. and optimally to reduce oscillations and stabilize the system. Tuning these parameters can use intelligent optimization methods, or what is commonly called artificial intelligence. By using intelligent methods based on Particle Swarm Optimization, the optimal PSS-SMES-CES parameters are obtained. With optimal tuning, the frequency response and The optimal rotor angle of the SMIB system is indicated by the minimum overshot response of the system. The controller is able to provide stability so that the overshoot oscillations can be damped, and the settling time performance is getting faster for the system to go to steady state. To test the stability of the SMIB system, case studies of addition and decomposer with load, with the proposed control method PSS-SMES-CES which is optimized using Particle Swarm Optimization.

Keywords: *PSS, SMES-CES, Particle Swarm Optimization, SMIB, Overshoot.*

I. INTRODUCTION

In the dynamic stability study, it is assumed that the torque change due to the governor response is negligible because the governor response is very slow compared to the excitation system response, so the controlling factor is the excitation system. The addition of an amplifier excitation circuit is less able to stabilize the system, especially for low-frequency oscillations. Low Frequency Oscillation between 0.2 - 2.0 Hz (1).

Lower frequencies can be extended to oscillations between areas, requiring additional controls such as Power System Stabilizer (PSS) control. PSS is an additional control device on the generator excitation which is used to provide additional damping to the generator excitation (2). In addition, it also serves to reduce local or global oscillations on the generator, in response to deviations that occur in predetermined variable values. Superconducting Magnetic Energy Storage (SMES) is a device for storing and releasing large amounts of power simultaneously. While Capacitive Energy Storage (CES) is a device for storing and releasing power. CES stores energy in the form of an electric field in a capacitor. The combination of the use of energy storage based on SMES and CES can improve system performance if the appropriate parameters are used. To get maximum results, proper and optimal PSS, SMES and CES settings are needed to reduce oscillations and stabilize the system. Tuning these parameters can use the optimization of intelligent methods, or what is commonly called artificial intelligence.

Particle Swarm Optimization (PSO) belongs to the Swarm Intelligence group, which is one type of paradigm development used to solve optimization problems where the inspiration used to solve problems comes from the behavior

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of particles in groups looking for food sources. The use of the PSO method is also used in this study as a method to improve control parameters. Several studies have described the application of intelligent methods to optimize generator control parameters and the results given to the system are very good in maintaining generator stability, such as the firefly method (3), bat algorithm (4), flower pollination (5), imperialist competitive (6), and cuckoo search (7).

Optimal parameter tuning from the controller will be very influential in stabilizing the system (8). However, the range of equipment parameters is very diverse and wide, so to quickly obtain parameter values, an optimization method using PSO is used. In several previous studies, the case study used to review the stability of the system was when a disturbance occurred when it started operating. This is certainly different if there is a disturbance while the system is operating. For this reason, in this study, the conditions at the load when the generator is operating will be analyzed. The response value is known by analyzing the overshoot and settling time values, while the objective function minimizes the Integral Time Absolute Error (ITAE) (9). The case study used is the Single Machine Infinite Bus (SMIB) system. SMIB is an electric power subsystem consisting of one or more generators connected to an infinite number of buses (10). Then analyze the simulation results by comparing the simulation results of the system without control, SMIB with PSS, SMIB with SMES, with CES, SMES-CES and with the proposed method SMIB with PSS-SMES-CES with PSO. In this study, the authors implemented an intelligent method based on ant colony to solve the optimization problem of determining the PSS-SMES-CES parameters on the SMIB system.

II. MODELING

a. Synchronous Machine Linear Modeling

The linear modeling of the synchronous machine is shown in Figure 1. In this model the main input parameter is the mechanical torque ΔT_m while the rotor angle $\Delta\delta$ is the main output parameter..

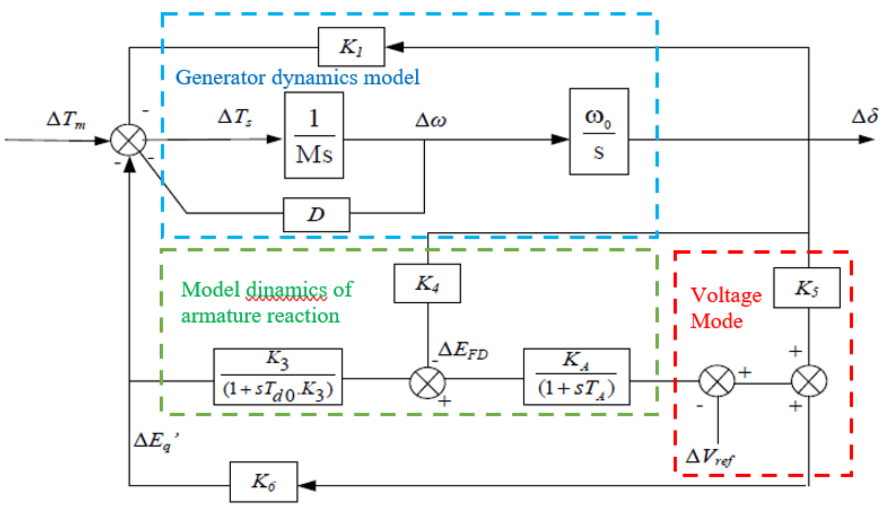

FIGURE 1. Synchronous Machine Linear Model

b. Excitation Modeling

Excitation equipment is one part of the system where the exciter can adjust the generator output variables, such as voltage, current and power factor The excitation model refers to the IEEE modeling shown in Figure 2 (11).

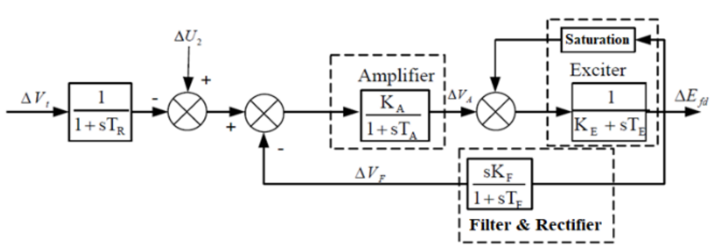

FIGURE 2. Block Diagram of Excitation

c. Governor Modeling

The governor is a controller that functions to regulate the value of the mechanical torque Tm which is the input from the generator (11). The modeling is shown in Figure 3.

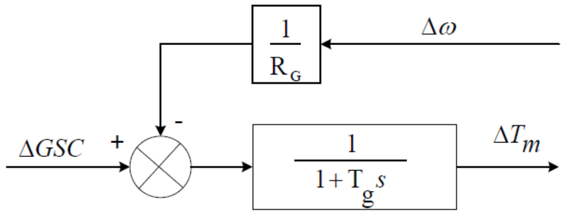

FIGURE 3. Modeling Governor

d. Turbine Modeling

Turbine modeling used is a steam power plant turbine model, from the IEEE model (12). The modeling is shown in Figure 4.

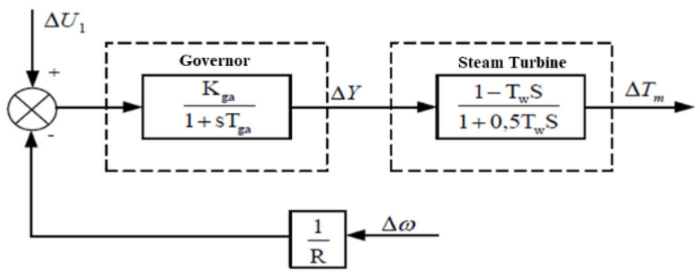

FIGURE 4. Turbine Model

e. Single Machine Infinite Bus (SMIB) Modeling

The overall system modeling is shown in the Single Machine Infinite Bus model (13) in figure 5.

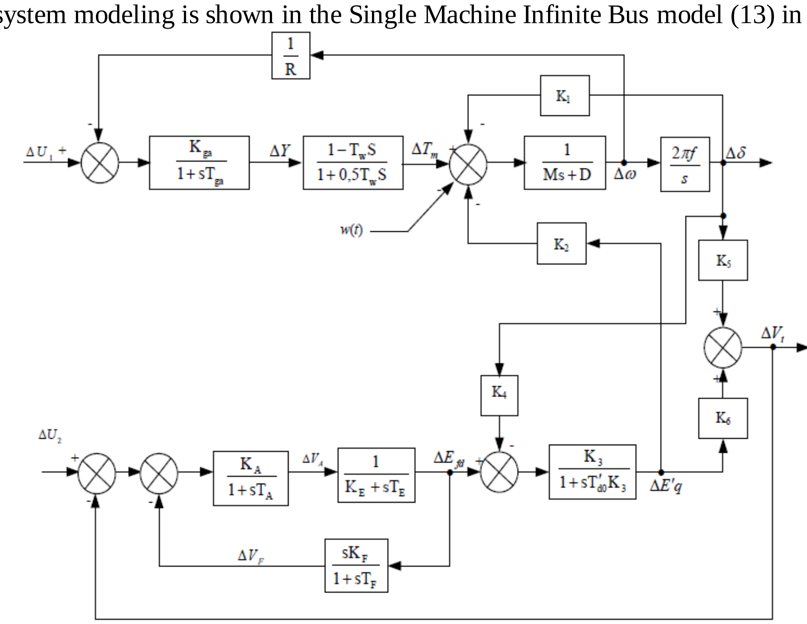

FIGURE 5. SMIB Modeling

f. Power System Stabilizer Modeling

Power System Stabilizer is a tool that can be used to increase the stability of the power system. PSS modeling in this study is shown in Figure 6.

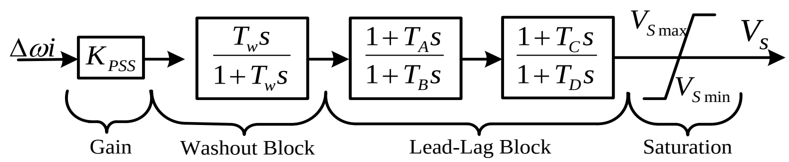

FIGURE 6. PSS Modeling

g. Modeling of Superconducting Magnetic Energy Storage

SMES is a device for storing and releasing large amounts of power simultaneously. The working principle of SMES is divided into three, charging, standby and discharging modes (14). SMES performance adjustment is done by adjusting the duty cycle (D) of the converter which in this case uses the Gate Turn Off (GTO) thyristor. Figure 7 shows a schematic diagram of the SMES.

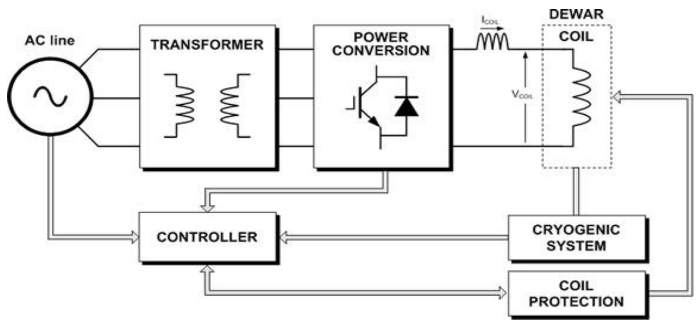

FIGURE 7. Schematic diagram of SMESe

For balance power control on the generator, SMES is installed on the generator terminals. From several SMES reference equations, SMES block diagrams can be made as follows.

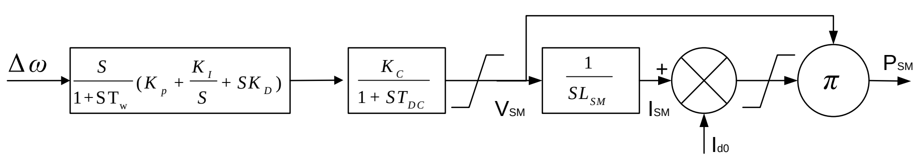

FIGURE 8. SMES Modeling

h. Capacitive Energy Storage Modeling

CES is a device for storing and releasing power. CES stores energy in the form of an electric field in a capacitor. A CES consists of a storage capacitor and a Power Converion System (PCS).

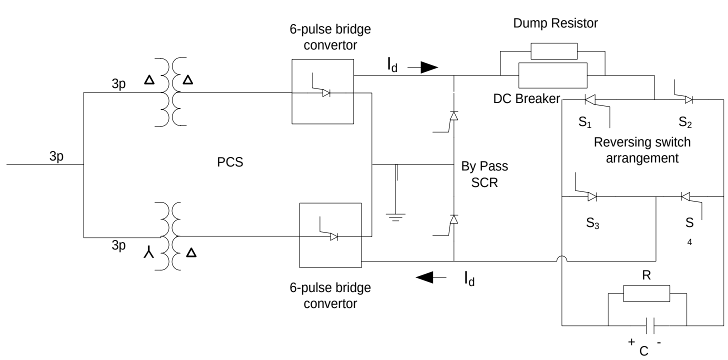

FIGURE 9. Capacitive Energy Storage

The CES voltage must return to its initial value quickly, so that after a load fault occurs the CES unit is ready to work for the next load disturbance. Therefore, the capacitor voltage deviation is used as a negative feedback signal in the CES control loop so that fast voltage recovery is achieved as shown in Figure 10.

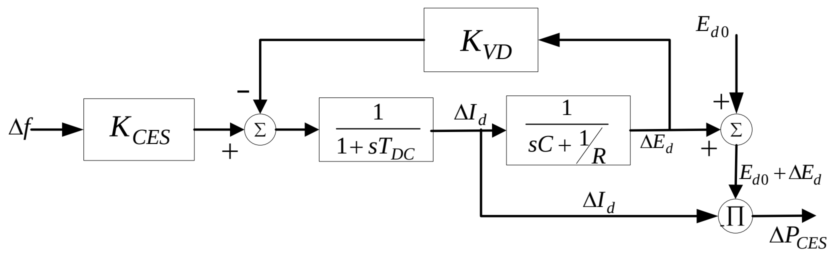

FIGURE 10. Block Diagram of CES

III. RESEARCH METHOD

a. Particle Swarm Optimization

PSO is a population-based optimization technique. PSO begins by spreading a group of particle populations in a problem space. These dispersed particles are called swarm (15). This particle holds information about its existence and the potential value generated by that existence. Particles will provide information to each other, so from the information obtained it will be known which particles occupy the location with the most optimal results on a movement. From this information, other particles will then move to that location based on a motion function called velocity. During the flight process, each particle determines its own position based on its own experience (this value is called Pbest) and based on the experience of other particles (this value is called Gbest). The process of finding Pbest and Gbest can be illustrated in Figure 11.

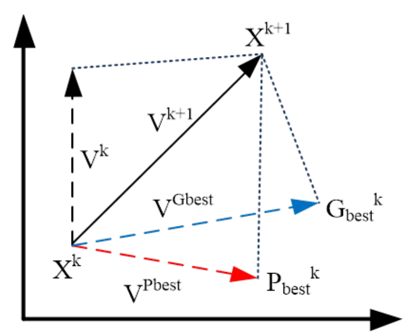

FIGURE 11. The concept of searching for PSO (15)

The speed of each particle can be formulated from (1).

$$v_{k+1} = w.v_k + c_1 rand \times (P_{best} - x^k) + c_2 rand \times (G_{best} - x^k) \quad (1)$$

Using (1), Pbest and Gbest can be calculated based on particle velocity. Current position can be obtained from (2).

$$x^{k+1} = x^k + v_{k+1} \quad . \quad k = 1,2 \ldots n \quad (2)$$

Where:

X^k = Current search point
X^{k+1} = Modified search position
V^k = Current speed
V^{k+1} = Modified speed
Vpbest = Speed based on P_{Best}
Vgbest = Speed based on Gbest
n = Number of particles in a group
m = The number of members in the particle
$pbest_i$ = Pbest from k
$gbest_i$ = Gbest from group

w = Weight
c_i = Weight coefficient for the following terms
- c1 and c2 are 2 positive constants
- r1 and r2 are random numbers 0-1

w is the weight of inertia and iteration function of k as follows (3).

$$w(k) = w_{max} - \left(\frac{w_{max} - w_{min}}{max.iter}\right) \times k \tag{3}$$

To ensure uniform speed of all dimensions, the maximum speed is as follows (4).

$$v^{max} = \frac{(x^{max} - x^{min})}{N} \tag{4}$$

Where N is the maximum number of iterations. Table I shows the PSO parameters used in this study.

TABLE I. Particle Swarm Optimization Parameters

Parameter	Value
Number of Particles	30
Max Iteration	50
Number of Variables	3
C2 (Social Constant)	2
C1 (Cognitive Constant)	2
W (Moment Inersia)	0.9

b. PSS-SMES-CES Tuning with Particle Swarm Optimization

The objective function used to test the stability of the system is the Integral Time Absolute Error (ITAE).

$$ITAE = \int_0^t t\left|\Delta\omega(t)\right| dt \tag{5}$$

The PSS-SMES-CES parameters tuned by Particle Swarm Optimization are Tdc, Ksmes, Kpss, T1, T2, T3, T4, Tdc, and KDE.

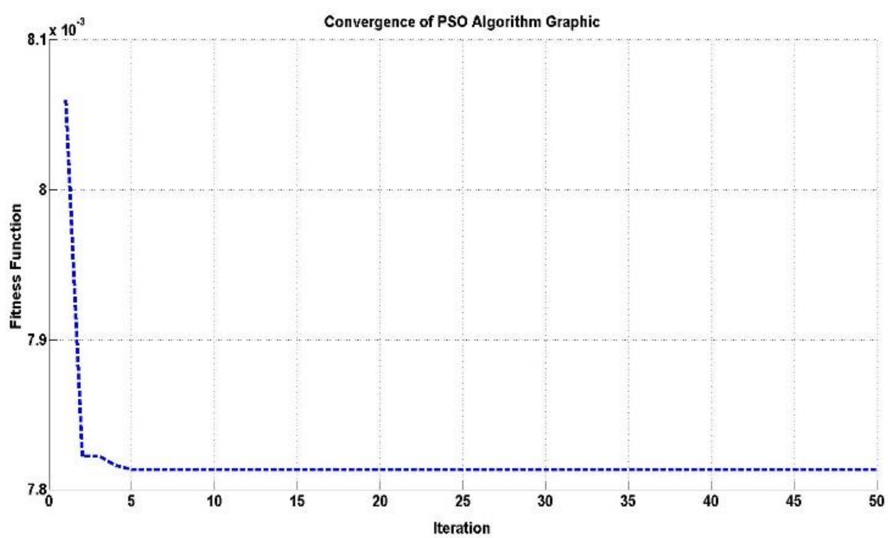

FIGURE 12. Convergence Graph

The right value will greatly affect the performance of the SMIB response designed in this study. The PSO algorithm requires a calculation process to find the optimal value. Figure 13 shows the optimization convergence graph using the PSO algorithm. Convergence is a fitness function value that describes the optimal criteria of an optimization problem.

Figure 12 shows a convergence graph for the optimization of the PSS-SMES-CES value using PSO, where based on the graph, it can be seen that the PSO algorithm does not take a long time to perform the optimization process, it can be seen in the 5th iteration the algorithm has found the optimal value with a fitness value of 0.007813. The optimization results are the optimal controller parameters, namely Tdc, Ksmes, Kpss, T1, T2, T3, T4, Tdc, and KDE. Table 2 shows the limits and values of the PSS-SMES-CES parameter optimization results tuned by PSO.

TABLE II. Limitations And Results of PSO

Parameter	Limits		Results
	Lower	Upper	
Tdc	0	11	0.0288
Ksmes	0	200	199.5044
Kpss	0	70	64.3794
T1	0	1	0.0397
T2	0	1	0.0401
T3	0	1	1.1169
T4	0	1	5.4299
Tdc1	0	1	0.0523
Kde	0	100	94.9493

IV. SIMULATION & ANALYSIS RESULTS

System analysis was carried out, namely the analysis of the system frequency and the SMIB rotor angle. The analysis was carried out using several control methods, such as systems without control, SMIB-PSS, SMIB-SMES, SMIB-CES, SMIB-SMES-CES and SMIB-SMES-CES-PSS. PSS, SMES and CES parameters are tuned using the Particle Swarm Optimization (PSO) algorithm. To test the stability of the system, the SMIB system is disturbed in the form of changes in load.

a. SMIB Frequency Response

The first analysis begins by reviewing the frequency stability response of the SMIB system. The simulation results are shown in Figure 13. Figure 13 shows the simulation results of the SMIB frequency response with several control methods.

From the simulation results, the SMIB system is given a load change disturbance of 0.01 pu at the 1st second, then a load discharge occurs at the 20th second of 0.005 pu. In the first load change, there is an increase in load, namely a condition where the electrical power is not the same as the mechanical power (Pm) in this condition Pe > Pm, so that the electrical torque and mechanical torque are not balanced. This condition causes the electrical frequency (Δf) to also change. During this instability the rotational speed of the rotor ($\Delta\omega$) becomes out of sync. In this condition, the frequency response graph goes down before returning to steady state. The function of the control system is then required to return to a steady state condition. The characteristics of the overshoot response in this condition are shown in table 3.

TABLE III. Frequency Deviation

Deviation	Overshoot (pu)
Uncontrol	-0.0002403 & 0.0001873
PSS-PSO	-0.0001992 & 8.215e-05
SMES-PSO	-0.0001512 & 5.479e-06
CES-PSO	-0.0001394 & 1.057e-07
SMES-CES-PSO	-0.0001078 & 9.557e-07
SMES-CES-PSS-PSO	-0.0001033 & 3.283e-07

Table 3 shows the characteristics of the system overshoot when there is a change in load in the 1st second in the form of an additional load. The SMIB system without control has an overshoot of -0.0002403 & 0.0001873 pu with a settling time of 15.2s. The SMIB system with PSS control obtained an overshoot of -0.0001992 & 8.215e-05 pu with a settling time of 5.6s. SMIB system with SMES control obtained overshoot of -0.0001512 & 5.479e-06 pu with settling time of 3.6s. The SMIB system with CES control obtained an overshoot of -0.0001394 & 1.057e-07 pu with a settling time of 3.2s. SMIB with SMES-CES control obtained overshoot of -0.0001078 & 9.557e-07 pu with settling time of 3.2s. Then with the proposed method using PSS-SMES-CES, the smallest overshoot obtained is -0.0001033 & 3.283e-07 pu with a settling time of 3.02s.

Then the next load change is in the form of a reduction in the load that causes the electrical power (Pe) to change. In this condition the electrical power is not the same as the mechanical power (Pm) Pe < Pm, so that the electrical torque and the mechanical torque are not balanced. This condition causes the electrical frequency (Δf) to also change. During this instability the rotational speed of the rotor (Δω) becomes out of sync. In this condition, the frequency response graph is upwards before returning to steady state. The function of the control system is then required to return to a steady state condition. The characteristics of the overshoot response in this condition are shown in table 4. Figure 14 is a graph of the system's electrical frequency response (Δf).

TABLE IV. FREQUENCY DEVIATION

Deviation	Overshoot (pu)
Uncontrol	-9.048e-05 & 0.0001202
PSS-PSO	-4.088e-05 & 9.764e-05
SMES-PSO	-1.145e-06 & 7.547e-05
CES-PSO	0 & 7.547e-05
SMES-CES-PSO	0 & 5.409e-05
SMES-CES-PSS-PSO	0 & 5.188e-05

Table 4 shows the characteristics of the system overshoot when there is a load change in the 20th second. The SMIB system without control has an overshoot of -9.048e-05 & 0.0001202 pu with a settling time of 34s. The SMIB system with PSS control obtained an overshoot of -4.088e-05 & 9.764e-05 pu with a settling time of 25s. The SMIB system with SMES control obtained an overshoot of -1.145e-06 & 7.547e-05 pu with a settling time of 24.74s. The SMIB system with CES control obtained an overshoot of 0 & 7.547e-05 pu with a settling time of 24.14s. SMIB with SMES-CES control obtained an overshoot of 0 & 5.409e-05 pu with a settling time of 22.43s. Then with the proposed method using PSS-SMES-CES, the smallest overshoot was obtained, namely 0 & 5.188e-05 pu with a settling time of 22.15s.

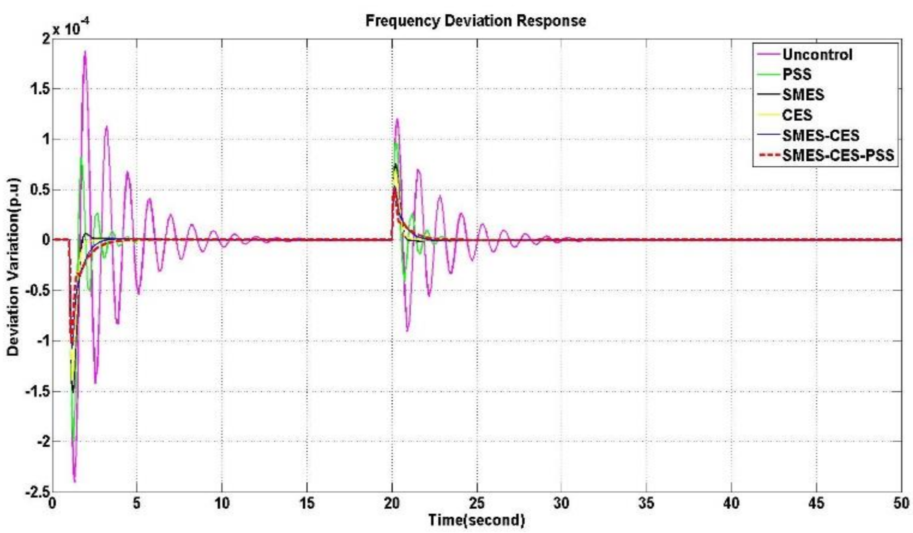

FIGURE 13. SMIB Frequency Response

b. Rotor Angle Response

The next analysis, looks at the performance of the SMIB rotor angle response with the installation of PSS-SMES-CES control. In this study, the test on SMIB was given in the form of a change of 0.05 pu at 1s. The intended change is an increase and an increase in expenses. The increase in load causes changes in electrical power to also increase. If the mechanical power of the generator is greater than the electrical power, it can result in an acceleration of the rotor, this rotor acceleration will also affect changes in the rotor angle, so that the rotor angle response will decrease or be negative from the conditions before the disturbance, as shown in Figure 15. The observed response from the change rotor angle, namely the value of overshoot and settling time, as shown in table 5.

TABLE V. Rotor Angle Deviation

Deviation	Overshoot (pu)
Uncontrol	-0.03623
PSS-PSO	-0.02471
SMES-PSO	-0.02308
CES-PSO	-0.02134
SMES-CES-PSO	-0.02233
SMES-CES-PSS-PSO	-0.02212

Table 5 shows the characteristics of the system rotor angle overshoot when there is a change in load in the 1st second in the form of an additional load. The SMIB system without control has an overshoot of -0.03623 pu with a settling time of 18.5s. The SMIB system with PSS control obtained an overshoot of -0.02471 pu with a settling time of 6.4s. The SMIB system with SMES control obtained an overshoot of -0.02308 pu with a settling time of 9.2s. The SMIB system with CES control obtained an overshoot of -0.02134 pu with a settling time of 8s. SMIB with SMES-CES control obtained an overshoot of -0.02233 pu with a settling time of 4.3s. Then with the proposed method using PSS-SMES-CES, the smallest overshoot is -0.02212 pu with a settling time of 4.2s.

Then the next load change is a reduction in the load at the 20th second. In this condition the mechanical power of the generator is smaller than the electrical power, resulting in a slowdown in the rotor, this rotor deceleration will also affect changes in the rotor angle, so that the rotor angle response will increase or be positive from the condition before the disturbance. This happens because the magnetic coupling will push the stator field with the rotor field, so that the rotor angle of the generator will increase, as shown in Figure 14. The characteristics of the system overshoot in this condition are shown in Table 6..

Table 6 shows the characteristics of the system rotor angle overshoot when there is a change in load at 20 seconds. The SMIB system without control has an overshoot of -0.0159 pu with a settling time of 30 seconds. The SMIB system with PSS control obtained an overshoot of -0.01235pu with a settling time of 25.17s. The SMIB system with SMES control obtained an overshoot of -0.009407 pu with a settling time of 24s. The SMIB system with CES control obtained an overshoot of -0.01024 pu with a settling time of 25s. SMIB with SMES-CES control obtained an overshoot of -0.009698 pu with a settling time of 24.5s. Then with the proposed method using PSS-SMES-CES, the smallest overshoot is -0.009833 pu with a settling time of 24s.

TABLE VI. Rotor Angle Deviation

Deviationn	Overshoot (pu)
Uncontrol	-0.0159
PSS-PSO	-0.01235
SMES-PSO	-0.009407
CES-PSO	-0.01024
SMES-CES-PSO	-0.009698
SMES-CES-PSS-PSO	-0.009833

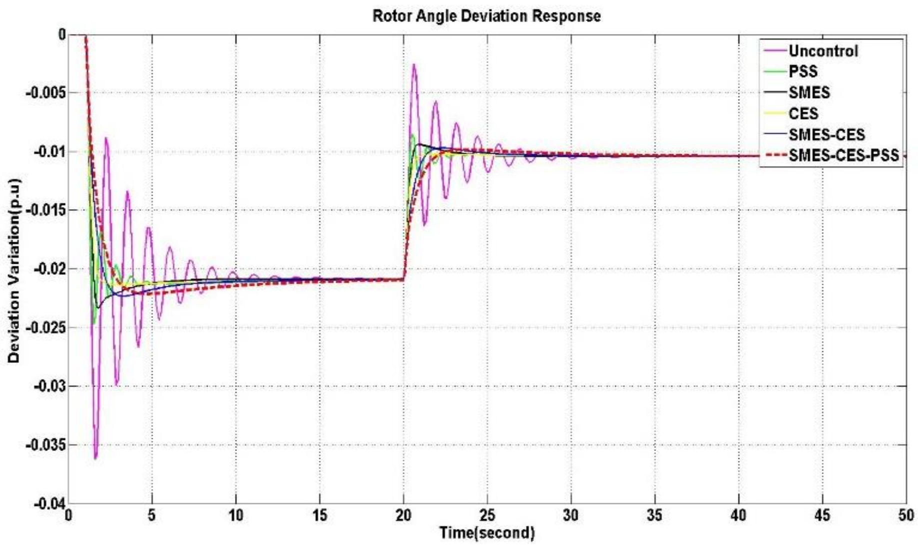

FIGURE 14. SMIB Rotor Angle Response

c. Eigenvalue Analysis

The next analysis is to look at the eigenvalue and damping system with several control schemes. The results of the analysis are shown in table 7. From the eigenvalue analysis of each control scheme, it shows that the more optimal results are the more negative the eigenvalues. While the damping value for each control scheme also shows a higher increase with the proposed control scheme.

TABLE VII. Eigenvalue System

	Eigenvalue	Damping	Frequency
Uncontrol	-3.97e-01 + 5.00e+00i	7.92e-02	5.01e+00
	-3.97e-01 - 5.00e+00i	7.92e-02	5.01e+00
	-9.66e+00 + 3.96e+00i	9.25e-01	1.04e+01
	-9.66e+00 - 3.96e+00i	9.25e-01	1.04e+01
SMES	0.00e+00	-1.00e+00	0.00e+00
	-3.16e+01	1.00e+00	3.16e+01
	-5.75e-01	1.00e+00	5.75e-01
	-4.42e+00 + 3.86e+00i	7.54e-01	5.87e+00
	-4.42e+00 - 3.86e+00i	7.54e-01	5.87e+00
	-8.52e+00 + 3.06e+00i	9.41e-01	9.05e+00
	-8.52e+00 - 3.06e+00i	9.41e-01	9.05e+00
PSS	-4.25e+01	1.00e+00	4.25e+01
	-1.14e+01	1.00e+00	1.14e+01
	-1.69e+00 + 6.97e+00i	2.35e-01	7.17e+00
	-1.69e+00 - 6.97e+00i	2.35e-01	7.17e+00
	-4.85e+00	1.00e+00	4.85e+00
	-4.35e-01	1.00e+00	4.35e-01
	-2.01e-01	1.00e+00	2.01e-01
SMES-PSS	0.00e+00	-1.00e+00	0.00e+00
	-4.23e+01	1.00e+00	4.23e+01
	-3.21e+01	1.00e+00	3.21e+01
	-4.71e+00 + 8.72e+00i	4.75e-01	9.91e+00
	-4.71e+00 - 8.72e+00i	4.75e-01	9.91e+00
	-1.35e+01	1.00e+00	1.35e+01
	-2.21e+00	1.00e+00	2.21e+00
	-2.01e-01	1.00e+00	2.01e-01
	-4.96e-01	1.00e+00	4.96e-01
	-5.00e-01	1.00e+00	5.00e-01

V. CONCLUSION

With optimal tuning, a perfect SMIB frequency response is obtained compared to the system without control, this is indicated by the improved system response, where the controller is able to provide stability so that the overshoot oscillations are muted, and the settling time performance is getting faster for the system to go to steady state. With proper tuning of the SMES-CES-PSS parameters, the Overshoot that occurs in this system can be reduced. In addition, the increase in the eigenvalues and damping system using the proposed control scheme shows that the system performance is getting more optimal. For future research, it can be combined with other control methods such as PID and Redox Flow Battery to get more optimal results. In addition, the development of artificial intelligence algorithms can be used for optimization of control parameters.

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