Power System Performance Enhancement using Superconducting Magnetic Energy Storage unit and Proportional Integral Derivative Control

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***Abstract*— Frequency oscillations in power systems may occur due to sudden load change or system disturbance. Such oscillations may result in unsynchronized and undamped signals. In a multi machine system where all generators must operate in synchronism, undamped oscillations may lead to instability. To overcome this issue, this paper proposes a damping control scheme consisting of Superconducting Magnetic Energy Storage (SMES) and Proportional Integral Differential (PID) controller to effectively damp frequency oscillations in multi-machine systems. Control parameters of the proposed SMES-PID system are tuned using Particle Swarm Optimization (PSO) algorithm. Simulation results reveal the effectiveness of the proposed controller in damping the frequency oscillations and maintain system dynamic and transient stability during various disturbance events. It is shown the design can find better quality solution in minimizing overshoot at frequency variations up to 78 % and accelerating the settling time up to 67 %.**

Keywords— Frequency oscillation, SMES, PID, PSO

I. Introduction

Low frequency oscillations are a common issue in multi-machine systems. If the system is not stiff enough or if it lacks proper damping control scheme, it may lead to instability and blackout. Suggested solutions to increase system damping is by the use of SMES unit and PID controller.

In this paper, a damping control scheme comprising SMES unit and PID is proposed for a multi-machine system. The addition of SMES is intended to increase the power system and system transients. It results the dampen out low frequency power oscillations and stabilizing the system frequency [1]. SMES is able to store excessive energy in high temperature superconductor inductors and release stored energy if it is needed [2].

PID is able to solve complex problems of automation and industrial control because it is simple, effective, and reliable. The combination of SMES and PID controller with optimum control parameters can effectively damp oscillations in power systems. This controls will work optimally with the right parameter value because it will be tuned by the PSO algorithm. PSO features simplicity and rapid convergence with high quality solution.

II. Fundamental Theory

A. Power System Stability

Power system stability is the ability of the system to retain normal operations after a sudden load change or severe disturbance without losing synchronism. Power system stability can be classified into several categories as summarised in Figure 1 [3].

B. Overview of SMES

SMES unit can be controlled to modulate both active and reactive power of the system it is connected to in four quadrant operation. It features very rapid response along with decoupled active and reactive power control.

In SMES unit, energy is stored in a superconducting coil of zero physical resistance. SMES unit comprises superconducting coil, Power Conditioning System (PCS), a cryogenic refrigerator and a cryostat or vacuum vessel at low temperature so it can keep superconducting state. The typical configuration of SMES is shown in Figure 2 [4].

The basic configuration of a thyristor-based SMES unit, which consists of a Wye- Delta transformer, an ac / dc thyristor controller bridge converter, and a superconductor coil is shown in Figure 3. The coil current is always unidirectional while the voltage across the coil can be varied within negative and positive values depends on the slope of the coil current. Hence power flow control can be achieved by controlling the slope of the current through the switches firing angles. Positive slope yield positive voltage i.e. power is being delivered to the coil (charging mode). On the other hand, negative slope for the coil current results in negative voltage and power is delivered from the system to the system (discharging mode) [5]. Converter operates in rectifier (charging) mode if it is less than 90^o and in inverter (discharging) mode if it is more than 90^o. During normal operation there should not be any energy exchange between the system and the SMES coil.

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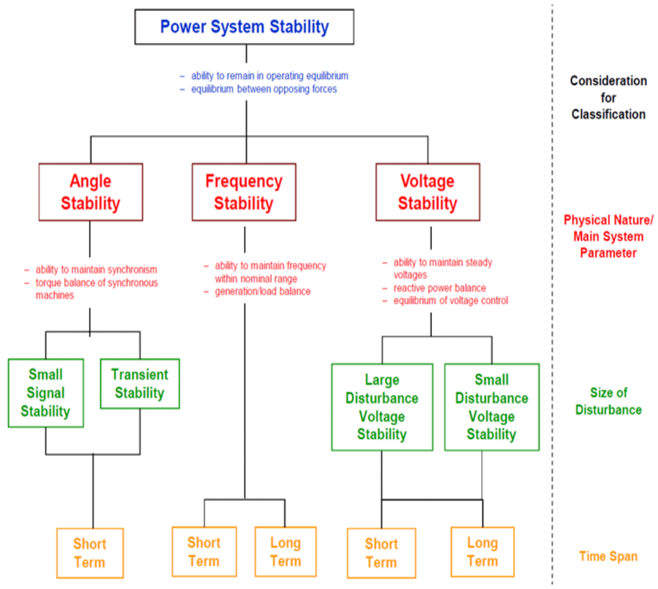


Figure 1 Power system stability classification [3]

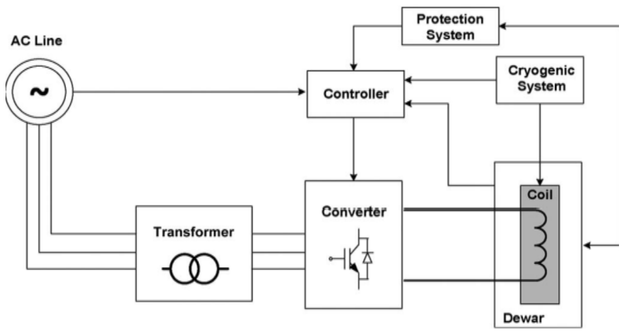


Figure 2 Typical schematic diagram of a SMES [4]

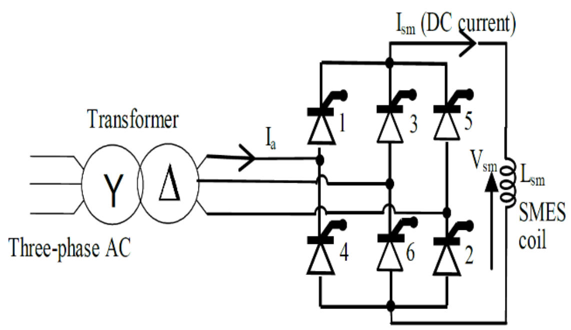


Figure 3 SMES Converter with 6-pulse bridge thyristors

C. PID Controller

PID controller can improve the dynamic response of power system and eliminate the error, with a simple structure, good stability and strong resilience [6]. It has the below transfer function:

$$u(t) = k_p\left[e(t) + \frac{1}{T_i}\int_0^t e(t)dt + T_d\frac{de_t}{dx}\right] \quad (1)$$

PID controller shown in Figure 4 functions include:

a) Overall action is provided by the propotional term (K_p) which is propotional to the error signal,
b) Steady-state errors are reduced by the integral term (K_i) through low frequency compensation,
c) Transient response is improved by the derivative term (K_d) through high-frequency compensation.

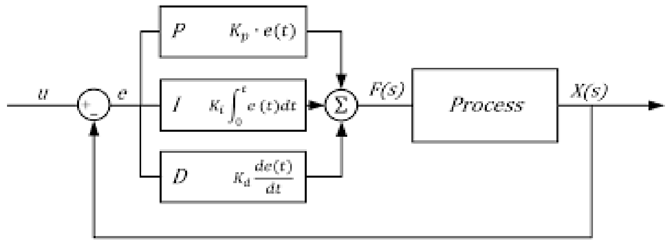


Figure 4 PID Control System

III. Methodology

A. Multi Machines Power System Modeling

In general, the power generation system can be described as shown in Figure 5.

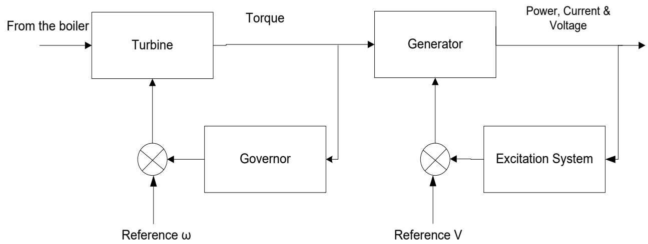


Figure 5 General Power Plant Model

The mechanical system includes, asynchronous generator, turbines and excitation system [3]. If there is a change in the generator output due to a change in the power demand, there will be a feedback function governed by the governor to readjust the rotor rotation. The proposed SMES-PID controller in this paper is employed for a multi machine systems (500 kV) that consists of 8 generators and 25 buses. SMES unit would be installed in Generator 1 which the highest capacities as shown in Figure 6.

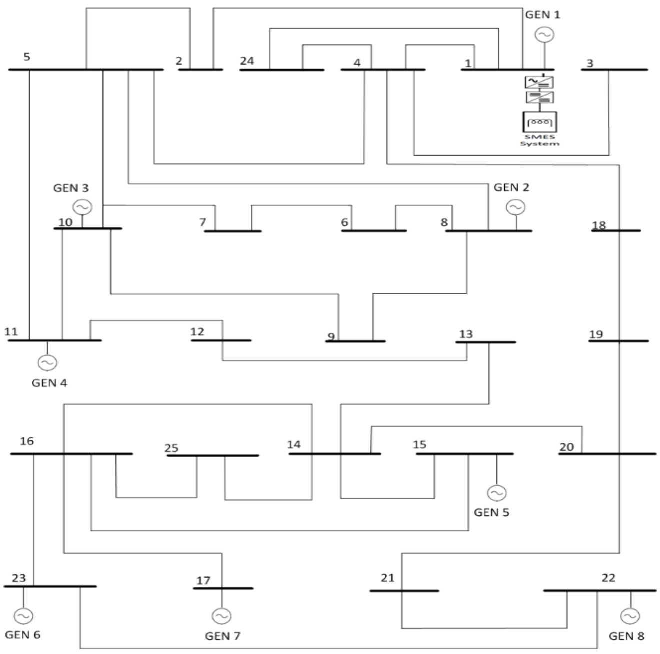


Figure 6 System Model

B. SMES Modeling

The block diagram of the proposed SMES model is shown in Figure 7. Since the I_{sm} current through the coil cannot be reversed, the active power P_{sm} exchange depends on the voltage V_{sm} polarity as per the below equations [7]:

$$P_{sm} = V_{sm} I_{sm} \tag{2}$$

$$\frac{dI_{sm}}{d_\tau} = \frac{(V_{sm} - R_{sm}I_{sm})}{L_{sm}} \tag{3}$$

Since the coil has almost zero resistance, and assuming initial current of the superconducting coil as I_{sm0}, then the current I_{sm} can be obtained as [8] :

$$I_{sm} = \frac{1}{L_{sm}} \int_{t_0}^{t} V_{sm} d\tau + I_{sm_0} \tag{4}$$

The amount of energy storage in the SMES coil is calculated by the following equation:

$$\mathbf{W_{sm}} = \mathbf{I_{sm_0}} + \frac{\mathbf{1}}{\mathbf{L_{sm}}} \int_{\mathbf{t_0}}^{\mathbf{t}} \mathbf{P_{sm}(\tau)\, d\tau} \tag{5}$$

where W_{sc0} is the amount of energy in the coil stored at $t = t_0$ and given as :

$$\mathbf{W_{sm_0}} = \frac{\mathbf{1}}{\mathbf{2}} \mathbf{L_d I_{sm_0}^2} \tag{6}$$

SMES voltage is regulated continuously depending on changes in the generator rotor speed .

$$\mathbf{\Delta V_{sm}} = \frac{\mathbf{K_c}}{\mathbf{1 + sT_{dc}}} \mathbf{\Delta\omega} \tag{7}$$

where K_c is the gain of control loop and T_{dc} is the control device time delay.

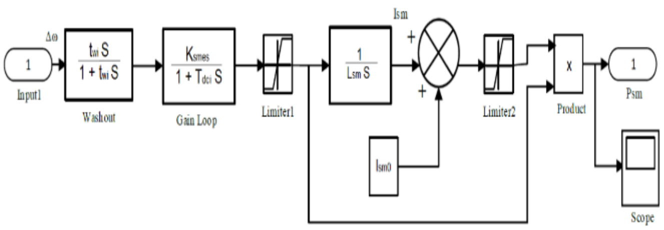


Figure 7 SMES Model [8]

To prevent the possibility of interrupted conduction during "discharging mode", the current inductor should not reach zero. Hence, the minimum limit of the inductor current must be set at 30% of I_{sm0} [9]. In addition, it is also necessary to regulate the maximum permitted energy absorption so that it is equal to the maximum permitted energy released by regulating the rated inductor current. A sudden increase and decrease in load makes SMES unit equally effective in swing damping. In this study, the designs using LTS pulse coils are listed in table 1. Based on research results [10], it was found that SMES coil sizes of 100 kJ and 1 MJ have low ac losses. There are 2 (two) types of coil options that will be analyzed.

Table 1 Parameters of the two investigated SMES Coils [10]

	100 kJ coil	1 MJ coil
Turns	938	2562
Layers	14	14
Height	402 Mm	1098 Mm
Outer Diameter	509 Mm	804 Mm
Inner Diameter	305 Mm	600 Mm
Length of Conductors	1200 M	5650 Mm
Inductance	0.2 H	2.0 H
Operating Current	1000 A	1000 A
Store Energy	100 Kj	1 MJ
Rated Output	50 Kw. 1 Sec	500 Kw. 1sec

C. PSO Algorithm

Particle Swarm Optimization (PSO) algorithm was introduced by Kennedy and Eberhart in 1955 and it was inspired by the social behavior of flocks of birds that fly together [11,12,13]. This social behavior consists of individual and group actions. Each individual behaves in a distributed manner by using self intelligence and is also influenced by the group.

When a particle finds the best position, then another particle will move towards the particle. But when there are other particles that find a better position than the first best particle, then all the particles will turn towards the better particle. This process will continue until it gets the best particle position. The speed of movement of each particle is formulated by equation (8). And the distance from the initial position of the particle to the best particle is defined by equation (9).

$$v_i^{k+1} = v_i + c_1 r_1 (Pbest_i - x_i^k) + c_2 r_2 (Gbest - x_i^k) \tag{8}$$

$$x_i^{k+1} = x_i + v_i^{k+1} \tag{9}$$

Where,
i = particle to
k = number of iterations
c1 and c2 = constants
Pbest = the best position ever achieved by each particle
Gbest = the best position achieved each iteration
r1 and r2 = random numbers

D. Objective Function

To get the optimal value, the PSO algorithm will work with the specified objective function. The best position of the PSO represents the best parameters of SMES and PID. The best combination will produce a system that has oscillations with the smallest overshoot and the fastest settling time. The best combination is obtained through evaluation on each combination of the SMES and PID parameter values. Evaluation is done by calculating the value of the objective function of the system response. In this study, the objective function used is to test the stability of Integral Time Absolute Error (ITAE) shown by the equation,

$$ITAE = \int_0^t t|ACE(t)|dt \tag{10}$$

IV. Simulation Results

Matlab / Simulink environment is used to simulate the multi-machine system along with the proposed SMES-PID control system. The PSO data are given in the Table 2 and the tuned control parameters using PSO are listed in Table 3. Two disturbance scenarios are assumed and investigated with two coil sizes as elaborated below.

Table 2 Parameters of PSO Algorithm

PSO Size	50
Maximum Iteration	50
Sum of_Variabels	12
C1 (social Constant)	2
C2 (Cognitive Constant)	2
W (PSO Momentum)	0.9

Table 3 Optimum control parameters obtained using PSO

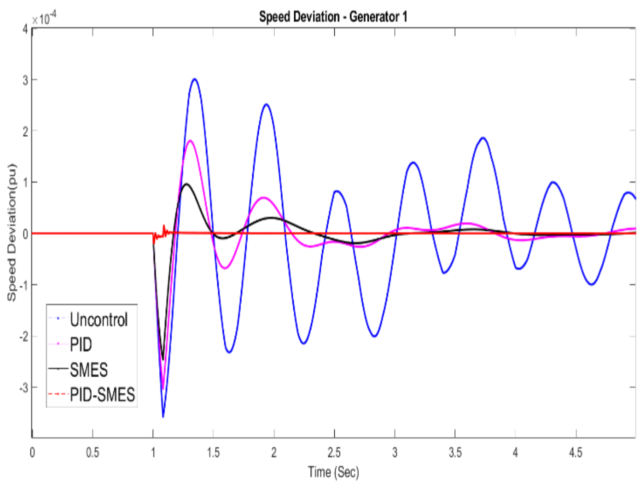
Description	Symbol	Value	Range Value
SMES			
SMES delay time constant	Tdci_s	5.1368	5 – 15
SMES washout time constant	twi _s	11.176	5 – 15
Strengthening of the control	Ksmes _s	8.64E+03	100000 –200000
PID Controller			
Proportional	Kp_s	181.0864	150-200
Integral	Ki_s	6.734	May-25
Derivatives	Kd _s	0.0002	0-25
SMES and PID			
SMES delay time constant	Tdci	8.7821	5 – 15
SMES washout time constant	twi	11.5347	5 – 15
Strengthening of the control	Ksmes	1.74E+03	100000 – 200000
Proportional	Kp	181.0864	150-200
Integral	Ki	51.0818	30-55
Derivatives	Kd	50.8617	30-55

A. Case 1: Load Changes of 0.05 pu.

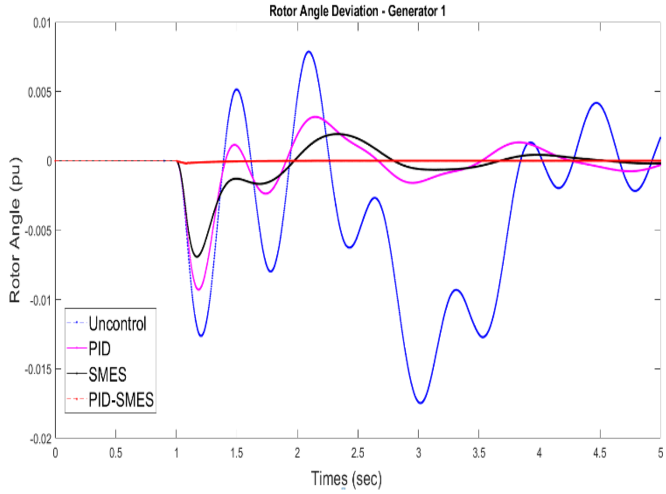
The system response due to a generation change of 0.05 pu at t= 1 s in generator 1 is shown in Figure 10 with Lsm = 0.2 H.

It can be seen that, without any control system the rotor speed exhibits substantial oscillations (Figure 8a). Using PID controller, the maximum overshooting of the speed oscillation is reduced however, settling time is still relatively high. When the SMES-PID controller is used, the oscillations of the rotor speed are effectively damped. Likewise, Figure 8 (b) and (c) reveal a better performance for the generator 1 terminal voltage and rotor angle when the proposed SMES-PID is employed.

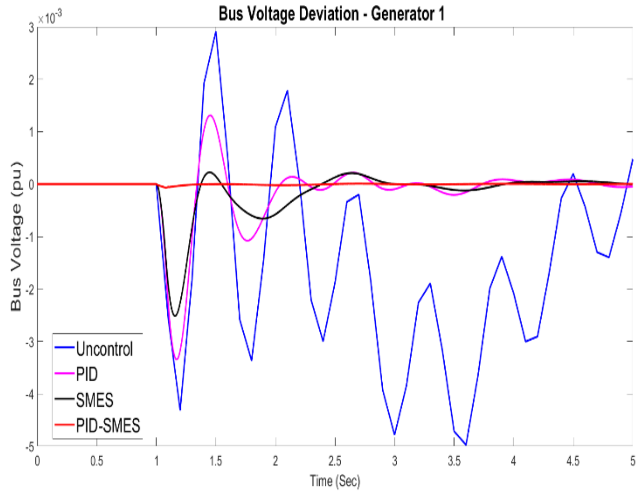
Table 4 shows a comparison of the maximum overshooting and settling time in various system parameters deviations including rotor speed, terminal voltage, and rotor angle for the system without and with the investigated controllers. It can be seen that when the SMES PID controller is employed, the system exhibits the smallest frequency oscillation and least settling time. Also the power fluctuation factor (*kp*) is getting close to zero with the proposed SMES-PID controller.



(a) Speed Deviation



(b) Rotor Angle Deviation



(c) Bus Voltage Deviation

Figure 8 System response due to 0.05 pu generation change at t=1s

Table 4 Comparison of settling time and overshooting

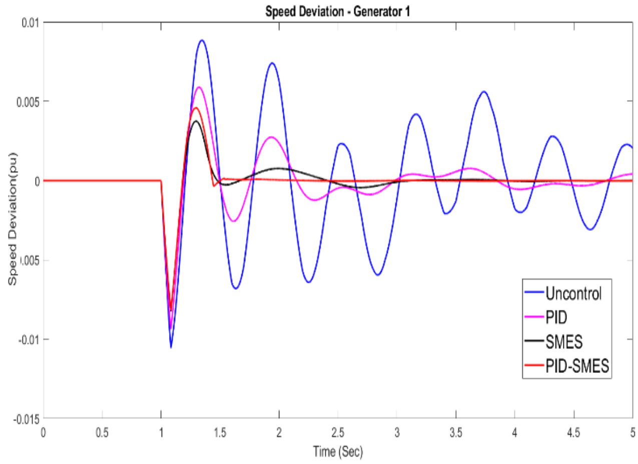
System	Maximum Overshoot (Pu)			Settling Time (s)			Peak-To-Peak Value/P	kp (%)
	$\Delta\omega$	ΔVt	$\Delta\delta$	$\Delta\omega$	ΔVt	$\Delta\delta$		
Uncontrol	3.00E-04	2.91E-03	3.00E-04	22.4	22.13	20.2	6.58E-04	66%
PID	1.80E-04	2.91E-03	1.80E-04	10.3	8.736	9.19	2.25E-04	23%
SMES	9.57E-05	2.24E-04	9.57E-05	5.67	7.09	5.33	4.72E-05	5%
PID + SMES	1.53E-05	7.40E-06	1.53E-05	1.19	2.457	1.66	3.58E-05	4%

B. Case 2: Three-Phase Fault at Line 10-11

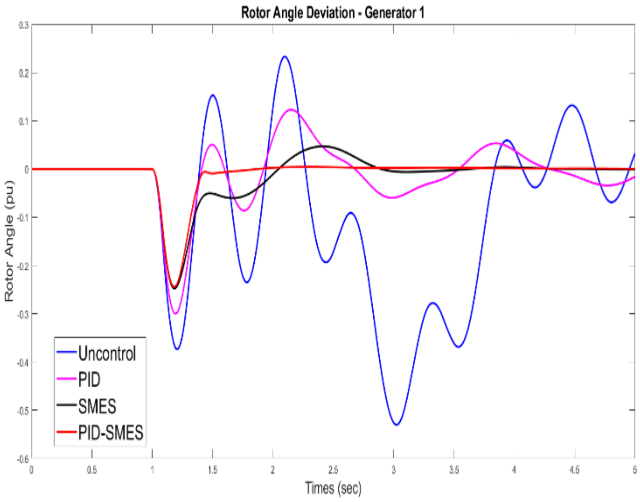
In this case, a large disturbance of three-phase fault at Line 10-11 is assumed. The disturbance is set at t=1 s and is assumed to last for 5 cycles, i.e. 0.083s (on a 60 Hz basis). Without controller, significant fluctuations in the rotor angle, speed and bus voltage deviation at generator 1 due to such disturbance can be observed as shown in Figure 9.

As shown in Figure 9, the generator rotor speed, bus voltage and rotor angle profiles are significantly improved with the use of SMES-PID controller. The system is stabilized at time t = 2.053 s.

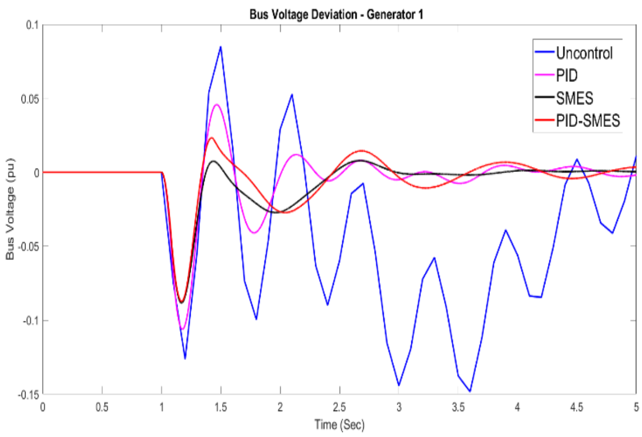
Figure 10 shows the SMES active power with two coil sizes 0.2 H and 2 H with and without the addition of the PID controller. It can be seen that, the SMES unit features a rapid response to system disturbance as it starts to inject active power to the system when the fault takes place at t=1s. with the increase of the coil size, energy stored in the coil is increasing however, this will be on the account of the system cost. The utilization of the PID does not affect the SMES power profile. It was observed that SMES with L_{sm} = 0.2 H and L_{sm} = 2 H has almost the same damping effect on damping power oscillations. L_{sm} coil of 0.2 H with stored energy of 100 kJ is adequate to stabilize the system under study. Overshooting values, settling time and fluctuation factors in system parameters are listed in the Table 5 which attest the robustness of the proposed SMES-PID controller.



(a) Speed Deviation



(b) Rotor Angle Deviation



(c) Bus Voltage Deviation

Figure 9 System Performance under three-Phase Fault

The frequency response graph from two cases above used 2 (two) different types of coil size in the system therefore it can be seen that the use of PSO-based PID SMES can reduce the system overshoot and speed up the system to stabilize. From the data table 6, it can be seen that SMES can improve system performance. The frequency response overshoot value can be reduced to 62% and increased to 75% by combining the SMES unit and PID controller compared to the uncontrolled frequency response when simulated with the SMES Lsm coil size = 0.2 H. The simulation results with the SMES Lsm coil size = 2 H will give an average decrease in overshoot up to 78%.

Whereas for the realization of settling time in the frequency response, it is seen that an acceleration occurs reaching a stable condition of the system by 60% through a combination of SMES and PID controller when simulated with a SMES coil size Lsm = 0.2 H and reaching 67% when it simulated with a SMES coil size Lsm = 2 H. The size of the SMES coil influences the design performance of the system being designed but it needs to be considered in planning the system requirements.

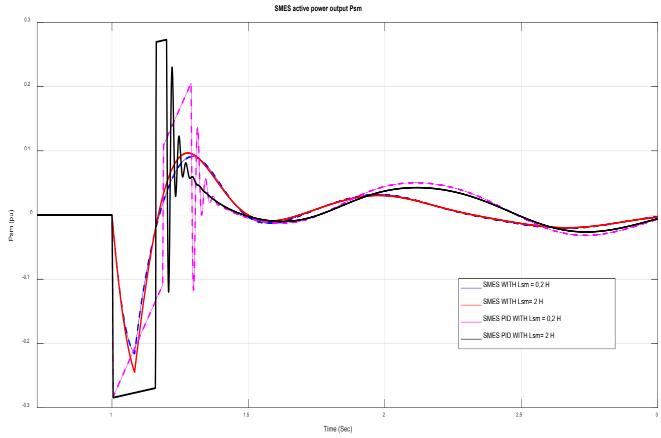


Figure 10 Active Power of the SMES - P_{sm}

Table 5 Comparison of settling time and overshooting

System	*Maximum Overshoot (Pu)*			Settling Time (S)			*Peak-To-Peak Value/P*	*kp (%)*
	Δω	ΔVt	Δδ	Δω	ΔVt	Δδ		
Uncontrol	3.76E-03	2.89E-03	7.92E-03	32.5	34.2	32.8	8.24E-03	82%
PID	2.26E-03	1.29E-03	3.20E-03	10.29	12.19	13.4	6.05E-03	60%
SMES	1.34E-03	2.08E-04	1.94E-03	4.126	7.39	3.05	3.89E-03	39%
PID + SMES	9.60E-04	7.15E-06	2.88E-06	2.859	6.11	2.08	3.53E-03	35%

Table 6 Overshoot of Response Frequency

			Coil Size Lsm = 0.2 H		Coil Size Lsm = 2 H	
UNIT	**No control**	**PID**	**SMES**	**PID-SMES**	**SMES**	**PID -SMES**
Generator 1	0.00376	0.00226	0.00134	0.00096	0.0012	0.00093
Generator 2	0.00209	0.00128	0.00078	0.00041	0.00071	0.00031
Generator 3	0.0015	0.00087	0.00053	0.00031	0.00049	0.00025
Generator 4	0.00106	0.00056	0.00034	0.00027	0.00033	0.00023
Generator 5	0.00168	0.00093	0.0006	0.00038	0.00056	0.00031
Generator 6	0.00137	0.00085	0.00056	0.00036	0.00053	0.0003
Generator 7	0.0016	0.0011	0.00082	0.00057	0.00078	0.00048
Generator 8	0.00123	0.00067	0.00042	0.00032	0.00041	0.00027
Average Percentage	**0%**	**40%**	**62%**	**75%**	**65%**	**78%**

Table 7 Settling Time of Respon Frequency

Unit	UN Control	PID	SMES (Coil Size Lsm = 0.2 H)	PID-SMES (Coil Size Lsm = 0.2 H)	SMES (Coil Size Lsm = 2 H)	PID-SMES (Coil Size Lsm = 2 H)
Generator 1	32.5	10.29	4.126	2.859	4.872	2.527
Generator 2	26.57	20.08	12.04	10.96	9.652	8.7
Generator 3	27.52	18.47	11.42	10.04	10.22	9.224
Generator 4	32.32	21.08	13.83	12.29	10.9	9.782
Generator 5	31.87	19.38	12.03	11.82	10.31	9.58
Generator 6	28.34	17.59	12.5	12.31	10.62	9.956
Generator 7	27.85	18.44	13.46	11.64	10.25	9.954
Generator 8	32.4	18.63	13.83	12.86	10.45	9.882
Average Percentage	**0%**	**32%**	**56%**	**60%**	**64%**	**67%**

CONCLUSIONS

This paper shows the application of PSO algorithm to tune the parameters of the SMES-PID controller to improve the performances of multi machine systems under small and severe disturbances. The performance of the investigated system is tested under three modes; without control system, with SMES unit and with SMES-PID controller. Results show that the SMES-PID controller provides the best control performance in terms of damping system oscillations, and stabilizing the system after small and severe disturbances. The system is able to reduce the overshoot value at the frequency response to 78% and the value of settling time acceleration occurs up to 60%.The selection of SMES coil size must be carefully considered due to its high cost. From the simulation results, the SMES coil size of 0.2 H and 2 H are of similar damping effect on power system oscillations.

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