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Optimization of SMES and TCSC using particle swarm optimization for oscillation mitigation in a multi machines power system

Dwi Lastomo [a,*], Herlambang Setiadi [b], Muhammad Ruswandi Djalal [c]

[a] *UPMB Institut Teknologi Sepuluh Nopember*
UPMB Building Jl Raya ITS, Surabaya 60117, Indoneisa
[b] *School of Information Technology & Electrical Engineering The University of Queensland*
Level 4 / General Purpose South Building (buliding 78) St. Lucia Campus, Brisbane, Australia
[c] *Department of Mechanical Engineering Ujung Pandang State Polytechnics*
Jl. Perintis Kemerdekaan 7 km. 10, Makassar, Indonesia

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Abstract

Due to the uncertainty of load demand, the stability of power system becomes more insecure. Small signal stability or low-frequency oscillation is one of stability issues which correspond to power transmission between interconnected power systems. To enhance the small signal stability, an additional controller such as energy storage and flexible AC transmission system (FACTS) devices become inevitable. This paper investigates the application of superconducting magnetic energy storage (SMES) and thyristor controlled series compensator (TCSC) to mitigate oscillation in a power system. To get the best parameter values of SMES and TCSC, particle swarm optimization (PSO) is used. The performance of the power system equipped with SMES and TCSC was analyzed through time domain simulations. Three machines (whose power ratings are 71.641, 163, and 85 MW) nine buses power system was used for simulation. From the simulation results, it is concluded that SMES and TCSC can mitigate oscillatory condition on the power system especially in lowering the maximum overshoot up to 0.005 pu in this case. It was also approved that PSO can be used to obtain the optimal parameter of SMES and TCSC.

Keywords: Power System Oscillation; FACTS; SMES; TCSC; PSO

I. Introduction

Electrical energy is one of the important requirements for modern society. In recent years, demand for electricity has increased significantly. Due to increasing of load demand, providers of electricity need to expand their transmission system and increase the generating capacity. Moreover, the entire system becomes more complex and larger. Stability is one of the common problems in a large system, especially when perturbation occurs. Small perturbation such as load fluctuation could contribute to system instability, such as low-frequency oscillation.

The low-frequency oscillation has a frequency range of approximately 0.1-2 Hz focusing in electromechanical mode either local or global problems [1]. If this oscillation is not well damped, the magnitude of this oscillation may keep growing until the system loses synchronism [2]. This oscillation can be decreased by putting damper windings in the rotor. However, over the times, the performance can be declined significantly. Another way is by using flexible AC transmission system (FACTS) devices. However, due to the uncertainty of the load, FACTS devices alone cannot address the low-frequency oscillation problems. Hence, the deployment of energy storage has become crucial.

In this era, there is numerous type of energy storage such as flywheel energy storage [3], battery energy storage [4], redox flow batteries [5], capacitive energy storage [6] and superconducting magnetic energy storage [7]. Superconducting magnetic energy storage (SMES) is the energy storage that is gaining popularity in recent year because of fast response

* Corresponding Author. Tel: +62 856 2981 144
E-mail address: dtomo23@gmail.com

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when storing and releasing energy. The most important part of SMES is the controller. To obtained the best controller parameter of SMES, metaheuristic algorithm approach can be the solution.

Metaheuristic Algorithm is an algorithm inspired by nature behavior. Metaheuristic algorithm can be classified into 3 types. Namely, social inspired, physical inspired, and biological inspired [2]. Particle swarm optimization (PSO) is metaheuristic algorithm based on the biologically inspired algorithm. PSO is widely used due to simple modeling and fast calculation to solve optimization problems.

The application of PSO for optimizing FACTS devices has been proposed by Shahgholian et all. [8]. In that research, FACTS based PSO has shown good performance for providing damping to the system when installed in the transmission line. Wei et all. made use of the SMES to mitigate oscillatory condition of multi-machines power system [9]. It can be seen in the research that SMES gives an attractive performance for providing damping by storing and releasing energy from the grid. Application of PSO for optimization method in power system has also been conducted by Kerdphol et all [10]. It can be stated that PSO shows marvelous performance to find the optimal capacity of battery energy storage in microgrid system. These researchers showed a good performance of FACTS devices and SMES to enhance small signal stability by mitigating the oscillatory condition of the power system. These researches also showed that PSO could provide fast calculation, simple modeling and accurate result for optimization problems. However, very scant attention has been paid for combining and coordinating FACTS devices and SMES to mitigate power system oscillation.

Thus, this research novelty is combining two different devices which are FACTS devices (TCSC) and energy storage (SMES) for small signal stability enhancement. The TCSC might improve the stability in the transmission line, while the energy storage (SMES) could contribute damping by providing active power instantaneously into the grid. Furthermore, this research also contributes on how to coordinate between the FACTS devices (TCSC) and energy storage (SMES) using one of the intelligent methods called PSO to mitigate oscillatory condition on power system due to load fluctuation.

The rest of this paper is organized as follows: Section II briefly explain about power system modeling, SMES dynamic model, and TCSC mathematical representation. PSO concept including the objective function of proposed method and modeling the entire system are described in section III. Section IV shows the time domain simulation results of the studied case. Section V presents the conclusion.

II. Fundamental theory

A. Power system modelling

For small signal stability study, power system model can be presented as a set of differential and algebraic equations as in Equations (1) and (2) [11].

$$\dot{x} = f(x, y, l, p) \tag{1}$$

$$0 = g(x, y, l, p) \tag{2}$$

where x is a state vector and y is a vector of algebraic variables. Dynamic stability studies can be done in two ways depending on the interest [11]. If the interest is to understand dynamic characteristic in the local behavior related to the particular plant, the single machine infinite bus (SMIB) can be used as study cases. If the interest is capturing both local and global problem, then every machine in the system should be modeled in detail [11].

1) Synchronous generator model

Assuming that the value of stator resistance is ignored, the condition is considered the balanced system, the core saturation on the generator is ignored, and the system load is considered being static. The well known Park's transformation [12] serves to transform current, voltage, and flux density into variables in three axes, namely direct axis, quadrature axis and stationary axis. Clear depiction of the Park's transformation can be seen in Figure 1.
The synchronous generator comprises of torque equation and field equation. The relationship between rotor angle and rotor speed can be written in a set of a differential equation as in Equations (3) and (4).

$$\dot{\delta}_i = \omega_i - \omega_B \tag{3}$$

$$\dot{\omega}_i = \frac{1}{M_i}[T_{mi} - T_{ei} - D_i(\omega_i - \omega_B)](4) \tag{4}$$

where T_{mi}, T_{ei}, D_i, ω_B, and M_i are mechanical torque, electric torque, the damping constant, base speed, and machine inertia. Equations (5) and (6) can express field equations.

$$\dot{E}'_{qi} = \frac{1}{T'_{doi}}\left[E_{fdi} - T'_{qi} - (x_{di} - x'_{di})i_{di}\right] \tag{5}$$

$$\dot{E}'_{di} = \frac{1}{T'_{qoi}}\left[-E_{fdi} - (x_{qi} - x'_{qi})i_{di}\right] \tag{6}$$

where T'_{doi}, T'_{qoi}, x_{di}, x'_{di}, x_{qi}, and x'_{qi} are the transient time constant in d axis, the transient time constant in q axis, reactance in d axis, transient reactance in d axis, reactance in q axis and transient reactance in q axis respectively.

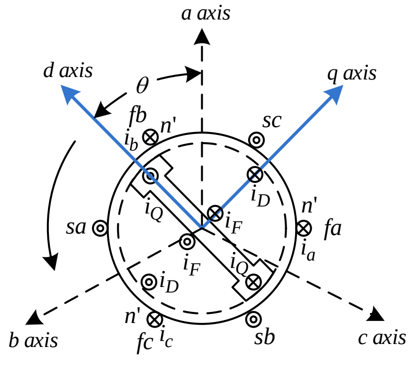

Figure 1. Park's transformation [12]

2) Excitation system

The synchronous generator consists of a stator with windings anchor and rotor with field windings. Rotor field windings must be injected with a direct current (DC) to generate a magnetic field. This particular system is called excitation system. Fast exciter model is used in this study. Fast exciter excitation is the simplest model consisting of one K_{Ai} gain and T_{Ai} time constant expressed in Equation (7) [13].

$$E_{fd} = \frac{K_A(V_t - V_{ref})}{1 - T_{AS}} \tag{7}$$

where K_{Ai} is gain and T_{Ai} is the time delay of the exciter [13]. Figure 2 shows the fast exciter block diagram.

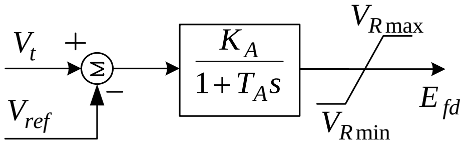

Figure 2. Fast exciter block diagram

3) Governor model

A governor is to regulate the magnitude of mechanical torque provided to the generator. Variation of mechanical torque in the governor is influenced by speed, load, and speed reference variation. The mathematical representation of governor model is shown in Equation (8) [14].

$$P_m = -\left[\frac{K_g}{1+T_g s}\right]\omega_d \tag{8}$$

where K_g, T_g, and R are gain constant, the time delay of the governor and droop constant respectively. The gain constant and the droop relationship is inversely proportional. Figure 3 depicts the block diagram of the governor.

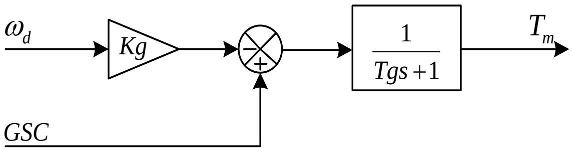

Figure 3. Governor block diagram

B. Superconducting magnetic energy storage

SMES is a device for storing and releasing the power in large number simultaneously. SMES saves energy in a magnetic field created by DC current in superconducting coils, and it is cooled by a cryogenic. SMES system has been used for a few years to improve the power quality industry and provide good voltage control when voltage fluctuation arises. SMES recharging can be done just a couple minute and can repeat the charge and discharge modes thousands time without reducing the magnet. Recharging time can be accelerated to meet specific criteria depending on the capacity of the system [15].

SMES was first introduced by Ferier in 1969, the man who first proposed the construction of a toroidal coil capable of supplying the daily storage of electrical energy across France [15]. However, the manufacturing cost was too expensive, so the idea was not met. In 1971 researchers at the University of Wisconsin the US began to explore the basic relationship between the energy storage unit to the electrical system passing multiphase bridge [15, 16]. SMES comprise of a superconducting inductor (SMES coil), cryogenic cooling system, and a power conditioning system (PCS) with controller and protection systems [15].

SMES in the power system used to effectively control the balance of power on the synchronous generator during periods of dynamic. SMES can be installed at a terminal bus of the power system. Figure 4 depicts the basic configuration of SMES consisting of a transformer, voltage sources converter, DC to DC chopper and superconducting coil. DC-DC converter and chopper are linked by a DC link capacitor [2, 15, 17].

The mathematical representation of SMES unit can be expressed using Equations (9) and (10).

$$\Delta \mathrm{E_d} = \frac{1}{1+\mathrm{sT_{dc}}}[k_0 \Delta\omega_1 - k_{Id}\Delta I_d] \tag{9}$$

$$\Delta I_d = \frac{1}{Ls}\Delta E_d \tag{10}$$

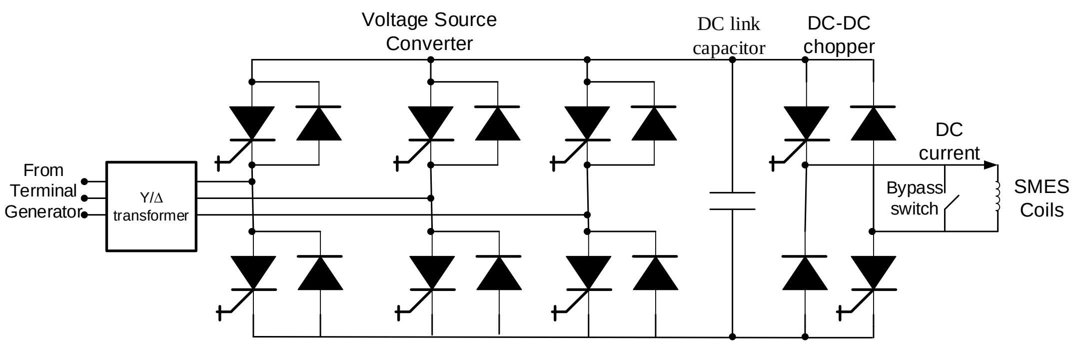

Figure 4. Schematic diagram of SMES [17]

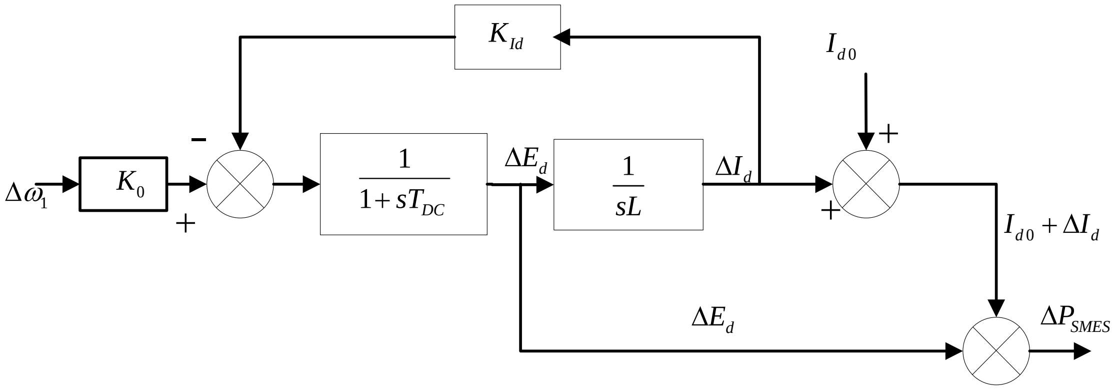

Figure 5. Block diagram of SMES [2, 18]

where T_{dc} is the converter time delay, ΔI_d is the current flowing through the inductor, ΔE_d is DC voltage applied to the inductor, k_0 is gain constant, L is the inductance of the coil, k_{Id} is the feedback gain, and $\Delta\omega_1$ is rotor speed oscillatory in generator 1 [2, 18]. Equation (11) expresses the deviation in the inductor real power of SMES [2, 18].

$$\Delta P_{smes}(t) = \Delta I_{d0}\Delta E_d + \Delta I_d \Delta E_d \quad (11)$$

where ΔP_{smes} is the real power that is released to the grid. Figure 5 shows the block diagram of SMES.

C. Thyristor controlled series compensator

Flexible AC Transmission Systems (FACTS) are becoming inevitable devices in transmission lines. FACTS devices provide parameter compensation in a transmission line to control the power flow. This device can control the magnitude of the voltage, line impedance, phase angle at the end of the channel and increase the security of the system. Thyristor controlled series compensator (TCSC) is one of FACTS devices that has become popular in recent years. TCSC is used for controlling transmission line reactance to provide load compensation [19]. TCSC consists of capacitor parallel connected with inductor and thyristor controlled reactor as depicted in Figure 6 [19].

In power flow study, TCSC can modify the transmission line. TCSC value level is a function of the reactance of the transmission line at the TCSC location. Moreover, TCSC can also be used as an oscillation damping controller. TCSC can be modeled as a variable reactance for the small signal stability study. The mathematical representation of TCSC can be described as in Equation (12).

$$\dot{X}_{tcsc} = \frac{1}{T_{tcsc}}\langle K_{tcsc}\left(X_{tcsc}^{ref} + U_{tcsc}\right) - X_{tcsc}\rangle \quad (12)$$

III. Design SMES and TCSC using particle swarm optimization

In this section, a dynamical model of the overall system is derived, and a brief explanation of particle swarm optimization (PSO) is described. At the end of this section, the objective function is presented based on the derived overall dynamical model. This objective function will be solved using PSO.

A. Power system model of overall system

Based on Equations (3) to (12), power system model in Equations (1) and (2) of the overall system can be expressed in Figures 7-9. Figure 7 shows the representation of the entire test system with TCSC installed in the transmission line. Figure 8 depicts a Simulink model of TCSC while Figure 9 illustrates a dynamic representation of power plant with exciter and governor. Furthermore, Figure 10 illustrates a dynamic model of a synchronous generator with SMES.

All of the systems is expressed in linear model representation. The parameters that will be optimized are gain constant of the SMES and parameters of the lead-lag block in the TCSC.

B. Particle swarm optimization

Particle swarm optimization (PSO) is an evolutionary computation optimization technique developed by Kennedy and Eberhart [20, 21, 22]. The system initially has a population of random solutions. Each potential solution is called a particle. Each particle is given a random velocity and is flown through the problem space. The particles have memory, and each particle keeps track of its previous best position (called the Pbest) and its corresponding fitness. There exist a number of Pbest for the respective particles in the swarm, and the particle with the greatest fitness is called the global best (Gbest) of the swarm.

The basic concept of the PSO technique lies in accelerating each particle towards its Pbest and Gbest locations, with a random weighted acceleration at each time step. The main steps in the particle swarm optimization and selection process are described as

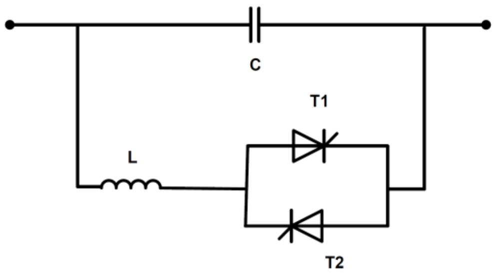

Figure 6. Schematic diagram of TCSC [19]

follows: (a) Initialize a population of particles with random positions and velocities in d dimensions of the problem space and fly them; (b) Evaluate the fitness of each particle in the swarm; (c) For every iteration, compare each particle's fitness with its previous best fitness (Pbest) obtained. If the current value is better than Pbest, then set Pbest equal to the current value and the Pbest location equal to the current location in the d-dimensional space; (d) Compare Pbest of particles with each other and update the swarm global best location with the greatest fitness (Gbest); (e) Change the velocity and position of the particle according to Equations (13) and (14) respectively;

$$V_{id} = \omega \times V_{id} + C_1 \times rand_1(P_{id} - X_{id}) + C_2 \times rand_2 \times (P_{gd} - X_{id}) \tag{13}$$

$$X_{id} = X_{id} + V_{id}(14) \tag{14}$$

(f) In this stage, repeat step procedure (a) to (e) until convergence is reached based on some desired single or multiple criteria.

C. Objective function and optimization method

The objective function for PSO can be determined using Equation (15).

$$E = \sum \int_0^{t1} t|\Delta\omega(t,X)|dt \tag{15}$$

where $\Delta\omega(t,X)$ is the oscillatory condition of generator rotor speed., X is composed by Kid of the SMES, and parameters T1, T2, T3, T4 of the TCSC, while t1 is the time frame of the simulation. Kid in SMES represents the feedback gain, while T1-T4 correspond to the lead-lag block of TCSC. In this research, the objective function is to minimize the value of E. Moreover the constraints of the problem are the SMES and the TCSC optimized parameter.

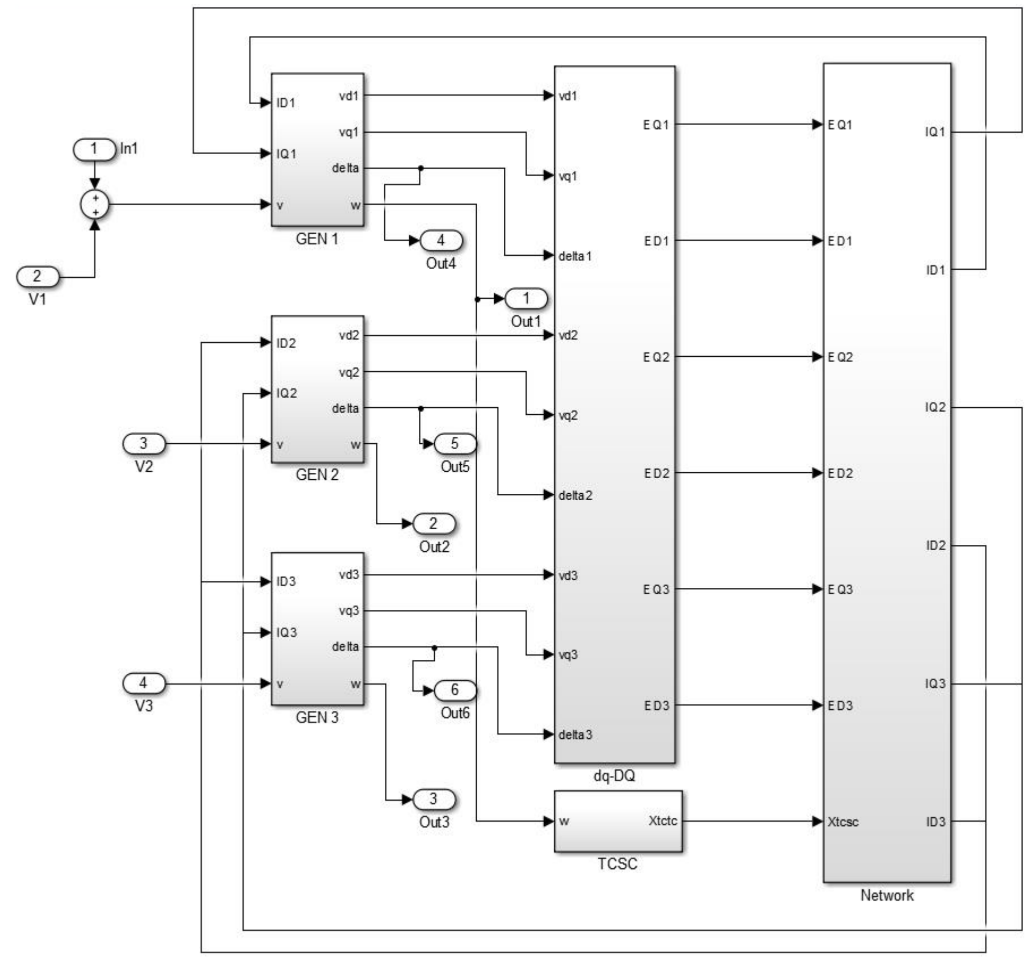

Figure 7. Simulink model of the test system

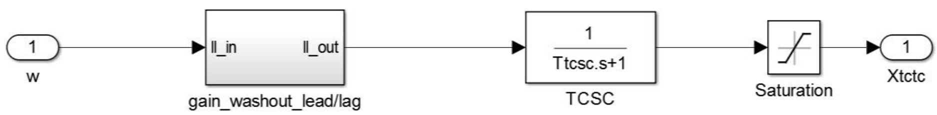

Figure 8. Simulink model of TCSC

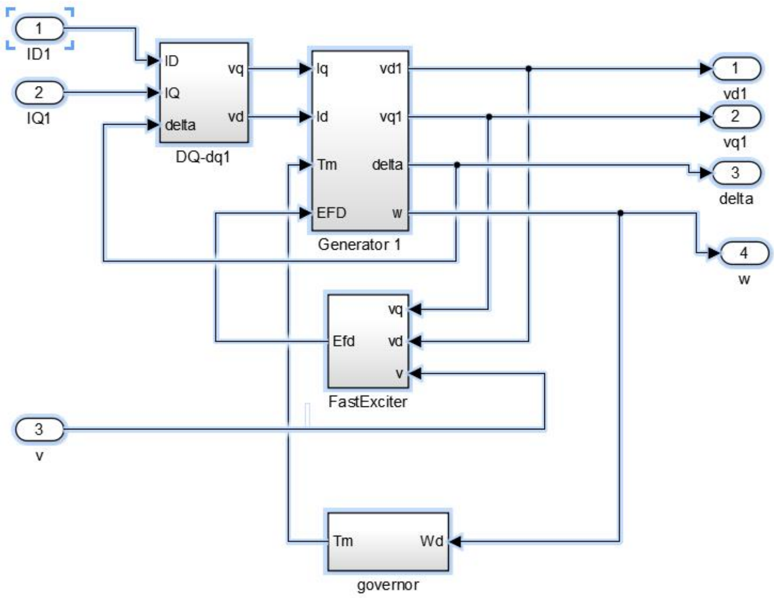

Figure 9. Simulink model of the power plant

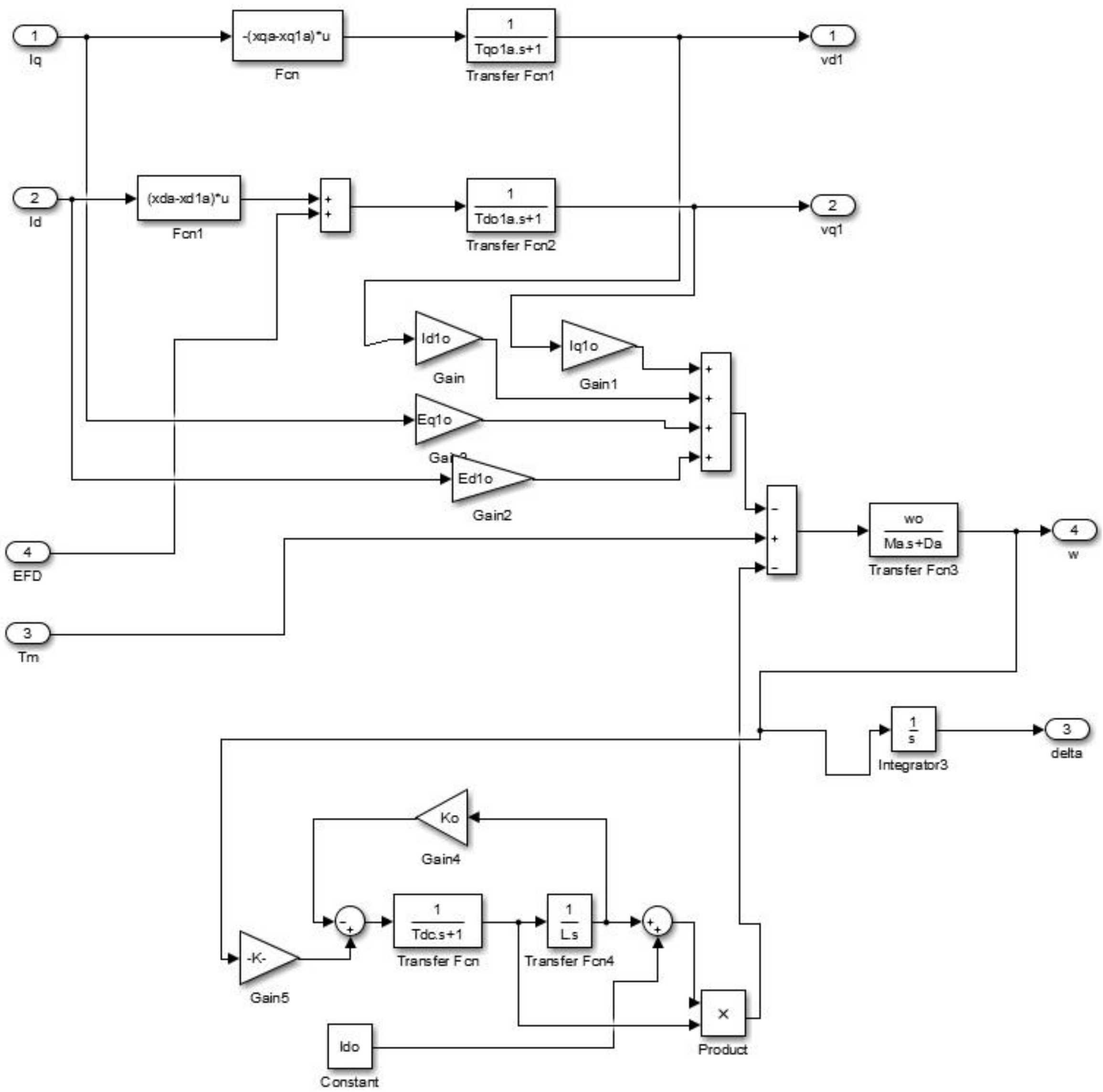

Figure 10. Simulink model of synchronous machine and SMES

Figure 11 shows the flowchart of the optimization algorithm used in this paper. The algorithm starts by initializing the multi-machine systems, SMES, TCSC and PSO parameters. Next, initialize the position and velocity of the particle by making a random matrix with particular constraint. Evaluation the objective function is done by finding the minimum error of the objective function. The next step is to update the local and global best of the particle. Then updating the velocity and the position of the particle is conducted. If the criterion is satisfied, then the algorithm will be stopped. If not, then the process will go back to initializing velocity of the particle. The iteration will stop depending on how many numbers of iteration is chosen.

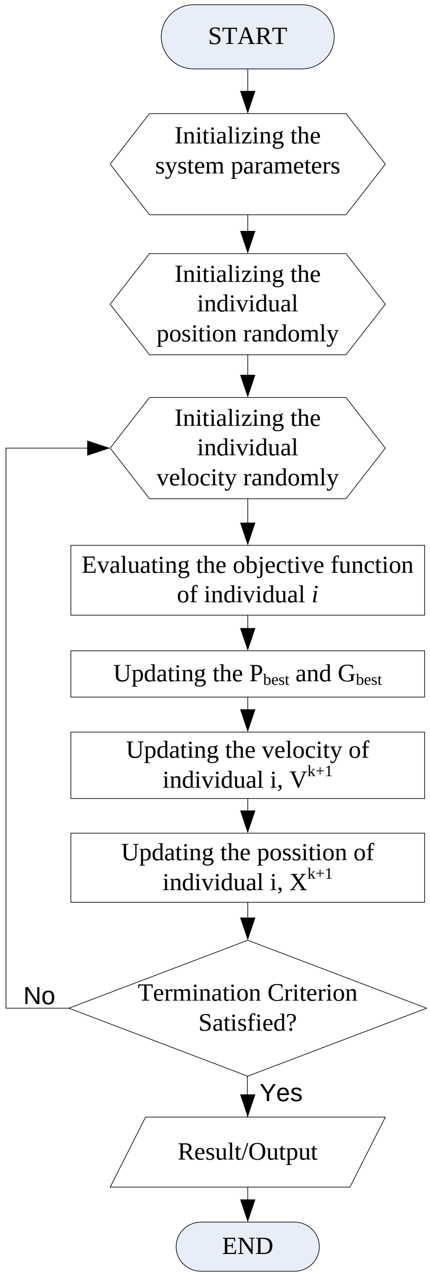

Figure 11. Flowchart of optimization procedure

IV. Result and discussion

An electrical power system shown in Figure 12 is investigated. It consists of 9 bus and 3 machines in which a SMES is installed in generator 1 bus and TCSCs are installed in lines between bus 5 and bus 7. The case study was simulated under MATLAB/SIMULINK environment in 50 seconds. In the simulation parameter setting, a continuous state with ode45 dormand-prince solver was set. PSO was used to optimize the parameter of SMES and TCSC.

Tables 1 and 2 [23, 24] show the power specification of the generators and loads and the specification of the bus resistance and reactance. Tables 3 and 4 list up the parameter values of generators and the exciters, respectively. The TCSC and SMES parameters values are listed in Table 5.

Table 1.
Power specification of the generators sna loads [23, 24]

Bus	Generating (MW)	Generating (MWar)	Load (MW)	Load (MWar)
1	71.641	27.046	0	0
2	163	654	0	0
3	85	-10.860	0	0
4	0	0	0	0
5	0	0	125	50
6	0	0	90	30
7	0	0	0	0
8	0	0	100	35
9	0	0	0	0

Table 2.
The Specification of bus resistance and reactance [23, 24]

Bus	R (pu)	X (pu)
1-4	0	0.0576
2-7	0	0.0625
3-9	0	0.0586
4-5	0.01	0.085
4-6	0.017	0.092
5-7	0.032	0.161
6-9	0.039	0.170
7-8	0.0085	0.075
8-9	0.0119	0.1008

Table 3.
Parameter values of the generators [23, 24]

Plant	Xd	Xd'	Td0'	Xq	Xq'	Tq0'
1	0.146	0.061	8.96	0.097	0.097	0.31
2	0.896	0.12	6	0.865	0.197	0.535
3	1.313	0.181	5.89	1.2	0.25	0.6

Table 4.
Parameter values of the exciters [2, 24]

Plant	H	Ka	Ta
1	23.64	20	0.2
2	6.40	20	0.2
3	3.01	20	0.2

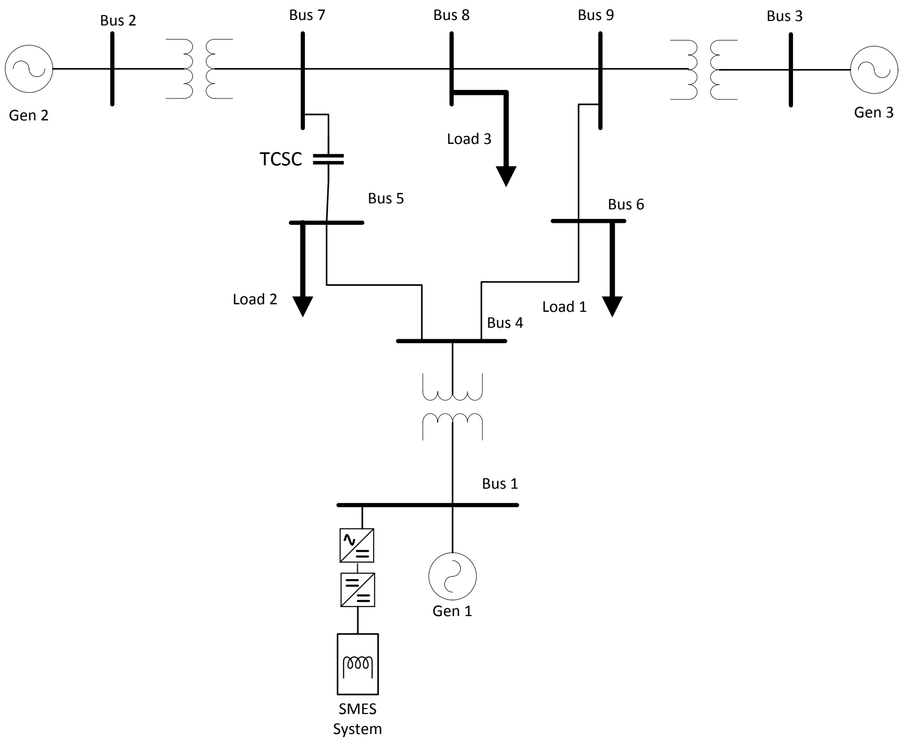

Figure 12. Schematic diagram of the three machines nine buses electrical power system with TCSC and SMES [23]

Figure 13 shows convergence curves of the fitness function during iteration of PSO. It is clear that after 10 iterations, the PSO found its convergence value. The optimum parameters values obtained through the iteration are listed in Table 6.

To investigate the effect of the application of PSO to the performance of the power system equipped with SMES and TCSC, three simulations have been conducted those are a simulation with TCSC (simulation 1), simulation with TCSC and SMES (simulation 2), and simulation with TCSC and SMES optimized by PSO (simulation 3). The operating condition in this case study is the initial condition of the multi-machine using Newton-Rapson method as power flow calculation. The Newton-Rapson method used 100 MVA and 0,001 as base power and

Table 5.
Parameter values of the TCSC and SMES [2, 24]

Parameter	Value	Parameter	Value
Ttcsc	15	Xmax	0.7
α	158	Xmin	0
Xtcsc	0.3591	σ	80
T1	0.4	Ido	4.5
T2	0.1	L	2.5
T3	0.3	Ko	5
T4	0.1	Kid	60
Tw	10	Tdc	0.05
Ktcsc	0.38		

Table 6.
Optimum parameters values obtained using PSO

Parameter	Value
T1	0.8296
T2	0.0987
T3	0.3935
T4	0.0999
Kid	89.608

Table 7.
Eigenvalue of three different cases (Simulations 1, 2, 3)

TSCS	SMES TCSC	SMES TCSC PSO
-0.0667+0.0000i	-0.0667+0.000i	-0.0667+0.0000i
-10.0000+0.0000i	-10.000+0.000i	-10.0100+0.0000i
-10.0000+0.0000i	-10.000+0.000i	-10.1317+ 0.0000i
-0.1000+0.0000i	-0.100+0.0000i	-0.1000+0.0000i
-9.2770+0.0000i	-10.004+7.405i	-10.016+10.5567i
-5.2446+0.0000i	-10.004-7.4053i	-10.0155-10.5567i
-3.1314+3.6219i	-9.275+0.0000i	-9.2757+0.0000i
-3.1314-3.6219i	-5.266+0.0000i	-5.2632+0.0000i
-2.4967+2.5493i	-3.132+3.6222i	-3.1316+3.6221i
-2.4967-2.5493i	-3.133-3.6222i	-3.1316-3.6221i
-2.5680+2.2782i	-2.500+2.5556i	-2.5011+2.5551i
-2.5680-2.2782i	-2.500-2.5556i	-2.5011-2.5551i
-0.4115+0.5351i	-2.569+2.2787i	-2.5687+2.2786i
-0.4115-0.5351i	-2.569-2.2787i	-2.5687-2.2786i
-0.4680+0.4572i	-0.925+0.0000i	-0.9493+0.0000i
-0.4680-0.4572i	-0.457+0.4755i	-0.4569+0.4754i
-0.0596+0.0000i	-0.457-0.4755i	-0.4569-0.4754i
-0.1440+0.0000i	-0.244+0.3941i	-0.2439+0.3941i
-0.3208+0.0000i	-0.244-0.3941i	-0.2439-0.3941i
-0.2462+0.3966i	-0.094+0.1621i	-0.0692+0.1398i
-0.2462-0.3966i	-0.094-0.1621i	-0.0692-0.1398i
-3.1546+0.0000i	-0.163+0.0000i	-0.0611+0.0000i
	-0.061+0.0000i	-0.1667+0.0000i
	-3.155+0.0000i	-3.1546+0.0000i

accuration while 50 and 230 kV were chosen as maximum iteration and base voltage. Figure 14 shows eigenvalue trajectories of simulation 1, simulation 2, and simulation 3. It can be seen that SMES and TCSC provide better performance in term of larger eigenvalues in the left half plane. Table 7 lists up those eigenvalues.

Time domain simulation was carried out to validate the eigenvalue trajectories. To observe the response, small load perturbation addressed in generator 1 by giving 0.05 step input. The oscillatory condition of rotor speed from generator, 1, 2 and 3 was shown in Figures 15-17. It was monitored that by installing SMES and TCSC to the system, the dynamic response of the system is enhanced which is indicated by less overshoot during small perturbation. It happened because of SMES gives active power, and TCSC gives load compensated to the system, so the stress of the generator was decreased. It was also noticeable that the best response is a system with SMES and TCSC optimized by PSO. Tables 8 shows the overshoot and settling time of generator, 1, 2 and 3.

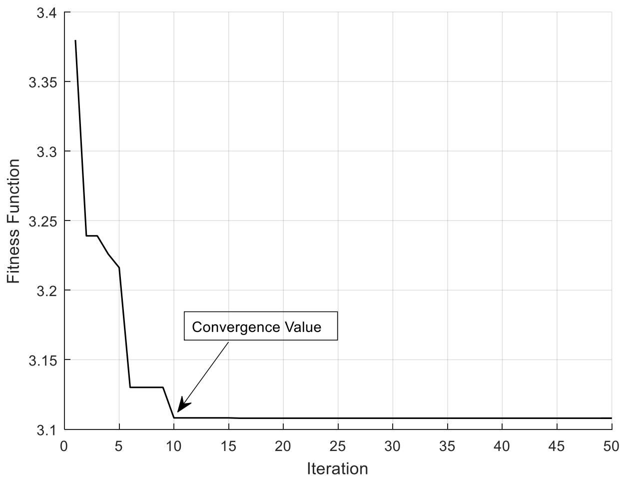

Figure 13. Convergence curve of PSO algorithm

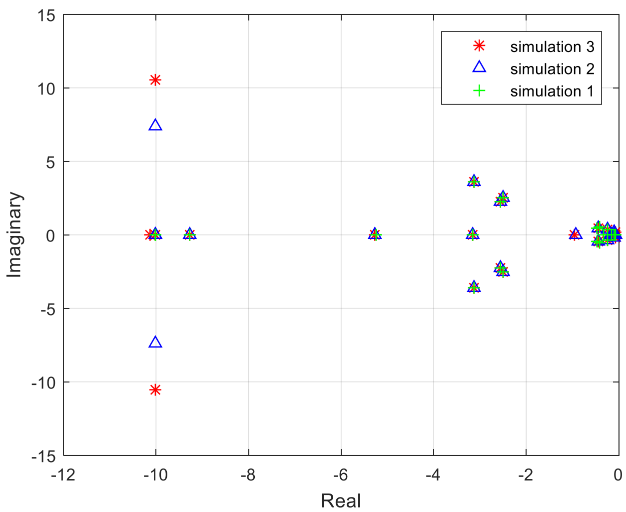

Figure 14. Eigenvalue trajectories (simulation 1, simulation 2, simulation 3)

Table 8.
Overshoot and settling time

Generator	Parameter	TCSC	TCSC SMES	TCSC SMES PSO
Generator 1	Overshoot (pu)	-0.1293	-0.09347	-0.08875
	Settling time (sec)	>100	>100	>100
Generator 2	Overshoot (pu)	-0.08789	-0.08558	-0.08522
	Settling time (sec)	>100	>100	>100
Generator 3	Overshoot (pu)	-0.0444	-0.03817	-0.03771
	Settling time (sec)	>100	>100	>100

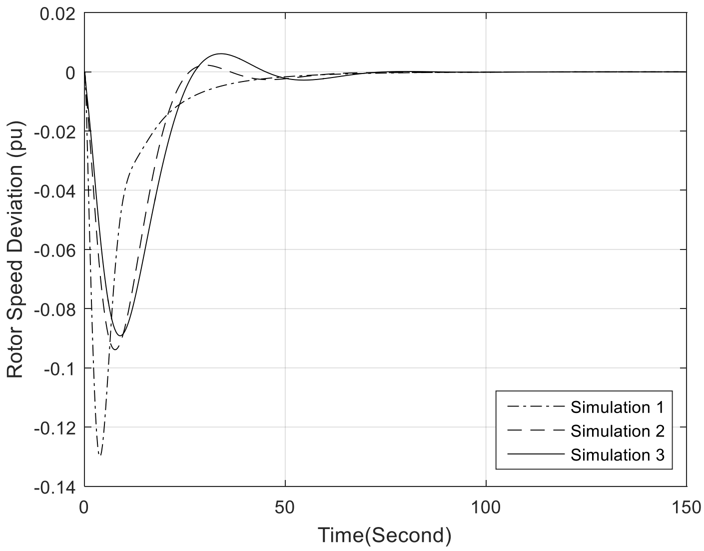

Figure 15. Rotor speed oscillatory condition of G1

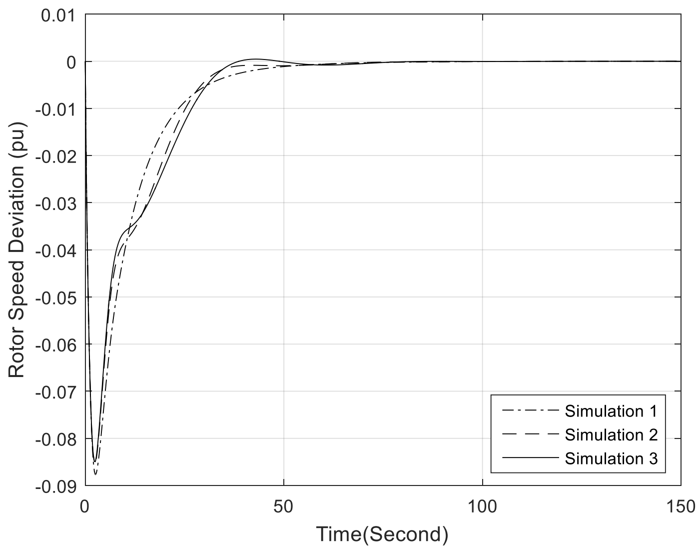

Figure 16. Rotor speed oscillatory condition of G2

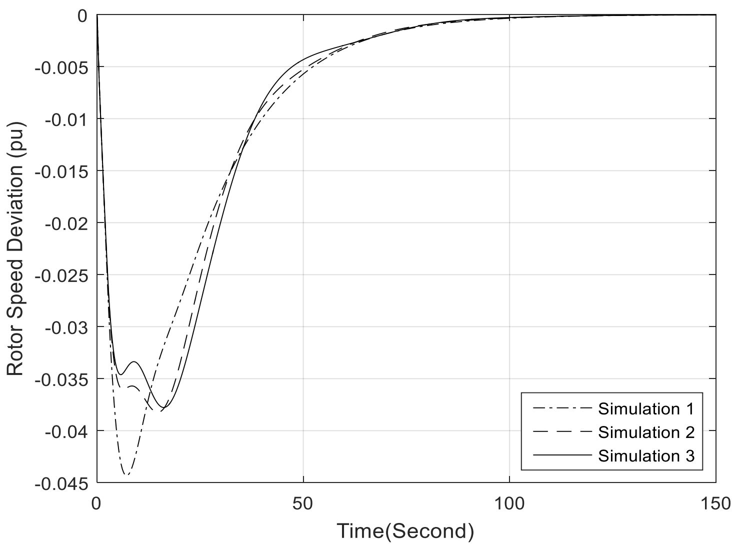

Figure 17. Rotor speed oscillatory condition of G3

V. Conclusion

This paper investigates the impact of utilizing SMES and TCSC for mitigating low-frequency oscillation in a multi machines power system of which their parameters values are optimized using PSO. From the case studies carried out through computer simulation, it is found that a combination of SMES and TCSC whose parameter values are optimized using PSO provide better performance in term of smaller overshoot and smaller settling time.

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