Low-Frequency Oscillation Mitigation usin an Optimal Coordination of CES and PSS based on BA

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Abstract— **Small signal stability represents the reliability of generator for transferring electrical energy to the consumers. The stress of the generator increases proportionally with the increasing number of load demand as well as the uncertainty characteristic of the load demand. This condition makes the small signal stability performance of power system become vulnerable. This problem can be handled using power system stabilizer (PSS) which is installed in the excitation system. However, PSS alone is not enough to deal with the uncertainty of load issue because PSS supplies only an additional signal without providing extra active power to the grid. Hence, utilizing capacitor energy storage (CES) may solve the load demand and uncertainty issues. This paper proposes a coordination between CES and PSS to mitigate oscillatory behavior of the power system. Moreover, bat algorithm is used as an optimization method for designing the coordinated controller between CES and PSS. In order to assess the proposed method, a multi-machine two-area power system is applied as the test system. Eigenvalue, damping ratio, and time domain simulations are performed to examine the significant results of the proposed method. From the simulation, it is found that the present proposal is able to mitigate the oscillatory behavior of the power system by increasing damping performance from 4.9% to 59.9%.**

***Keywords*- BA, CES, damping ratio, eigenvalue, low-frequency oscillation, PSS, time domain simulation.**

I. INTRODUCTION

The demand for electrical energy is increasing significantly in the last few decades. Increasing demand for electrical energy has been the main issue for electrical company in order to provide secure, stable and reliable electricity for the consumers. The stability and the security of power system can deteriorate due to perturbation, such as increasing load demand, uncertainty characteristic of the demand and small changes of the systems parameter. One of the stability that can effected by those perturbations is small-disturbance angle stability.

The ability of power system to maintain the synchronization after small perturbation is called small-disturbance angle stability or low-frequency oscillation is the ability of a power system to maintain the synchronization after being exposed to a small perturbation [1, 2]. This instability characteristic is emerging due to the existence of sufficient damping from the system and can be divided into two categories. The first one is a local oscillation with the frequency ranging from 0.7 to 2 Hz. The other one is a global oscillation (inter-area oscillation) with the frequency ranging from 0.1 to 0.7 Hz [1-3]. If this stability is not well maintained, the magnitude of the oscillation may grow larger

$$\begin{bmatrix} \Delta v_d \\ -\Delta v_F \\ 0 \\ \Delta v_q \\ 0 \\ \Delta T_m \\ 0 \end{bmatrix} = -\begin{bmatrix} r & 0 & 0 & \omega_0 L_q & \omega_0 k M_Q & \lambda_{q0} & 0 \\ 0 & r_F & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & r_D & 0 & 0 & 0 & 0 \\ -\omega_0 L_d & -\omega_0 k M_F & -\omega_0 k M_D & r & 0 & -\lambda_{d0} & 0 \\ 0 & 0 & 0 & 0 & r_Q & 0 & 0 \\ \frac{\lambda_{q0} - L_d i_{q0}}{3} & \frac{-kM_F i_{q0}}{3} & \frac{-kM_D i_{q0}}{3} & \frac{-kM_Q i_{d0}}{3} & \frac{kM_Q i_{d0}}{3} & -D & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 & 0 \end{bmatrix} \begin{bmatrix} \Delta i_d \\ \Delta i_F \\ \Delta i_D \\ \Delta i_q \\ \Delta i_Q \\ \Delta \omega \\ \Delta \delta \end{bmatrix} - \begin{bmatrix} L_d & kM_F & kM_D & 0 & 0 & 0 & 0 \\ kM_F & L_F & M_R & 0 & 0 & 0 & 0 \\ kM_D & M_R & L_D & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & L_q & kM_Q & 0 & 0 \\ 0 & 0 & 0 & kM_Q & L_Q & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -\tau_j & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \Delta \dot{i}_d \\ \Delta \dot{i}_F \\ \Delta \dot{i}_D \\ \Delta \dot{i}_q \\ \Delta \dot{i}_Q \\ \Delta \dot{\omega} \\ \Delta \dot{\delta} \end{bmatrix} \quad (1)$$

and lead to unstable condition. There are several incident (fully and partial black out) happened due to low frequency oscillation problems as reported in [4]. The latest incident related to low frequency oscillation is happened in Continental Europe electricity on December 2016 [5]. Generally, this instability can be overcome by simply adding damper windings into the rotor of the synchronous generator but the performance can deteriorate over the time. Another way to handle this problem is by using power system stabilizer (PSS) as the additional controller [6]. However, PSS alone is out of date to overcome this problem as the load demand is increased over the years and the load demand is tend to have the uncertainty characteristic. Hence, energy storage devices can be considered to handle the increasing capacity of load demand as well as the uncertainty of it.

Energy storage becomes reality in the practical power system. For example, redox flow batteries, battery energy storage, superconducting magnetic energy storage, and capacitor energy storage have been used to solve several problems in power system [7-13]. Among them, capacitor energy storage (CES) is becoming popular due to large capacity and fast response for storing and releasing energy from the grid. However, designing the controller of CES is huge efforts especially if CES is installed in a large power system.

One way out of the above dilemma is by employing an optimization method based on the nature-inspired algorithm which has been utilized to solve complex engineering problems [14-22]. An algorithm such as particle swarm optimization, genetic algorithm, differential evolution algorithm, imperialist competitive algorithm, artificial immune system, firefly algorithm, cuckoo search algorithm and bat algorithm were demonstrated to perform well in solving optimization problems [14-22]. In particular bat algorithm (BA) has shown a good performance finding the optimum parameter for optimization problems [16].

Hence, the main contribution of this paper is to propose a method for mitigating the low-frequency oscillation of a power system using a coordinated control between CES and PSS. Moreover, to obtain the optimum performance, the parameters of CES and PSS are optimized by BA.

II. Fundamental Theory

A. *Synchronous generator, excotation, and governor model*

For low frequency oscillation study, capturing the dynamic characteristic of the synchronous generator is essential. As consequences, transforming the non-linear model of synchronous machine to linear model and all of the parameters in direct and quadrature (DQ) axis is required. Fig. 1 shows the DQ transformation of the synchronous generator. Furthermore, the mathematical representation of linear model synchronous generator can be described as (1). The detailed linear model of the synchronous generator can be found in [23].

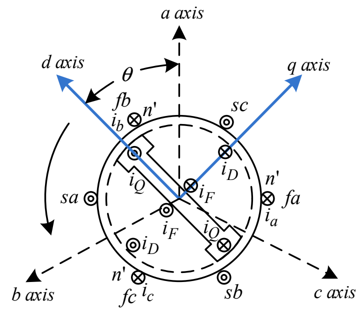

Fig. 1 DQ transformation of the synchronous generator.

The purpose of excitation system is to set the output of the generator such as voltage, current, and power factor. These variables will be adjusted by changing the field in the generator [23, 24]. To handle a small perturbation such as load changing, the exciter increases the current injection magnitude so the terminal voltage will be increased. The purpose of this process is to handle to the slow response of the governor to adjust the power input to the generator when the disturbance occurs. In this study, the excitation system can be represented as time delay and gain controller as shown in Fig. 2 [23, 24].

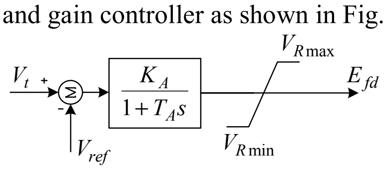

Fig. 2 Block diagram of fast exciter system.

Governor is a controller that serves to set the value of mechanical torque into the input of the generator. For small signal stability study, the governor is represented as a constant gain and first order time delay as illustrated in Fig. 3 [23].

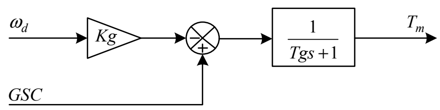

Fig. 3 Block diagram of governor system.

B. Power system stabilizer

In power system study, PSS is widely used to enhance the dynamic performance of power systems. PSS is applied as an excitation system controller to damp the oscillatory condition of the power system. To produce a damping component, PSS produces an electric torque component corresponding to the rotor speed deviation. It receives inputs in the form of a rotor speed deviation to generate an additional signal to the exciter, which affects the magnitude of the field voltage and the magnetic flux on rotor side. It shall be noted that magnetic flux is directly proportional to the electrical torque generated on the machine. The electric torque that counters the mechanical torque of the engine to reduce the oscillation of frequencies occurring on the machine. Fig. 4 depicts the PSS model used in this study [25].

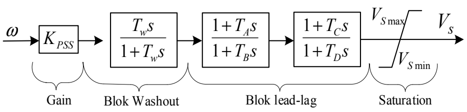

Fig. 4 Block diagram of PSS.

C. Dynamic model of CES

A devices that can releasing as well as storing power in large quantities is CES. The device consist of storage capacitors and power electronics devices with the associated controller as well security function. The schematic diagram of CES is illustrated in Fig. 5 [26, 27].

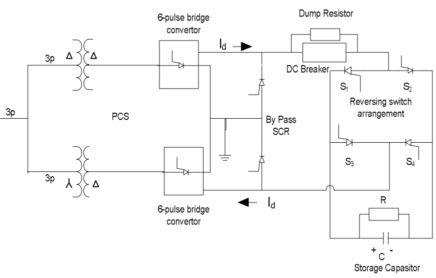

Fig. 5 Schematic diagram of CES.

Several capacitors connected in parallel and denoted by C capacitance is the representation of storage capacitor in CES. Moreover, resistance that denoted by R is also connected in parallel with the capacitor. 12 pulse back to back converters are used as an interface between the storage capacitor and grid. When the converters fails, the current I_d use bypass thyristor as a path. Moreover, if the converters fails, the I_d current will be diverted to the discharge point of R_D by the DC-disconnect. The E_d voltage can then be described as (2) [26, 27].

$$E_d = 2E_{d0}\cos\alpha - 2I_d R_D \quad (2)$$

To vary the capacitor voltage E_d, changing of phase angle is required α. The changes in the direction of current during charge and discharge are overcome by arranging switches in reverse using GTO. To operate CES in charging mode, switch 2 and 3 are off, while switch 1 and 4 are on. For discharging operating condition, the switches are operated in the other way around. E_{d0} can be described in Eq. (3) [26, 27].

$$E_{d0} = \frac{[E_{d\max}^2 + E_{d\min}^2]^{1/2}}{2} \quad (3)$$

It is worth mentioning that capacitor voltage shall not exceed the specified upper and lower limits. When the system is exposed by disturbance, if the capacitor voltage is too low and if another interference emerges before the voltage returns to its normal value, the energy will be rapidly drawn from the capacitor which can lead to a discontinuous condition. To solve this problem, the lower and upper limit for the voltage of the capacitor has to be set as presented in (4) and (5) [26, 27].

$$E_{d\min} = 30E_{d0} \quad (4)$$

$$E_{d\max} = 1.38E_{d0} \quad (5)$$

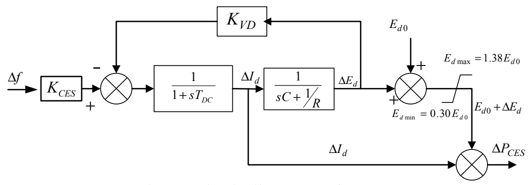

Fig. 6 Block diagram of CES.

After the voltage reaches the rating value, the voltage is maintained at this value with a continuous supply of PCS. Hence, it is sufficient to overcome the resistive drop. Since E_{d0} is very small, the firing angle of α is close to 90^0. The stored energy is released immediately via power electronics converters as an AC pulse when there is a sudden increase in load. After that to regulate the system in the new operating condition the governor and other control mechanisms start to work. By absorbing some of the excess energy in the system, CES can immediately be recharged to full value. After that, the steady state condition of the system can be achieved [26, 27]. CES can be presented as a second-order differential equation as shown in Fig. 6 [26, 27]. The block diagram of Fig. 6 can be described as using (6)-(8) [26, 27].

$$\Delta I_{di} = \frac{[K_{CES}.\Delta f - K_{VD}.\Delta E_d]}{1 + sT_{DC}} \quad (6)$$

$$\Delta E_d = \left[\frac{1}{sC + 1/R}\right]\Delta I_d \quad (7)$$

$$\Delta P_{CES} = (E_{d0} + \Delta E_d).\Delta I_d \quad (8)$$

III. Design CES and PSS based on BA

Bat algorithm is a metaheuristic algorithm inspired by bats behavior. This algorithm was first established in 2010 by Yang [28]. Bats use a type of sonar called an echolocation to detect food, avoid obstacles and search for a nest in the dark. With the echolocation abilities, bats are able to fly in the night looking for food without crashing. From this characteristic, the bat algorithm can be developed with the following rules:

- Bats use echolocation to sensor distance and distinguish between food and obstacles even in the darkness.
- Bats fly randomly to search for food at a speed v_i and at position x_i with a fixed f_i frequency, wavelength variation λ_i and noise level (A_i).
- It can be assumed the noise level varies from that the maximum (A_0) to minimum constant (A_{min}).

It is noted that d_i is the dimension to find the space or renewed space. The new solution and speed are indicated by x_i^t and v_i^t. The mathematical representation of bat velocity and position can be described in Eq. (9) [28, 29].

$$f_i = f_{\min} + \left(f_{\max} - f_{\min}\right)\beta$$
$$v_i^{t+1} = v_i^t + \left(x_i^t - x^*\right) f_i \qquad (9)$$
$$x_i^{t+1} = x_i^t + v_i^t$$

where β is a random vector taken from a uniform distribution. Here x^* is the optimal location of the whole bat solutions after comparing all the solutions among all bats on each iteration t. As the result of the multiplication between λ_i and f_i the velocity of the bats increases. λ_i or f_i , can be used to adjust the velocity change and enhance the other factors depending on the type of the problem that will be solved. In the implementation f_{min}=0 and f_{max}=1 are applied depending on the requirement [28, 29].

Noise level (A_i) and the pulse emitted from each bat are always updated according to the iteration process. Noise in bats decreases when bats have found their prey, while pulse pants increase. The noise can be selected according to the exact value, for instance, A_0=100 and A_{min}=1 can be used. To make it easier, A_0=1 and A_{min} =0 are also employed. Assuming A_{min} =0 means that bats have just found their prey and temporarily stopped emitting sound. Hence the mathematical representation can be described in Eq. (10) [28, 29].

$$A_i^{t+1} = \alpha A_i^t,$$
$$r_i^t = r_i^0\left[1 - \exp(-\gamma t)\right] \qquad (10)$$

where α and γ are a constant value. For every 0< α <1 and γ>0, the mathematical representation can be described in Eq. (11) [28, 29].

$$A_i^t \to 0, r_i^t \to r_i^0, t \to \sim \qquad (11)$$

In the simplest problem, α=γ and α=γ=0.9. In this paper, BA is used to optimize the parameter of CES and PSS to mitigate the low-frequency oscillation on the power system. To find the optimal parameter of CES and PSS, comprehensive damping index is used as the objective function of the BA which can be calculated using (12) [30].

$$CDI = \sum_{i=1}^{n}\left(1 - \xi_i\right) \qquad (12)$$

IV. RESULTS AND DISCUSSIONS

Investigation of the impact of CES and the proposed method in low frequency oscillation is reported in this paper. MATLAB/SIMULINK environment is used as the software tools to investigate the case study. The test system that use in this paper is well known two-area power plant. A modification has been made by adding 100 MW CES in generator 1. Furthermore, PSS is installed in generator 3. Fig. 5 shows the schematic diagram of the test system. For identifying the efficiency of optimal coordination of PSS and CES using BA in the system, analyzing the eigenvalue and damping performance of electromechanical (EM) mode are conducted. Finally, to verify the eigenvalue as well as the damping value results, comparison of linear time domain analysis is conducted.

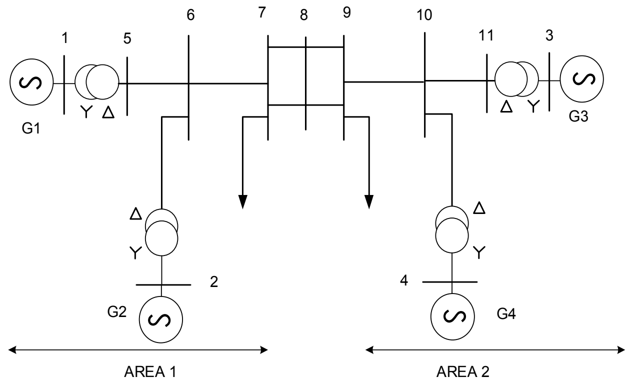

Fig. 5 Test systems.

A. Case study 1

The comparison of EM mode under different cases is shown in Table 1. It is found that the eigenvalue of inter-area and local mode area-1 are moved towards left-half plane when CES is added in the generator bus 1. This movement is caused by decreasing of generator stress due to the additional active power from CES. It is also monitored that the location of CES has a significant influence in the system dynamic indicated by the movement of local mode area 2 that relatively remain in its position. Furthermore, the proposed method is shown the best eigenvalue performance compared to any other scenario indicated by the more negative eigenvalue.

The damping performance of different scenario is illustrated in Table. 2. It is monitored that by installing PSS in generator-3, the damping ratio of all EM mode are increased gradually. This occurs due to additional signal damping from the PSS to the system. The similar pattern is investigated when CES is installed in the generator-1 bus. The damping of local mode area-1 increases significantly from 4.8% to 36%. Furthermore, the damping of inter-area mode also enhances from 2.6% to 7.7%. However, as mentioned before, that the location of CES has a significant impact to the system. Hence, the damping of local mode area-2 is remained in its position.

The damping performances of all EM modes increase significantly after CES and PSS are installed in the system.

Moreover, the proposed method (coordination between CES and PSS using BA) shows the best performance compared to the other scenarios indicated by the high value of the damping performance. It is also found that the oscillation in local mode area-1 is completely wiped out indicated by the damping value that becomes 100%. This condition takes place due to an optimal coordination between CES and PSS based on BA that can supply large additional signal damping to the system.

Table 1 The comparison of eigenvalue under different cases.

Cases	Local mode 1	Local mode 2	Inter-area
Base case	-0.324+6.77i	-0.342+7.02i	-0.071+2.61i
Considering PSS	-0.324+6.76i	-0.357+7.03i	-0.071+2.61i
Considering CES	-2.67+6.78i	-0.34+7.02i	-0.21+2.67i
Considering CES PSS	-2.63+6.82i	-2.23+9.80i	-0.390+2.96i
Proposed method	-3.7263	-8.26+11i	-0.42+3.41i

Table 2 The comparison of EM mode damping under different cases.

Cases	Local mode 1	Local mode 2	Inter-area
Base case	4.8	4.85	2.6
Considering PSS	4.8	4.88	2.59
Considering CES	36.65	4.85	7.77
Considering CES PSS	36	22.17	13.09
Proposed method	100	59.97	12.25

To verify the eigenvalue analysis, time domain analysis is carried out. To excite the dynamic response of the system, small perturbation is made in the system. Figs. 7 shows the time domain response of rotor speed for generator. Table 3 illustrates the detailed overshoot and settling time comparison of different scenarios. A blue line represents the oscillatory condition of base case system (generic two-area power system) while green line is for the dynamic response of the rotor speed equipped with PSS. The yellow line represents the rotor speed dynamic performance due to small perturbation with CES, while the red line is for the oscillatory condition of the rotor speed with CES and PSS. Furthermore, a system with proposed method is presented with black lines. It is monitored that the best oscillatory condition compared to the others scenario is a system with the proposed method. This time domain simulation also verifies the eigenvalue analysis and damping value analysis by showing that the best performance compared to other scenarios is obtained when the proposed method is applied in the system.

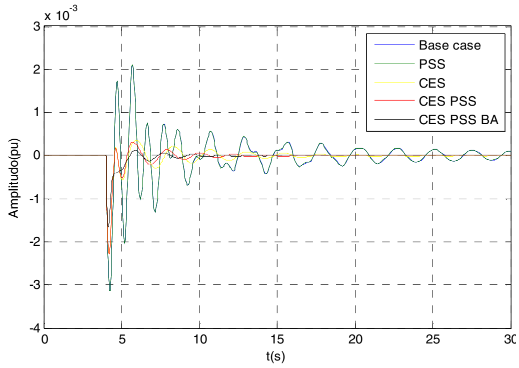

Fig. 7 The time domain response of rotor speed G1.

Table 3 Detailed time domain response of rotor speed G1.

Cases	Overshoot (pu)	Settling time (s)
Base case	-0.003136	>30
With PSS	-0.03134	>30
With CES	-0.02283	16.03
CES PSS	-0.001981	11.74
Proposed method	-0.001658	8.26

B. *Case study 2*

In the second case study, comparison of damping performance of the proposed method with other algorithm. In this paper imperialist competitive algorithm (ICA) is used to tune the CES and PSS parameter. Fig 8 illustrates the damping comparison of EM mode between the proposed method and CES and PSS based on ICA.

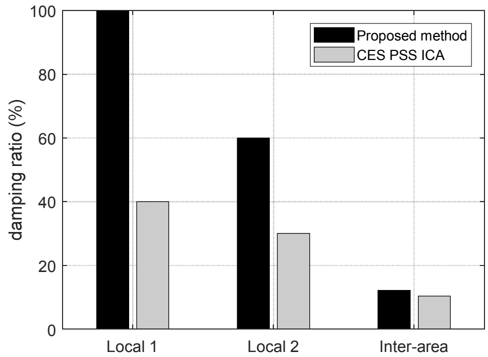

Fig. 8 Damping comparison.

It is noticeable that the proposed method (using BA) provide a better damping ratio compared to CES and PSS based on ICA indicated by higher percentage of the damping.

V. CONCLUSIONS

This paper investigates the significant impact of installing CES on the small signal stability performance of two-area power system. A method to mitigate the low-frequency oscillation by employing coordinated control between CES and PSS based on BA is proposed. From the simulation results, it is observed that the damping of the system increases when PSS is utilized in the system. It is monitored that CES enhances the damping performance of the system by injecting additional active power to the grid and the location of CES plays an important role in the system dynamic. By adding PSS and CES to the system, the stability of the power system increases significantly indicated by increasing damping performance of EM mode. The damping performance of EM mode increases from 4.8% to 100 % for local mode area 1, 4.9% to 59.9 for local mode area 2, and 2.6% to 12.3% for inter-area. The reliability of the power system also augments indicated by the time domain results of generator 1 and 4. Furthermore, the proposed method is able to damp the low-frequency oscillation significantly. Further research needs to be conducted by considering high penetrations of renewable energy sources (RESs) such as large-scale wind power system or large-scale PV generation. Installing another PSS such as dual input PSS, and multi-band PSS may be considered to handle low-frequency oscillation from different sources. Another optimization method such as whale algorithm, artificial immune system clonal selection and firefly algorithm can be used for designing a coordinated control between PSS and CES.

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