Coordination of SPS and CES to Mitigate Oscillatory Condition on Power Systems

Rahmat Septian Wijanarko¹, Herlambang Setiadi², Teguh Aryo Nugroho³
¹,³Departmen Teknik Elektro, Universitas Pertamina, Jl Teuku Nyak Arief, Jakarta 12220, Indonesia
²School of Information Technology & Electrical Engineering, The University of Queensland, St Lucia, Queensland 4072, Australia
*Corresponding author, e-mail: rahmat.sw@universitaspertamina.ac.id¹, h.setiadi@uq.edu.au², teguh.an@universitaspertamina.ac.id³

Abstract
Oscillatory condition on power system (low-frequency oscillation) is one of the important factors to determine the quality of the power system. With the increasing number of load demand, this condition is getting worse in recent years. Hence, utilizing addition devices to maintain and mitigate the oscillatory condition of power system is crucial. This paper proposed a method to mitigate power system oscillation by installing one of the flexible AC transmission system (FACTS) devices called solid phase shifter (SPS) and energy storage devices called capacitor energy storage (CES). To analyze the performance of power system with SPS and CES, the eigenvalue and damping ratio analysis are used. Time domain simulation is also investigated to analyze the dynamic behaviors of power system considering SPS and CES. Furthermore, increasing number of load demand is carried out to analyze how much load can be increased without increasing power to the grid. From the simulation, it is found that SPS and CES can mitigate low-frequency oscillation on power system indicated by highest damping, smallest overshoot, and fastest settling time. It is also found that load demand can be increased significantly when SPS and CES installed to the system.

Keywords: oscillatory condition, SPS, CES, eigenvalue, damping ratio.

1. Introduction
Human population growth in the last few decades tends to increase significantly. With the population growth and development of technology, the electric power demand is increasing significantly as well. The increasing number of electricity load demand can affect power system instability. One of the stability that can be effected by increasing load demand is small-signal stability/oscillatory condition in power system. This oscillatory condition may be very troublesome if they are not damped. Kundur and .co in [1,2] studied the different modes of oscillations that exist in a weakly interconnected power system which was the root cause to many blackouts in the recent times (North India, July–2012, Bangladesh November–2014, South Brazil 1999, United States and Canada 1965).

The small-signal stability is the ability of power system to maintain stable condition after being exposed by a small perturbation [3]. This condition has a frequency range from of 0.1-2 Hz. This stability can be handled by installing damper windings in the rotor of the generator. Another way is by adding power system stabilizer in excitation system [2]. The application of PSS to mitigate oscillatory condition has been investigated extensively in the last few decades [4-7]. However, PSS alone is not effective enough to overcome oscillatory condition because of significant increasing of load demand. Hence, additional devices such as energy storage devices and flexible AC transmission systems (FACTS) device can be a prominent alternative.

There are some energy storages which have been proposed in recent years such as battery energy storage and redox flow battery [8-12]. Another type is called superconducting magnetic energy storage and capacitor energy storage [13-16]. Among of energy storage type, capacitor energy storage is becoming most favorable due to its fast response and large capacity. CES is generally uses as a frequency, voltage control, and peak load shaving.
However, CES utilized as a small-signal stability enhancement have not been investigated, yet due to its capability, it can be one promising solution.

This paper proposed a novel solution using CES combined with one of FACTS devices called Solid Phase Shifter (SPS) to mitigate oscillatory condition in power system. By implementing this new method, damping ratio of the system was intended can be improved significantly and the increasing load demand in the system could be handled. The rest of the paper is organized as follow: Section II provides a dynamic model of the power system, CES, and SPS. This section also provides a brief explanation of oscillatory condition on the power system and how to analyze it. Eigenvalue, damping ratio and time domain simulation are presented in section III. Section IV highlights the contribution, conclusion and future direction for this research.

2. Research Method

2.1. Power System Model

For small signal stability study, the power system can be presented as two different models depending on the research interest. If the interest only to capture local behavior (local mode) a simple single-machine infinite bus system (SMIB) can be used. If the interest is to capture local and global dynamic behaviors, a complete multi-machine model can be utilized. In this research, the only local mode is investigated [17]. Hence, a simple model of power system called SMIB is used. Figure 1 illustrates the dynamic representation of SMIB [18,19].

![Figure 1. A dynamic model of single machine infinite bus [18,19]](image)

2.2. Capacitor Energy Storage Model

In recent years, the application of energy storage increases significantly due to the development of power electronic devices. Capacitor energy storage (CES) is one type of energy storage that has become popular to handle frequency fluctuation on the power system. CES can store and release power to the grid instantaneously. For small signal stability application, dynamic characteristic of CES is crucial. The mathematical model of CES can be described using Equation (1)-(3) [20-22].
\[ \Delta I_{di} = \frac{k_{ces}\Delta \omega - k_{vd} \Delta E_d}{1 + sT_{dc}} \quad (1) \]

\[ \Delta E_d = \left( \frac{1}{sC + \sqrt{R}} \right) \Delta I_d \quad (2) \]

\[ \Delta P_{ces} = (\Delta E_{d0} + \Delta E_d) \Delta I_d \quad (3) \]

Where \( \Delta I_{di} \) and \( \Delta E_d \) are current deviation flowing through the capacitor and DC voltage applied to the capacitor. While \( \Delta P_{ces} \) and \( C \) are active power delivered to the grid and capacitance of the capacitors. Several parameters corresponding to resistance on the capacitors \( R \), gain feedback \( (k_{vd}) \), gain constant \( (k_{ces}) \), and time delay of the converter \( (T_{dc}) \) [20-22]. From the equation (1)-(3), CES can be modeled into block diagram as shown in Figure 2.

Figure 2. Block diagram of capacitor energy storage [20-22]

### 2.3. Solid Phase Shifter Model

The application of FACTS devices in power system has been increased significantly over the past few decade. FACTS can be used to control and maintaining, voltage, load flow, frequency as well as damping performance [23]. The solid phase shifter (SPS) is one of the FACTS devices that become favorable in recent years as one of oscillation damping on the power system. The purpose of SPS is to shift the voltage angle by reducing actual angle with angle come from SPS [24]. Hence, oscillatory condition on power system can be mitigated by controlling either the internal voltage of the power system or the voltage angle [24]. Figure 3 shows the block diagram representation of SPS for small signal stability [24].

Figure 3. Block diagram of solid phase shifter [24]

### 2.4. Oscillatory Condition on Power System

Oscillatory condition on power system (small signal stability) falls under small disturbance rotor angle stability [25,26]. This oscillatory condition emerges due to lack of damping torque and insufficient of synchronizing. If this stability is not well maintained, the
magnitude of oscillation potentially growing until the system loses synchronization [26,27]. This will cause the system blackout [26,28]. The oscillatory condition problem has been the cause of many incidents such as in Canada system incident on 1996 and China blackout on 2003 as reported in [26].

The oscillatory condition can local and global problems. The local problems associated with local power plant again in one particular area with frequency ranging from 0.7-2 Hz [26,27]. While global phenomenon related to a large number of power system again each other. This phenomenon has frequency oscillation in the range of 0.1-0.7 Hz [26,27]. Eigenvalue analysis is used to analyze the oscillatory condition of the power system. To determine the eigenvalue of the system, linearized of the system is crucial. Linearized of the investigated system can be represented as state space model investigated through (4) and (5) [26,29]. Where \( \Delta x \) states variables, \( \Delta y \) is algebraic variables, \( \Delta u \) is related to input vector [26,29]. \( A \) and \( B \) are plant and control matrices respectively, while \( C \) and \( D \) are output and feedforward matrices respectively.

Using matrix system, \( A \) eigenvalue can be determined using (6) [26,29].

\[
\Delta x = A\Delta x + B\Delta u 
\]  
\[
\Delta y = C\Delta x + D\Delta u 
\]  
\[
det (\lambda I - A) = 0 
\]

Where \( I \) is identity matrix, and \( \lambda \) is eigenvalues of matrix \( A \). Moreover, complex eigenvalue can be stated as (7) [26,30]. Then to calculate frequency oscillation on the power system, eq. (8) can be used. Several parameters corresponding to real component from eigenvalue \( (\sigma_i) \), imaginary component from eigenvalue \( (\omega_i) \) [26,30]. The imaginary part of eigenvalue is a component of frequency oscillation, while the real parts corresponded to the system damping. Finally, the damping ratio can be described using (9) [26,30].

\[
\lambda_i = \sigma_i \pm j\omega_i 
\]  
\[
f_i = \frac{\omega_i}{2\pi} \text{ (Hz)} 
\]  
\[
x = \frac{\sigma_i}{\sqrt{\sigma_i^2 + \omega_i^2}} 
\]

3. Results and Analysis

Two case studies are reported in this work to propose SPS and CES for mitigating oscillatory condition on the power system. All of the case studies were simulated in MATLAB/SIMULINK environments. The comparison of eigenvalue and damping ratio of electromechanical mode (EM) were conducted to analyze the influence of SPS and CES in oscillatory condition on the power system. Furthermore, the increased load demand was conducted to understand how much load can be increased after installing SPS and CES on the power system.

3.1. Case Study 1

In this case study, the SMIB work under normal condition. The SMIB system consists of the ninth-order model including exciter and governor. While CES and SPS represented as a second-order model and fourth-order model. Table 1 shows the comparison on eigenvalue electromechanical (EM) mode. It was found that by installing SPS in the system, the eigenvalue trajectories move to left-half plane moderately. It was noticeable that the movement was more significantly when installing with CES. Figure 4 illustrates the damping ratio EM mode of investigated system. It was shown that the damping was increased significantly when CES was installed on the system. It was also noticeable that the best damping ratio was a system with SPS and CES with damping value was 18%, while the standard was 5% [31].
Table 1. Eigenvalue of electromechanical mode

| Initial condition | With SPS  | With CES  | With SPS and CES |
|-------------------|-----------|-----------|------------------|
| -0.2943+9.5328i   | -0.3722+9.5499i | -0.7271+9.6342i | -0.8115+9.6539i |

Figure 4. Damping ratio of the cases study

To validate the eigenvalue analysis, time domain simulation were then conducted. To excite the sensitivity of the eigenvalues, a small disturbance was applied to the system. Figure 5 shows time domain simulation of the rotor speed of the investigated system. It was noticeable that the initial condition (black lines) has the highest overshoot and the longest settling time. It means that the system without controller was not robust enough to handle the small perturbation. After SPS was installed (blue lines) in the transmission line, the response of the rotor speed was better than the initial condition due to shifted voltage angle of the system. Better response was produced when CES was installed in the load bus. It was found that CES could gave instantaneously active power to the load when there were load changing. Hence this make the burden of the synchronous generator decreased when small load perturbation occurs. The best response was system with SPS and CES indicated by smallest overshoot and fastest settling time. The detailed rotor speed response enhancement shown in Table 2.

Figure 5. The oscillatory condition of rotor speed
The same pattern was found in the rotor angle oscillatory condition when small perturbation emerges as shown in Figure 6. It was also monitored that the worst oscillatory condition was in the system without SPS and CES (black lines) or in the initial condition of the system. Table 3 illustrates the detailed comparison of rotor angle oscillatory condition. System in initial condition has overshoot -0.02578 pu and settling time more than 20 second. System with SPS has less overshoot than the initial condition which has -0.02566 pu and settling time 17.76 second. While system with CES has better overshoot and settling time than the initial condition and system with SPS (overshoot is -0.0244 and settling time is 10.35). According to the Paserba [32], the maximum settling time of small signal stability is around 10 second. Hence, only system with SPS and CES was capable to achieved this standard (settling time 7.73 second).

![Figure 6. The oscillatory condition of rotor angle](image)

**Table 2. Overshoot and settling time of rotor speed**

| Parameter          | Initial condition | With SPS       | With CES       | With SPS and CES |
|--------------------|-------------------|----------------|----------------|------------------|
| Overshoot (pu)     | 0.0004466         | 0.0004353      | 0.0003838      | 0.0003731        |
| Settling Time (Sec)| 22.99             | 17.12          | 10.72          | 8.61             |

**Table 3. Overshoot and settling time of rotor angle**

| Parameter          | Initial condition | With SPS       | With CES       | With SPS and CES |
|--------------------|-------------------|----------------|----------------|------------------|
| Overshoot (pu)     | -0.02578          | -0.02566       | -0.0244        | -0.02429         |
| Settling Time (Sec)| 20.64             | 17.76          | 10.35          | 7.73             |

### 3.2. Case Study 2

This case study investigated how much load could be increased if the system was installed with SPS and CES. To analyze the impact of increasing load demand on small signal stability, damping ratio plot of EM mode was carried out. Figure 7 shows the damping value fluctuation due to increasing number of the load. It was found that by increasing load demand, the damping of the system was decreased. It was also found that if the system only used CES alone, the load demand could not be increased more than 55%. If the load was increased more than 55%, it could exceed the minimum standard of damping ratio (5%), and it may lead to the unstable condition. It was also noticeable that by combining SPS and CES, the load demand could be increased more than 55%. Hence, by installing SPS and CES, it could stabilize the performance even thought there was increasing load demand on the system.
Coordination of SPS and CES to Mitigate Oscillatory Condition .... (Rahmat Septian Wijanarko)

4. Conclusion

This paper proposed a method to mitigate oscillatory condition on power system by using FACTS devices called solid phase shifter (SPS) and energy storage devices called capacitor energy storage (CES). From the simulation result, it was found that by installing SPS and CES to SMIB, the damping ratio of the system was increased significantly. It was also noticeable that SPS and CES could mitigate the oscillatory condition of power system indicated by small overshoot and fastest settling time. It was also found that by installing SPS and CES, the load demand of the system could be increased. Further research is required to be conducted by using larger case study such as two area power system, nine-bus 3 machine power system and New England power system. Furthermore, to enhance the performance of SPS and CES, optimization method based on metaheuristic algorithm can be used to tune SPS and CES parameter.

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