SIMULTANEOUS COORDINATED TUNING OF CES AND PSS FOR SINGLE-MACHINE USING GENETIC ALGORITHM

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ABSTRACT

This paper presents a new coordinated design between Power System Stabilizer (PSS) and Capacitive Energy Storage (CES) using Genetic Algorithm (GA). A GA will determine optimal parameters for PSS and CES by tuning parameters PSS and CES simultaneously. The optimization results can change the value of PSS and CES parameters which can also cause oscillation on the system. This problem is formulated as an objective function with limits consisting of damping ratio and damping factor. The approach is successfully tested on single-machines generator models. The optimization results show that this method is effective enough to damp the oscillation, so as to give an idea of the dynamic stability of the single-machine system.

Keywords: CES, PSS, Single-Machine, Genetic Algorithms

1. INTRODUCTION

The power system stability has been considered as an important issue to protect power system operation. The pattern of load changes that occur so fast in an interconnected system causes oscillations on each machine that connected to the system. These oscillations affect each other, so the interconnected machines interacted to reduce these oscillations in order to reach the stable condition [1][26].

The large oscillations cause system instability. This condition does not guarantee that the system will return to the steady-state condition. So many researchers developed various types of controllers to dampen these oscillations so the system back in a steady-state condition with a relatively short time after the fault [2] - [7]. This stability analysis focuses on dynamic stability caused by small disturbances, such as changes of the load when peak load condition.

CES (Capacitive Energy Storage) is a device for large power storage and release simultaneously. CES consists of the capacitor storage and Power Conversion System (PCS) with integrated control and protection functions. The normal operating point of the capacitor can be arranged so that the maximum energy absorption equals to the maximum energy discharge. This condition makes CES very effective in reducing oscillations caused by load changes [8-11], [23-24].

The PSS (Power System Stabilizer) installation as the controller has been shown in reference [3] intended to improve the controller performance in reducing oscillations. In its operation, the controller is working together with AVR (Automatic Voltage Regulator). These controllers are effectively used to dampen electromechanical oscillations. Therefore, this paper proposes the use of CES and PSS as an alternative method for reducing the system oscillation [12], [16-18], [20-22].

Generally, tuning parameters of PSS and CES are multimodal optimization problems. Therefore, most algorithms fail to get a fairly accurate solution, especially on large systems. Additionally, the optimization parameter limits make it harder to find the optimal solution. To solve all the above problems, this paper proposed a Genetic Algorithm (GA) to obtain optimal parameters that used as constants in the optimal coordination of CES and PSS operations simultaneously.

The genetic algorithm is an optimization method that imitates natural biological evolution metaphor [14], [24]. GA is used to solve nonlinear equations by finding random values and optimizing very complex problems. GA uses probabilistic transition rules in place of deterministic rules and addresses the population of potential solutions called individuals or chromosomes that develop iteratively. Each iteration of this algorithm is
called a generation. Development of solutions is
simulated by fitness functions and genetic operators
such as reproduction, mutation, and crossover.

In this paper, GA is presented for optimizing the
use of PSS and CES in a single-machine infinite
bus (SMIB) synchronous generator. The PSS and
CES parameters are effectively tuned with GA to
obtain sufficient damping for oscillations due to
load changes. The attenuation to the oscillations
occurring is used as an objective function. Then the
attenuation is converted to a fitness function using
the Integral Time Absolute Error (ITAE) method.
ITAE optimizes the absolute error and completion
time not achieved by other methods [27]. Then the
fitness value that has been obtained will be
evaluated to get the optimal oscillation damping
value. Thus, system security can avoid unwanted
incidents.

2. SYNCHRONOUS GENERATOR MODEL

Single-machine generator model in this
paper is shown in figure 1 [13]. This generator
model is a synchronous generator modeling in
detail, including its control components. Generally,
there are two main controllers on this generator
modeling, Load Frequency Control (LFC) and
Automatic Voltage Regulator (AVR). Both
controllers maintain frequencies and voltages in
stable conditions in accordance with their
limitations when there is a load changing on the
system. The active power change affects the rotor
angle $\delta$ which will directly affect the frequency.
While the change of reactive power will affect the
voltage magnitude. The excitation system will keep
the voltage stable, but it does not affect the LFC.

LFC will work independently to maintain
frequency stability due to active power change.

$$\frac{2H d^2 \Delta \delta}{\omega_s dt^2} = \Delta P_m - P_e \quad (1)$$

With speed expressed in per unit, without explicit per unit notation,

$$\frac{d \Delta \omega}{dt} = \frac{1}{2H} (\Delta P_m - \Delta P_e) \quad (2)$$

Laplace Transform of equation (xxx) is

$$\Delta \Omega(s) = \frac{1}{2Hs} [\Delta P_m(s) - \Delta P_e(s)] \quad (3)$$

By deriving the swing equation of the
synchronous generator in equation (1) - (3) there is
a correlation between the mechanical power of
the generator $P_m$ and the electrical power of the load $P_e$ as shown figure (1).

2.1 LFC Model

LFC will keep the frequency stable at its limit.
The frequency change will be known through the
rotor angle change then the rotor angle error will be
corrected. The error signal will be amplified and
converted to active power. Then prime-mover will
compensate for the change of active power. Figure
(2) shows the LFC block diagram in the synchronous
generator.

$$\frac{\Delta \Omega(s)}{\Delta P_L(s)} = \frac{(1+TP_s)(1+T_f)}{(2Hs+D)(1+TP_s)(1+T_f)s+1/R} \quad (4)$$

Change of $\Delta \omega$ as input and frequency
deviation $\Delta \Omega$ as the output of block diagram of
LFC in figure (4). Close-loop transfer function
between load changes $\Delta P_L(s)$ and changes in
frequency deviation $\Delta \Omega(s)$ as equation (4).

2.2 AVR Model

The reactive power of the generator is controlled by
the excitation system using AVR. AVR will
maintain the voltage magnitude of the generator
terminal at the specified limit. Figure (3) shows a
simplified automatic voltage regulator block.

Figure 1. Mechanical power and the electrical
power block diagram

Figure 2. LFC block diagram
The addition of reactive power on the load will cause the voltage drop at the generator terminal. The voltage magnitude will be censored by the potential transformer (PT), then will be rectified to DC voltage by the rectifier. The DC signal will be compared with the set point so that the error signal will be compensated by the exciter so that the current on the generator field coil increases. The field current will amplify the emf on the generator so that the reactive power increases and the voltage return to the desired value.

\[
\frac{v_i(s)}{v_{ref}(s)} = \frac{K_A K_E K_R K_s (1+\tau_A s)}{(1+\tau_R s)(1+\tau_E s)(1+\tau_P s)(1+\tau_G s)+K_A K_E K_R K_s} \quad (5)
\]

Closed Loop transfer function between the terminal voltage generator \(V_t(s)\) to the reference voltage \(V_{reff}(s)\) is represented by equation (5).

3. CES (Capacitive Energy Storage)

CES consists of the capacitor storage and Power Conversion System (PCS) with control and integrated protection functions. Figure 4 shows the basic configuration of CES in electric power systems. Capacitor storage \(C\) consists of several discrete capacitors that connected in parallel. Resistance \(R\) connected in parallel to the capacitor \(C\) is leaking and dielectric losses of the capacitor bank at CES. Storage capacitor connected to the grid through the Power Conversion System (PCS), which consists of ac to dc rectifier and dc to AC inverter. Two sets of six-pulse bridge converter are used to reduce harmonics that occurred. The function of bypass thyristors to provide a pathway for currents \(I_d\) when converter failure occurs. DC breaker allows the currents \(I_d\) to flow through resistor \(R_D\), the energy disposal if the converter fails. Neglecting the losses, bridge voltage \(E_d\) is as equation (7).

\[
E_d = 2E_{d0} \cos \alpha - 2I_d R_D \quad (7)
\]

By changing the phase angle \(\alpha\) with a range value from 0° to 180° the capacitor voltage \(E_d\) able to be varied from a maximum positive value until the maximum negative value [10]. This conditions will make CES is very effective in reducing oscillations caused by load changes because the normal operating point of the capacitor can be arranged so that the maximum energy absorption equals the maximum energy discharge. If \(E_{d0}\) shows the initial voltage value, \(E_{dmax}\) and \(E_{dmin}\) shows the minimum and maximum voltage limits, then:

\[
\frac{1}{2} CE_{dmax}^2 - \frac{1}{2} CE_{d0}^2 = \frac{1}{2} CE_{d0}^2 - \frac{1}{2} CE_{dmin}^2 \quad (6)
\]

\[
E_{d0} = \frac{|E_{dmax}^2 + E_{dmin}^2|}{2} \quad (7)
\]

CES voltage must be returned to the initial value quickly, so after a fault occurs CES ready to work for the next fault. Therefore, the capacitor voltage deviation is used as a negative feedback signal in the CES loop control so voltage recovery is achieved quickly as shown in figure 5 below.

\[
\Delta \bar{I}_d = \frac{[K_{CES} \Delta f - K_{VD} \Delta E_d]}{1+\tau_{DC}} \quad (8)
\]

With the capacitor voltage deviation \(\Delta E_d\) are as follows:
CES output power that released to the system during load changes are as follows:

\[ \Delta P_{CES} = (E_{d0} + \Delta E_d) \Delta I_d \]  

(9)

While the washout components prevent offset voltage on a steady state. With this transfer function on equation (11), PSS can be used to generate a positive damping torque which the magnitude and phase can be regulated.

\[ V_S = \frac{sK_{PSS} T_w}{1 + sT_w} \left( 1 + \frac{\sqrt{\alpha}}{\delta} \right)^2 \]  

(10)

This controller was effective, economical, and secure in the power system to dampen oscillations. However, this controller is not effectively used for large electric power systems that interconnected with the generator layout that far apart. Therefore, the oscillation interarea usually occurs in such a system [5].

### 2.3 CES and PSS Coordination

CES and PSS coordination in the system shown in Figure 7. CES dampen oscillations by detecting the frequency of feedback and then provide damping in the form of power CES \((P_{CES})\). While PSS dampen oscillations by detecting the frequency of feedback and then provide damping through the excitation system. Figure 7 shows the modeling of the generator by the addition of CES and PSS. In Table 1, have also shown some initial parameters of CES.
An individual is evaluated by a certain function as a measure of its performance. In nature evolution, individuals who have higher fitness will be alive while individuals that have low fitness will die. In this study, a solution searched to minimize the function $h$ (minimization problem) so that the function $h$ cannot be used directly. This is due to the rule that individuals with higher fitness values can survive in the next generation. Therefore the value of fitness that can be used according to the equation:

$$f = \frac{1}{h}$$  \hspace{1cm} (13)

that means that the smaller the value 'h', the greater the value 'f'. To avoid the value 'f' infinite due to the value of 'h' is equal to zero, should be added a number which is considered very small so the fitness value becomes:

$$f = \frac{1}{h + a}$$  \hspace{1cm} (14)

The $h$ function is a damping function obtained using the ITAE method. In this paper, the objective function (ITAE) is obtained using the equation (15).

$$h = \int_{0}^{\infty} t|e(t)|dt$$  \hspace{1cm} (15)

After obtaining the value of fitness then will be ranked according to the following equation:

$$f(i) = f_{\text{max}} - (f_{\text{max}} - f_{\text{min}}) \left( \frac{R(i) - 1}{N - 1} \right)$$  \hspace{1cm} (16)

where $R$ (i) declare the i-th individual rank. The selection of two pieces of chromosomes as parents, which will be crossed over, carried out proportionally based on the fitness value. The selection method that used in this research is the roulette wheel method. A chromosome with greater fitness value will substitute another chromosome with lower fitness value. Crossover is done to avoid the early convergences. Each chromosome will choose its partner to do crossover randomly. The frequency of the crossover operator controlled by the value of $P_c$. In any population, as many as $P_c \times$ the population size, do the crossover. The higher the value of the crossover probability, then the sooner a new structure introduced in the population. In this research, crossover probability $P_c$ used is 0.8.

Random mutations in a gene carried by a small probability. In this program, the probability of mutation is $P_m = 0.3$. The process repeated from the beginning for an every new population.
6. RESULTS AND DISCUSSION

Simulations were conducted to prove the suitability of the method. Table 2 is a parameter of the GA as a method to obtain optimal values of CES and PSS constants. Value optimization of system performance in each generation in the convergence-plot on a graph shown in Figure 5.

<table>
<thead>
<tr>
<th>No.</th>
<th>CES Parameter</th>
<th>PSS Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>K&lt;sub&gt;ces&lt;/sub&gt;</td>
<td>K&lt;sub&gt;pss&lt;/sub&gt;</td>
</tr>
<tr>
<td>2</td>
<td>C</td>
<td>T&lt;sub&gt;W&lt;/sub&gt;</td>
</tr>
<tr>
<td>3</td>
<td>R</td>
<td>T&lt;sub&gt;A&lt;/sub&gt;</td>
</tr>
<tr>
<td>4</td>
<td>E&lt;sub&gt;D0&lt;/sub&gt;</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>K&lt;sub&gt;v&lt;/sub&gt;</td>
<td>T&lt;sub&gt;C&lt;/sub&gt;</td>
</tr>
<tr>
<td>6</td>
<td>T&lt;sub&gt;dc&lt;/sub&gt;</td>
<td>0.0825</td>
</tr>
</tbody>
</table>

These parameters will be used as control constants in CES and PSS operations. Thus, the performance of CES and PSS becomes optimum.

a. Frequency Changes Response

CES and PSS simulation application in a single-machine is optimized using Genetic Algorithms. To test the dynamic stability of the system, interruption of 1 p.u load change is given at 10th second. From the simulation obtained response of frequency change per unit (p.u) shown in Figure 8.
From the picture above, the red graph shows the frequency response when an interruption occurs without CES and PSS installed. While the blue graph shows the frequency response using CES and PSS which has been optimized using GA algorithm. From the graph, it appears that with the addition of CES and PSS that have been coordinated and optimized using GA in the system causes the system performance against disruption becomes better. It can be seen from the reduction in the oscillation frequency of the system.

Overshoot frequency generator data in single-machine models are shown in the table below.

**Table 4. Frequency Overshoot Value**

<table>
<thead>
<tr>
<th>Without Controller (pu)</th>
<th>CES and PSS (pu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>max</td>
<td>0.005608</td>
</tr>
<tr>
<td>min</td>
<td>-0.06857</td>
</tr>
<tr>
<td>mean</td>
<td>0.001317</td>
</tr>
<tr>
<td>max</td>
<td>0.0524</td>
</tr>
</tbody>
</table>

From the table above it can be seen that with the addition of CES and PSS in the system, making the frequency overshoot in the system becomes smaller.

**b. Rotor Angle Responses**

From the simulation results can also be analyzed for the rotor angle changes as shown in Figure 9.

![Figure 11. Rotor Angle Generator Response](image)

From the picture above, the red graph shows the response of rotor angle when an interruption occurs without CES and PSS installed. While the blue graph shows the response of rotor angle using the CES and PSS. From both graphs can also be seen that the addition CES and PSS can reduce rotor angle oscillation due to a load change disturbance. Overshoot rotor angle data system single-machine generator are shown in the table below.

**Table 5. Rotor Angle Overshoot Value**

<table>
<thead>
<tr>
<th>Without Controller (pu)</th>
<th>CES and PSS (pu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>max</td>
<td>1.098x10^-35</td>
</tr>
<tr>
<td>min</td>
<td>-0.176</td>
</tr>
<tr>
<td>mean</td>
<td>-0.141</td>
</tr>
<tr>
<td>max</td>
<td>1.097x10^-35</td>
</tr>
<tr>
<td>min</td>
<td>-0.176</td>
</tr>
<tr>
<td>mean</td>
<td>-0.136</td>
</tr>
</tbody>
</table>

Table 5 also indicates that, with the addition of CES and PSS in the system, making rotor angle overshoot becomes smaller.

**c. Voltage Responses**

Analysis of simulation results of voltage parameters due to the installation of CES and PSS are shown in Figure 10.

![Figure 12. Generator Voltage Responses](image)

Based on the figure 10, the red graph shows the voltage response when an interruption occurs without CES and PSS installed. While the blue graph shows the voltage response using CES and PSS. These images show that CES and PSS installation can reduce the voltage oscillation. However, overshoot that occurs due to the installation of CES and the PSS in the system becomes larger.

Overshoot voltage data in single-machine generator models are shown in the table below.

**Table 6. Voltage Overshoot Value**

<table>
<thead>
<tr>
<th>Without Controller (pu)</th>
<th>CES and PSS (pu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>max</td>
<td>9.065</td>
</tr>
<tr>
<td>min</td>
<td>-0.2513</td>
</tr>
<tr>
<td>mean</td>
<td>9.065</td>
</tr>
<tr>
<td>max</td>
<td>9.065</td>
</tr>
<tr>
<td>min</td>
<td>-0.2429</td>
</tr>
</tbody>
</table>

The table also indicates that, with the addition of CES and the PSS in the system, making voltage overshoot becomes smaller.
7. CONCLUSION

The results of proposed method showed that the installation of CES and the PSS in the single-machine generator models can reduce the oscillation due to load changes failure. The use of GA optimization algorithm parameters used as constants in the CES and PSS proved effective enough to get the optimum value so that the oscillation due to a disturbance becomes smaller. This will make the system safe from unwanted events, untuk kedepannya diharapkan penelitian ini dapat diimplementasikan pada sistem nyata.

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