Subsynchronous Resonance Damping Using SMES Optimized by Quantum Behaved Particle Swarm Optimization

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Abstract—Subsynchronous resonance (SSR) problems appeared due to resonance between the turbine and the series capacitor on transmission line is damped by installing superconducting magnetic energy storage (SMES) unit which the parameters are optimized by quantum behaved particle swarm optimization (QPSO). The proposed objective function is comprehensive damping index (CDI) of SSR damping. To accommodate the formation of SSR mode, the method is developed on the nominal plant at Java-Bali 500 kV electrical power system. The turbine is modeled in a rather detailed model of four levels. Models of other power system components follow the standard linear model for dynamic stability study.

Keyword—Subsynchronous resonance (SSR), SMES, CDI

I. INTRODUCTION

The installation of series capacitors on transmission line may cause sub-synchronous resonance (SSR). Sub-synchronous resonance (SSR) can cause seriously damage the mechanical shaft system and electrical instability at oscillation frequency lower than the normal system frequency. The phenomenon of SSR is getting widely attention associated with twin shaft failures occurred in the Mohave Power Station in 1970-1971 [1]. Since then sub-synchronous resonance has been investigated and analyzed in detail [1, 2]. To avoid the shaft damage, several methods have been proposed to damp the oscillations such as reactive power control [3], control of excitations [1, 4], By-Pass Filter Damping [1] and Superconducting Magnetic Energy Storage unit (SMES) [5].

SMES have the ability to store energy in low resistance coil. This energy can be given to the electric power system if energy is needed. The total of energy supplied by the SMES or received can be controlled by controlling the firing angle of the converter in the SMES unit. In this paper, a proportional-integral-derivative (PID) controller is used to control a SMES unit for increasing the torsional modes damping of the generator. The \( K_p \), \( K_i \), \( K_d \) PID controller and \( K_{smes} \) gains are determined using the Quantum Behaved Particle Swarm Optimization in order to shift the eigenvalues of the torsional modes to the better prespecified points. Eigenvalue analysis and time domain simulation are performed on the Java-Bali 500 kV electrical power system to demonstrate the effectiveness of the proposed controller.

This paper is organized as follows. Section II describes the modeling of power system, SSR, SMES, and QPSO studies. Implementation of the proposed method to the system is discussed in Section III. The evaluation and analysis of the simulation result are presented in Section IV. Finally, there are conclusions.

II. THEORETICAL BACKGROUND

A. Multimachine Power System Modeling

The Java-Bali 500 kV electrical power system is used as a plant in this research. Components of power systems such as turbines, generators, circuit excitation, governor, transmission lines, transformers, and loads are modeled as linear. In this research, the generator model used was a Philip-Heffron model. The MATLAB/SIMULINK block diagram of this model describe in the Figure 1.

Figure 1. Generator modeling using Philip-Heffron model

Excitation systems used in this research is type 1. With this exciter type is expected to have a better transient response and the issues can be focused on the SSR stability. The governor was modeled as a first-order transfer function. The turbine structure has been selected to analyze the SSR phenomenon described in Figure 2. Block diagram of the turbine model in MATLAB/SIMULINK shown in Figure 3 and 4.

Figure 2. Radial system series compensator

Figure 3. Block diagram of the turbine model in MATLAB/SIMULINK

Figure 4. Block diagram of the turbine model in MATLAB/SIMULINK
Subsynchronous Resonance (SSR)

The application of series capacitors, while providing many advantages, can cause subsynchronous resonance (SSR) oscillation. Equivalent circuit of electric power system in Figure 5 is used to explain the phenomena of SSR. Resonance will occur at a frequency,

$$\omega_n = \frac{1}{\sqrt{LC}} \approx \frac{\omega_o}{\sqrt{(\omega_o L)(\omega_o C)}} = \omega_o \sqrt{\frac{X_C}{X_L}} \text{ rad/s} \quad (1)$$

To demonstrate all the sub-synchronous frequencies generated by the turbine, the turbine will be modeled in details as shown in Figure 2. In this paper, an analysis of the SSR phenomenon has been done on the Suralaya Generator because its location close to the transmission line which installed the series capacitors.

Superconducting Magnetic Energy Storage (SMES) Unit

The configuration of the SMES unit contains a \( Y - \Delta / Y - Y \) connected transformer, a 12 pulse cascaded bridge type AC/DC convertor, and a DC superconducting inductor shown in Figure 6.

Quantum Particle Swarm Optimization (QPSO)

A quantum model of PSO called QPSO contains of state of the particles described by wave functions \( \psi(x,t) \) (Schrodinger equation) [6], instead of position and velocity. Dynamic behavior of particles is widely different from that of the particle in classical PSO systems, in that the exact values of \( x \) and \( v \) can’t be determined simultaneously. In this context, the probability of the particle’s appearing in position \( x \) with probability density function \( |\psi(x,t)|^2 \), depends on the potential field the particle lies and can be found in [7]. Using the Monte Carlo method, the particles move according to the following iterative equation,

$$\begin{align*}
x_{id}(t+1) &= P_{id} + \beta \cdot | M_{best} - x_{id}(t) | \cdot \ln(1/u), \text{ if } k \geq 0.5 \\
x_{id}(t+1) &= P_{id} - \beta \cdot | M_{best} - x_{id}(t) | \cdot \ln(1/u), \text{ if } k < 0.5
\end{align*} \quad (2)$$

where \( x_{id}(t+1) \) is the position for the \( d \)-th dimension of the \( i \)-th particle in \( t \)-th generation. \( M_{best} \) is the global point called mainstream thought or mean best (Mbest) for the \( j \)-th dimension, \( \beta \) is a design parameter called contraction expansion coefficient, \( u \) and \( k \) are values generated according to a uniform probability distribution in range [0, 1] and \( P_{id}(t) \) is local point (local attractor). The mainstream thought or mean best (Mbest) is the mean of the \( P_{best} \) of all particles and it is given by

$$M_{best} = \frac{1}{N} \sum_{d=1}^{N} P_{id}(t) \quad (3)$$

where \( N \) is the population size of particles. In this research, the local attractor to guarantee convergence of the PSO can be expressed as follow,
\[ P_{i,d}(t) = \frac{c_1 P_{i,j} + c_2 P_{g,j}}{c_1 + c_2} \] (4)

where \( P_{i,j} \) (Pbest) is the best previous \( j \)-th dimension of the \( k \)-th particle and \( P_{g,j} \) represents the \( j \)-th dimension of the best particle (Gbest) of the population. Positive constants \( c_1 \) and \( c_2 \) are the cognitive and social components, respectively, which are the acceleration constants responsible for varying the particle velocity towards \( P_{\text{best}} \) and \( G_{\text{best}} \), respectively.

III. IMPLEMENTATION OF THE PROPOSED METHOD TO THE SYSTEM

In this section, the application of the proposed method for tuning parameters of Superconducting Magnetic Energy Storage (SMES) to obtain the minimum value of Comprehensive Damping Index (CDI) was presented. The CDI value is used as a function fitness of the \( i \)-th particle. The real eigenvalue and damping ratio used as constraints.

The procedures for implementing the proposed method for tuning \( K_{\text{smes}}, K_p, K_c, K_s \) SMES parameters can be expressed as follow,

1. Initialization of the parameter setup : Determine the multimachine data of Java-Bali 500 kV electrical power system and the key parameters that control the QPSO, namely population size of particles, boundary constraints of optimisation variables, cognitive component \( (c_c) \), social component \( (c_s) \), contraction expansion coefficient \( (\beta) \) and the stop criterion \( (t_{\text{max}}) \).
2. Initialization of the particle population : Initialize a population (array) of particles with random positions in the \( d \)-dimensional problem space using a uniform probability distribution function. The position of the particle shows the value of \( K_{\text{smes}}, K_p, K_c, K_s \) SMES parameters.
3. Evaluation of the particles population : Evaluate the fitness value of the \( i \)-th particle using CDI value as follow,

\[
\text{CDI} = \sum_{i=1}^{n} \left( 1 - \zeta_i \right)
\]

\[
\zeta_i = \frac{-\sigma_i}{\sqrt{\sigma_i^2 + \omega_i^2}}
\]

\[
\lambda_i = \sigma_i + j \omega_i
\]

4. Comparison of each particle’s útness with its \( P_{\text{best}} \) : Compare each particle’s útness with the particle’s \( P_{\text{best}} \). If the current value is better than \( P_{\text{best}} \), then set the \( P_{\text{best}} \) value equal to the current value and the \( P_{\text{best}} \) location equal to the current location in \( d \)-dimensional space.
5. Comparison of each particle’s útness with its \( G_{\text{best}} \) : Compare the útness with the population’s overall previous best. If the current value is better than \( G_{\text{best}} \), then reset \( G_{\text{best}} \) to the current particle’s array index and value.
6. Updating of \( M_{\text{best}} \) : Calculate the \( M_{\text{best}} \) using equation (3).
7. Comparison of each particle’s útness with its \( P_{\text{best}} \) : Compare the fitness value of the \( i \)-th particle with \( P_{\text{best}} \). If the current position value is better than \( P_{\text{best}} \), set the \( P_{\text{best}} \) value equal with the current value and position particles.
8. Updating of local attractor and position of particles : Change the \( P_{i,d}(t) \) and position of the particle using equation (4) and (2), respectively.
9. Repeating the evolutionary loop : Loop to step 3 until a stopping criterion is reached. The maximum number of genera-tions is implemented in this paper.

IV. TESTED SYSTEM AND RESULT

A. Tested System

The proposed method was tested in the Java-Bali 500kV electrical power system which consists of 8 generator, 30 transmission line and 25 buses. The load data used in this research was taken on April 19th, 2011 with peak loads during that day at 13.30 pm with the total load are 10361 MW and 3565 MVAR. The MVA base used is 1000 MVA and the kV base is 500 kV. The data of Java-Bali 500kV was obtained from PT.PLN (Persero). The single line diagram of Java-Bali 500kV system is described in Figure 8.

B. Experimental Result

The Suralaya turbine shaft generator has 5 mass, so there are 4 modes of torsional oscillation. The shaft torsional oscillation modes of Suralaya turbine-generator before compensation shown in Table 1.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Eigenvalue</th>
<th>Damping</th>
<th>Freq. (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.000000000</td>
<td>0.0000000000</td>
<td>0.0000000000</td>
</tr>
<tr>
<td>1</td>
<td>-1.68e-001 ± 5.89e+001</td>
<td>2.32e-03</td>
<td>10.32</td>
</tr>
<tr>
<td>2</td>
<td>-4.17e-001 ± 1.13e+001</td>
<td>3.86e-03</td>
<td>16.39</td>
</tr>
<tr>
<td>3</td>
<td>-1.52e-001 ± 1.20e+002</td>
<td>9.28e-04</td>
<td>20.86</td>
</tr>
<tr>
<td>4</td>
<td>-1.16e+000 ± 1.95e+002</td>
<td>5.63e-03</td>
<td>30.57</td>
</tr>
</tbody>
</table>

Figure 8. Single line diagram of Java-Bali 500kV System
A rotational shift of each mass relatively for each mode oscillation is given by the right eigenvector of the eigenvalue. Mode value shown in Table 1 can be represented in Figure 9.

In this research, a series capacitor installed between Suralaya and Cilegon bus system with compensation level 50%. An eigenvalue analysis is used to see the oscillation modes that appear due to the SSR phenomenon. The identification result for the turbine-generator mode oscillations after compensation can be seen in Table 2.

Without compensation, the Suralaya generator has mode frequency 1, 2, 3 and 4 are 10.4, 16.4, 20.8 and 30.5 Hz respectively. With increasing in compensation levels, the frequency of torsional modes have small variations and the damping ratio also changing. When the compensation level was 50%, the torsional mode be unstable. It is characterized that the eigenvalue for mode 4 is positive (1.63e+000 ± 1.91e+002i) and there is interaction between the torsional modes of four turbine-generator and transmission line mode system.

The QPSO parameters were used as below,
\[ \text{Number of Particle} = 50; \text{Maximum Generation} = 70; \]
\[ \beta^{\text{Min}} = 0.4; \beta^{\text{Max}} = 1; \text{Number of Dimension} = 4. \]

The conventional and optimal SMES can reduce the torsional oscillation modes, so it can stabilize up to 50% the compensation level. Figure 10 and 11 are comparison result of proposed method. Comparison in performance of rotor angle deviation is shown in Figure 10, while comparison in speed rotor angle deviation is shown in Figure 11. Table 8 shows that QPSO achieves steady state faster than the other, indicates better stability. From Table 9, we know that QPSO has lower overshoot value, which means that it has better damp ability compare to other methods.
CONCLUSION

This paper presents a new method using QPSO for optimizing the SMES unit for controlling the unstable modes arising from the phenomenon of subsynchronous resonance. The controller is implemented with generator speed deviation as the input signals. It has been shown through time-domain simulation that shaft oscillations at subsynchronous frequencies can be successfully damped using the proposed optimization method.

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