
Ahmad Memaripour, Sayed Mojtaba Shirvani Boroujeni and Reza Hemmati
Department of Electrical Engineering, Boroujen Branch, Islamic Azad University, Boroujen, Iran

Abstract: This study presents the application of Unified Power Flow Controller (UPFC) to improvement dynamic stability of a multi-machine electric power system installed with UPFC. Since UPFC is considered to mitigate Low Frequency Oscillations (LFO) and stability enhancement, therefore a supplementary stabilizer based on UPFC (like power system stabilizer) is designed to reach the defined purpose. Intelligence optimization methods such as Particle Swarm Optimization (PSO) and Genetic Algorithms (GA) are considered for tuning the parameters of UPFC supplementary stabilizer. To show effectiveness of UPFC and also comparing these two optimization methods, the proposed methods are applied and simulated. Several nonlinear time-domain simulation tests visibly show the ability of UPFC in damping of power system oscillations and consequently stability enhancement. Also Simulation results emphasis on the better performance of PSO based Stabilizer in comparison with GA based Stabilizer.

Key words: Damping power system Oscillations, flexible AC transmission systems, unified power flow controller

INTRODUCTION

The rapid development of the high-power electronics industry has made Flexible AC Transmission System (FACTS) devices viable and attractive for utility applications. FACTS devices have been shown to be effective in controlling power flow and damping power system oscillations. In recent years, new types of FACTS devices have been investigated that may be used to increase power system operation flexibility and controllability, to enhance system stability and to achieve better utilization of existing power systems (Hingorani and Gyugyi, 2000). UPFC is one of the most complex FACTS devices in a power system today. It is primarily used for independent control of real and reactive power in transmission lines for flexible, reliable and economic operation and loading of power systems. Until recently all three parameters that affect real and reactive power flows on the line, i.e., line impedance, voltage magnitudes at the terminals of the line, and power angle, were controlled separately using either mechanical or other FACTS devices. But UPFC allows simultaneous or independent control of all these three parameters, with possible switching from one control scheme to another in real time (Faried and Billinton, 2009; Jiang et al., 2010; Jiang et al., 2010; Mehraeen et al., 2010; Farrag and Putrus, 2011). Also the UPFC can be used for voltage support and transient stability improvement by damping of low frequency power system oscillations. Low Frequency Oscillations (LFO) in electric power system occur frequently due to disturbances such as changes in loading conditions or a loss of a transmission line or a generating unit. These oscillations need to be controlled to maintain system stability. Many in the past have presented lead-Lag type UPFC damping controllers (Wang, 1999; Tambey and Kothari, 2003; Guo and Crow, 2009; Zarghami et al., 2010). They are designed for a specific operating condition using linearized models. More advanced control schemes such as Particle-Swarm method, Fuzzy logic and genetic algorithms (Eldamaty et al., 2005; Al-Awami, 2007; Hao et al., 2008; Singh et al., 2009) offer better dynamic performances than fixed parameter controllers.

The objective of this study is to investigate the ability of UPFC for dynamic stability improvement via damping low frequency oscillations at a multi machine electric power system. Intelligence optimization methods such as Particle Swarm Optimization (PSO) and Genetic Algorithms (GA) are considered for tuning the parameters of UPFC supplementary stabilizer. A multi machine power system installed with a UPFC is considered as case study. A classical Power System Stabilizer (PSS) is connected to UPFC and the parameters of this UPFC based stabilizer are adjusted using PSO and GA. The
advantages of the proposed methods are their feasibility and simplicity. Different load conditions are considered to show effectiveness of UPFC and also comparing the performance of PSO and GA. Simulation results show the validity of UPFC in LFO damping and stability enhancement at large electric power systems.

**METHODOLOGY**

**System under study:** Figure 1 shows a multi machine power system installed with UPFC (Kundur, 1993). The static excitation system, model type IEEE - ST1A, has been considered.

The UPFC is assumed to be based on Pulse Width Modulation (PWM) converters. Detail of the system data are given in (Kundur, 1993). To assess the effectiveness and robustness of the proposed method over a wide range of loading conditions, three different cases as nominal, light and heavy loading are considered and listed in Table 1.

**Dynamic Model of the System with Upfc:** The nonlinear dynamic model of the system installed with UPFC is given as (1). The dynamic model of the system is completely presented in (Kundur, 1993) and also dynamic model of the system installed with UPFC is presented in (Nabavi-Niaki and Iravani, 1996; Wang, 2000).

\[
\begin{align*}
\dot{\omega}_i &= \frac{(P_m - P_e - D\omega)}{M} \\
\dot{\delta}_i &= \omega_0 (\omega - 1) \\
E_{q*} &= \frac{(-E_q + E_{fd})}{T_{do}} \\
e_{fd} &= \frac{E_{fd} + K_a (V_{ref} - V_r)}{T_a} \\
\dot{V}_{dc} &= \frac{3m_E}{4C_{dc}} \left( \sin(\delta_E)I_{Ed} + \cos(\delta_E)I_{Eq} \right) \\
+ \frac{3m_B}{4C_{dc}} \left( \sin(\delta_B)I_{Bd} + \cos(\delta_B)I_{Bq} \right)
\end{align*}
\]

where;

\( i = 1, 2, 3, 4 \) (the generators 1 to 4)

\( \delta \) : rotor angle

\( \omega \) : rotor speed

\( P_m \) : mechanical input power

\( P_e \) : electrical output power

\( E_q \) : internal voltage behind \( x_d \)

\( E_{fd} \) : equivalent excitation voltage

\( T_e \) : electric torque

\( T_{do} \) : time constant of excitation circuit

\( K_a \) : regulator gain

\( T_a \) : regulator time constant

\( V_{ref} \) : reference voltage

\( V_t \) : terminal voltage

\( m_b \) : pulse width modulation of series inverter. By controlling \( m_b \), the magnitude of series injected voltage can be controlled

\( \delta_b \) : phase angle of series injected voltage.

\( m_e \) : pulse width modulation of shunt inverter. By controlling \( m_e \), the output voltage of the shunt converter is controlled

\( \delta_e \) : phase angle of the shunt inverter voltage
The series and shunt converters are controlled in a coordinated manner to ensure that the real power output of the shunt converter is equal to the power input to the series converter. The fact that the DC-voltage remains constant ensures that this equality is maintained. UPFC controllers: In this study two control strategies are considered for UPFC:

- DC-voltage regulator
- UPFC supplementary stabilizer

**DC-voltage regulator:** In UPFC, the output real power of the shunt converter must be equal to the input real power of the series converter or vice versa. In order to maintain the power balance between the two converters, a DC-voltage regulator is incorporated. DC-voltage is regulated by modulating the phase angle of the shunt converter voltage. Figure 2 shows the structure of DC-voltage regulator. In this study the parameters of DC-voltage regulator are considered as \( K_{di} = 39.5 \) and \( K_{dp} = 6.54 \).

**UPFC supplementary stabilizer:** A stabilizer controller is provided to improve damping of power system oscillations. This controller is considered as a lead-lag compensator and it provides an electrical torque in phase with the speed deviation in order to improve damping of power system oscillations. The transfer function model of the classical stabilizer is as (2). Where, \( \Delta \omega \) is the deviation of speed from the synchronous speed. This type of stabilizer consists of a washout filter, a dynamic compensator. The output signal is fed as a supplementary input signal to the UPFC. The washout filter, which essentially is a high pass filter, is used to reset the steady state offset in the output of the PSS. In this study the value of the time constant (\( T_w \)) is fixed to 10 s. The dynamic compensator is made up to two lead-lag stages and an additional gain. The adjustable stabilizer parameters are the gain of the Stabilizer, \( K_{dc} \), and the time constants, \( T_1-T_4 \). The lead-lag block present in the system provides phase lead compensation for the phase lag that is introduced in the circuit between the UPFC input and the electrical torque.

\[
U = K \cdot \frac{STW \cdot (1 + ST1 + ST3)}{1 + ST1} \cdot \frac{1}{ST2 + ST4} \cdot \Delta \omega
\]  

(2)

**Stabilizer design:** Stabilizer controllers design themselves have been a topic of interest for decades, especially in form of classical Power System Stabilizers (PSS) which are connected to the excitation system of generator. But classical PSS cannot control power transmission and also can not support power system stability under large disturbances like 3-phase fault at terminals of generator (Mahran et al., 1992). For these problems, in this study a stabilizer controller based on UPFC is provided to mitigate power system oscillations. Two optimization methods such as PSO and GA are considered for tuning stabilizer controller parameters. In the next section an introduction about PSO is presented.

**Particle swarm optimization:** PSO was formulated by Edward and Kennedy in 1995. The thought process behind the algorithm was inspired by the social behavior of animals, such as bird flocking or fish schooling. PSO is similar to the continuous GA in that it begins with a random population matrix. Unlike the GA, PSO has no evolution operators such as crossover and mutation. The rows in the matrix are called particles (same as the GA chromosome). They contain the variable values and are not binary encoded. Each particle moves about the cost surface with a velocity. The particles update their velocities and positions based on the local and global best solutions as shown in (3) and (4) (Randy and Sue, 2004):

\[
V_{m,n}^{new} = w \cdot V_{m,n}^{old} + \Gamma_1 \cdot r_1 \cdot (P_{m,n}^{local} - P_{m,n}) + \Gamma_2 \cdot r_2 \cdot (P_{m,n}^{global} - P_{m,n})
\]  

(3)

\[
P_{m,n}^{new} = P_{m,n}^{old} + \Gamma \cdot V_{m,n}^{new}
\]  

(4)

where,

- \( V_{m,n} \) = particle velocity
- \( P_{m,n} \) = particle variables
- \( W \) = inertia weight
- \( r_1, r_2 \) = independent uniform random numbers
- \( \Gamma_1 = \Gamma_2 \) = learning factors
- \( P_{m,n}^{local} \) = best local solution
- \( P_{m,n}^{global} \) = best global solution

**PSO based stabilizer design:** In this section the parameters of the proposed stabilizer controller are tuned using PSO. Four control parameters of the UPFC (\( m_{E}, \delta_{G}, m_{V} \) and \( \delta_{V} \)) can be modulated in order to produce the damping torque. The parameter \( m_{E} \) is modulated to output of damping controller and speed deviation is also considered as input of damping controller. The structure of supplementary stabilizer has been shown in (2). The optimum values of \( K \) and \( T_1-T_4 \) which minimize an array of different performance indexes are accurately computed using PSO. In optimization methods, the first step is to define a performance index for optimal search. In this study the performance index is considered as (5). In fact, the performance index is the Integral of the Time multiplied Absolute value of the Error (ITAE).

\[
ITAE = \int_{0}^{t}\int_{0}^{t}\int_{0}^{t}\int_{0}^{t}\int_{0}^{t}\int_{0}^{t}|\Delta \omega|\,dt + |\Delta \omega_2|\,dt + |\Delta \omega_3|\,dt + |\Delta \omega_4|\,dt
\]  

(5)
Table 2: optimal parameters of stabilizer using PSO and GA

<table>
<thead>
<tr>
<th></th>
<th>PSO</th>
<th>GA</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>41.4988</td>
<td>1.4792</td>
</tr>
<tr>
<td>T_1</td>
<td>0.2717</td>
<td>0.2059</td>
</tr>
<tr>
<td>T_2</td>
<td>0.1784</td>
<td>0.1918</td>
</tr>
<tr>
<td>T_3</td>
<td>0.8603</td>
<td>0.9818</td>
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<tr>
<td>T_4</td>
<td>0.221</td>
<td>0.2131</td>
</tr>
<tr>
<td>KT</td>
<td>1.4792</td>
<td>0.2131</td>
</tr>
</tbody>
</table>

Table 3: The values of performance index (ITAE)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Light</th>
<th>Nominal</th>
<th>Heavy</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSO</td>
<td>0.4150</td>
<td>0.0434</td>
<td>0.0459</td>
</tr>
<tr>
<td>GA</td>
<td>0.5548</td>
<td>0.0591</td>
<td>0.0651</td>
</tr>
</tbody>
</table>

Fig. 3: Simulation results under scenario 1 in the nominal operating condition

where; \( \Delta \omega \) is the frequency deviation and parameter "t" in ITAE is the simulation time. It is clear to understand that the controller with lower ITAE is better than the other controllers. To compute the optimum parameter values, a 6 cycle three phase fault is assumed in bus 8 and the performance index is minimized using PSO. In order to acquire better performance, number of particle, particle size, number of iteration, \( \Gamma_1 \), \( \Gamma_2 \) and \( \Gamma \) are chosen as 24, 5, 50, 2, 2 and 1, respectively. Also, the inertia weight, \( w \), is linearly decreasing from 0.9 to 0.4. The optimum values of parameters, resulting from minimizing the performance index is presented in Table 2. Also in order to show effectiveness of PSO method, the parameters of stabilizer controller are tuned using the other optimization method, GA. In GA case, the performance index is considered as PSO case and the optimal parameters of stabilizer controller are obtained as shown in Table 2.

RESULTS AND DISCUSSION

In this section, the designed PSO and GA based stabilizers are exerted to damping LFO in the under study
In order to study and analyze system performance under different scenarios, two scenarios are considered as disturbance:

**Scenario 1:** disconnection of the line between bus 8 and bus 9 by breaker

**Scenario 2:** 6 cycle three phase short circuit in bus 8

It should be noted that the PSO and GA based stabilizers have been designed for the nominal operating condition. In order to demonstrate the robustness performance of the proposed stabilizers, the ITAE is calculated under two scenarios at all operating conditions (Light, Nominal and Heavy) and results are listed at Table 3. Following disturbances, the PSO based stabilizer has better performance than the GA based stabilizer at all operating conditions and all scenarios.

Also the simulation results are presented in Fig. 3-4. Following cases have been considered and simulated: Each figure contains three parameters as follows: PSO based stabilizer (solid line), GA based stabilizer (dashed line) and system without stabilizer (dotted line). The simulation results show that applying the supplementary stabilizer signal greatly enhances the damping of the generator angle oscillations and therefore the system becomes more stable. The PSO stabilizer performs better than the GA stabilizer. With changing operating condition from the nominal to heavy, while the performance of GA supplementary stabilizer becomes poor, the PSO stabilizer has a stable and robust performance. It can be concluded that the PSO supplementary stabilizer have suitable parameter adaptation in comparison with the GA supplementary stabilizer when operating condition changes. Also in all figures, the system responses without any supplementary stabilizer have been shown. It is clear to seen that the system without stabilizer does not have enough damping and the responses go to fluctuate after disturbance. The both stabilizers (GA and PSO) greatly enhanced power system damping, but in view of comparison the PSO based stabilizer can inject more stabilizing signal than GA.
The results clearly show that in large electric power systems, UPFC can successfully increase damping of power system oscillations and the system with UPFC based stabilizer is more robust and stable after disturbances. In regular papers, short circuit is considered in order to study of system under disturbance but in this study, considering different types of disturbances (disconnection of line and short circuit) helps to comprehensive study of UPFC under real world disturbances.

CONCLUSION

In this study Genetic Algorithms and Particle Swarm Optimization have been successfully exerted to design a supplementary stabilizer based on UPFC. A multi machine electric power system installed with a UPFC with various load conditions and disturbances has been assumed to demonstrate the ability of UPFC in stability enhancement via LFO damping. Considering real world type disturbances such as disconnection of line and three phase short circuit guarantee the results in order to implementation of controller in industry. Simulation results demonstrated that the designed UPFC based stabilizers capable to guarantee the robust stability and robust performance under a different load conditions and disturbances. Also, simulation results show that the PSO technique has an excellent capability in comparison with GA method. Application to a multi machine electric power system which is near to practical systems can increase admission of the technique for real world applications.

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REFERENCES