Abstract

This paper presents the application of Unified Power Flow Controller (UPFC) to enhance damping of Low Frequency Oscillations (LFO) at a Single-Machine Infinite-Bus (SMIB) power system installed with UPFC. Since UPFC is considered to mitigate LFO, a supplementary UPFC like power system stabilizer is designed to reach the defined purpose. Simulated Annealing (SA) is used to tune UPFC supplementary stabilizer. To show effectiveness, the proposed method is compared with another optimization method named Genetic Algorithms (GA). Several linear time-domain simulation tests visibly show the validity of proposed method in damping of power system oscillations. Also simulation results emphasis on the better performance of SA in comparison with GA.

Keywords: Flexible AC Transmission Systems, Unified Power Flow Controller, Low Frequency Oscillations, Simulated Annealing, Genetic Algorithms

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 et al., 2010). 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 et al., 2009; Alasooly et al., 2010; Mehraeen et al., 2010; Jiang et al., 2010; Jiange et al., 2010). Also UPFC can be used for transient stability improvement by damping of Low Frequency Oscillations (LFO) in power system. Low Frequency Oscillations 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 (Zarghami et al., 2010; Guo et al., 2009; Tambe et al., 2003; Wang et al., 1999). They are designed for a specific operating condition using linear models. More advanced control schemes such as Particle-Swarm method, Fuzzy logic and genetic algorithms (Taher et al., 2008; Al-Awami et al., 2007; Eldamaty et al., 2005) offer better dynamic performances than fixed parameter controllers.

The objective of this paper is to investigate the ability of optimization methods such as Simulated Annealing (SA) and Genetic Algorithms (GA) for UPFC supplementary stabilizer controller design. A Sigel Machine Infinite Bus (SMIB) power system installed with a UPFC is considered as case study and a UPFC based stabilizer controller whose parameters are tuned using SA and GA is considered as power system stabilizer. Different load conditions are considered to show effectiveness of the proposed methods and also comparing the performance of these two methods. Simulation results show the validity of proposed methods in LFO damping.

System under study

Fig. 1 shows a SMIB power system installed with UPFC (Hingorani et al., 2010). The UPFC is installed in one of the two parallel transmission lines. This configuration (comprising two parallel transmission lines) permits to control of real and reactive power flow through a line. The static excitation system, model type IEEE-ST1A, has been considered. The UPFC is assumed to be based on Pulse Width Modulation (PWM) converters. The nominal system parameters are given in appendix.

Dynamic model of the system

Nonlinear dynamic model

A non-linear dynamic model of the system is derived by disregarding the resistances of all components of the system (generator, transformers, transmission lines and converters) and the transients of the transmission lines and transformers of the UPFC (Nabavi-Niaki et al., 1996; Wang et al., 2000). The nonlinear dynamic model of the system installed with UPFC is given as (1).


\[
\omega = \frac{(P_m - P_e - D\Delta\omega)}{M} \\
\delta = \omega_o - \omega_o \frac{(\omega - 1)}{\Delta\omega} \\
E'_{q} = \frac{(-E_q + E_{id})}{T_{do}} \\
E_{id} = \frac{-E_{td} + k_v (V_{sc} - V_i)}{T_i} \\
V_{dc} = \frac{3m}{4C_{dc}}(\sin(\delta_e)I_{td} + \cos(\delta_b)I_{iq}) + \frac{3m}{4C_{dc}}(\sin(\delta_p)I_{id} + \cos(\delta_b)I_{iq}) \\

\text{The equation for real power balance between the series and shunt converters is given as (2).} \\
\text{Re}(V_e I_{q} + V_i I_{q}^*) = 0 \\
\text{Linear dynamic model} \\
\text{A linear dynamic model is obtained by linearizing the} \\
\Delta\dot{\delta} = w_o \Delta w \\
\Delta\dot{\phi} = (-\Delta P_e - D\Delta\phi)/M \\
\Delta\dot{E}'_{q} = (-\Delta E_q + \Delta E_{id})/T_{do} \\
\Delta\dot{E}_{td} = -\frac{1}{T_a}\Delta E_{td} - \frac{K_A}{T_a}\Delta V \\
\Delta V_{dc} = k_x\Delta\delta + k_t\Delta E'_{q} + k_{dc}\Delta v_{dc} + k_{ce}\Delta m_e + k_{ce}\Delta\delta_e + k_{qb}\Delta m_b + k_{vb}\Delta\delta_b \\
\text{nonlinear dynamic model around nominal operating condition. The linear model of the system is given as (3). Where} \\
\Delta P_e = k_x\Delta\delta + k_{ed}\Delta E'_{q} + k_{pd}\Delta v_{dc} + k_{pe}\Delta m_e + k_{pe}\Delta\delta_e + k_{qg}\Delta m_b + k_{qg}\Delta\delta_b \\
\Delta E_q = k_x\Delta\delta + k_{ed}\Delta E'_{q} + k_{pd}\Delta v_{dc} + k_{pe}\Delta m_e + k_{pe}\Delta\delta_e + k_{qg}\Delta m_b + k_{qg}\Delta\delta_b \\
\Delta V_i = k_x\Delta\delta + k_{ed}\Delta E'_{q} + k_{pd}\Delta v_{dc} + k_{pe}\Delta m_e + k_{pe}\Delta\delta_e + k_{qg}\Delta m_b + k_{qg}\Delta\delta_b \\
\text{Fig. 2 shows the transfer function model of the system including UPFC. The model has numerous constants denoted by } k_x\text{. These constants are function of the system parameters and the initial operating condition. Also the control vector } U \text{ in Fig. 2 is defined as (4).} \\
U = [\Delta m_e \quad \Delta\delta_e \quad \Delta m_b \quad \Delta\delta_b]^T \\
\text{Where:} \\
\Delta m_e: \text{Deviation in pulse width modulation index } m_b \text{ of series inverter. By controlling } m_b, \text{ the magnitude of series- injected voltage can be controlled.} \\
\Delta\delta_e: \text{Deviation in phase angle of series injected voltage.} \\
\Delta m_b: \text{Deviation in pulse width modulation index } m_e \text{ of shunt inverter. By controlling } m_e, \text{ the output voltage of the shunt converter is controlled.} \\
\Delta\delta_b: \text{Deviation in 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. Dynamic model in state-space form 
\text{The dynamic model of the system in state-space form is as (5).} \\
\Delta\dot{\Delta} \text{ } \Delta\dot{\delta} = \begin{bmatrix} 0 & w_o & 0 & 0 \\
K_e & 0 & 0 & -K_e \\
K_i & 0 & 1 & 0 \\
K_{ic} & 0 & 0 & K_{ic} \\
\end{bmatrix} \Delta \text{ } \Delta \delta \\
\Delta V_{sc} = \begin{bmatrix} 0 & 0 & 0 & 0 \\
K_{ed} & K_{ed} & 0 & 0 \\
K_{pd} & K_{pd} & 1 & 0 \\
K_{pe} & K_{pe} & 0 & K_{pe} \\
\end{bmatrix} \Delta \text{ } \Delta \delta \\
\Delta \text{ } \Delta m_b = \begin{bmatrix} 0 & 0 & 0 & 0 \\
K_{ed} & K_{ed} & 0 & 0 \\
K_{pd} & K_{pd} & 1 & 0 \\
K_{pe} & K_{pe} & 0 & K_{pe} \\
\end{bmatrix} \Delta \text{ } \Delta \delta_b \\
U = \begin{bmatrix} 0 & 0 & 0 & 0 \\
K_{ed} & K_{ed} & 0 & 0 \\
K_{pd} & K_{pd} & 1 & 0 \\
K_{pe} & K_{pe} & 0 & K_{pe} \\
\end{bmatrix} \Delta \text{ } \Delta \delta \\
\text{UPFC controllers} \\
\text{In this research two control strategies are considered for UPFC:} \\
i. DC-voltage regulator 
ii. Power system oscillation-damping controller 
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. In this paper a PI type controller is considered to control of DC voltage. The parameters of this PI type DC-voltage regulator are considered as } K_c = 39.5 \text{ and } K_p = 6.54. 
Power system stabilizer 
A stabilizer controller is provided to improve damping of power system oscillations. This controller may be considered as a lead-lag compensator. However an electrical torque in phase with the speed deviation should be produced to improve damping of power system oscillations. The transfer function model of the stabilizer controller is shown in Fig. 3 (Yu et al., 1983). 
\text{Eigen value analysis} 
For the nominal operating condition the eigenvalues of the system are obtained using state-space model of the system presented in (5) and these eigenvalues are shown in Table 1. It is clearly seen that the system is unstable and needs to power system stabilizer (damping controller) for stability. 
Stabilizer controllers design themselves have been a topic of interest for decades, especially in form of Power System Stabilizers (PSS). But PSS cannot control power transmission and also cannot support power transmission and also cannot control power transmission and also cannot support power
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*Stabilizer design based UPFC*  
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system stability under large disturbances like 3-phase fault at terminals of generator. For these problems, in this paper a stabilizer controller based UPFC is provided to mitigate power system oscillations. Two optimization methods such as SA and GA are considered for tuning stabilizer controller parameters. In the next section an introduction about SA is presented.

Simulated annealing

In the early 1980s the method of simulated annealing (SA) was introduced in 1983 based on ideas formulated in the early 1950s. This method simulates the annealing process in which a substance is heated above its melting temperature and then gradually cooled to produce the crystalline lattice, which minimizes its energy probability distribution. This crystalline lattice, composed of millions of atoms perfectly aligned, is a beautiful example of nature finding an optimal structure. However, quickly cooling or quenching the liquid retards the crystal formation, and the substance becomes an amorphous mass with a higher than optimum energy state. The key to crystal formation is carefully controlling the rate of change of temperature.

The algorithm analog to this process begins with a random guess of the cost function variable values. Heating means randomly modifying the variable values. Higher heat implies greater random fluctuations. The cost function returns the output, f, associated with a set of variables. If the output decreases, the new variable set replaces the old variable set. If the output increases, then the output is accepted provided that:

\[ r \leq e^{-\left( f(P_{\text{old}}) - f(P_{\text{new}}) \right)/T} \]  

(6)

Where, \( r \) is a uniform random number and \( T \) is a variable analogous to temperature. Otherwise, the new variable set is rejected. Thus, even if a variable set leads to a worse cost, it can be accepted with a certain probability. The new variable set is found by taking a random step from the old variable set as (7).

\[ P_{\text{new}} = dP_{\text{old}} \]  

(7)

The variable \( d \) is either uniformly or normally distributed about \( P_{\text{old}} \). This control variable sets the step size so that, at the beginning of the process, the algorithm is forced to make large changes in variable values. At times the changes move the algorithm away from the optimum, which forces the algorithm to explore new regions of variable space. After a certain number of iterations, the new variable sets no longer lead to lower costs. At this point the value of \( T \) and \( d \) decrease by a certain percent and the algorithm repeats. The algorithm stops when \( T = 0 \). The decrease in \( T \) is known as the cooling schedule. Many different cooling schedules are possible. If the initial temperature is \( T_0 \) and the ending temperature is \( T_n \), then the temperature at step \( n \) is given by (8).

\[ T_n = T_0 - n(T_0 - T_n)/N \]  

(8)

Where, \( f \) decreases with time. Some potential cooling schedules are as follows:

- Linearly decreasing: \( T_n = T_0 - n(T_0 - T_n)/N \)
- Geometrically decreasing: \( T_n = 0.99 T_{n-1} \)
- Hayjek optimal: \( T_n = c/\log(1+n) \), where \( c \) is the smallest variation required to get out of any local minimum.

Many other variations are possible. The temperature is usually lowered slowly so that the algorithm has a chance to find the correct valley before trying to get to the lowest point in the valley. This algorithm has been applied successfully to a wide variety of problems (Randy and Sue, 2004).

Stabilizer design using SA

In this section the parameters of the proposed stabilized controller are tuned using SA. Four control parameters of the UPFC \( (m_e, \delta_e, m_b \) and \( \delta_b) \) can be modulated in order to produce the damping torque. The parameter \( m_e \) is modulated to output of damping controller and speed deviation \( \Delta \omega \) is also considered as input of damping controller. The structure of supplementary stabilizer controller has been shown in Fig. 3. The parameters in Fig. 3 are as follow:

- \( K_{DC} \): the stabilizer gain
- \( T_w \): the parameter of washout block
- \( T_1 \) and \( T_2 \): the parameters of compensation block

The optimum values of \( K_{DC}, T_1 \) and \( T_2 \) which minimize an array of different performance indexes are accurately computed using SA and \( T_w \) is considered equal to 10. In optimization methods, the first step is to define a performance index for optimal search. In this study the performance index is considered as (9). In fact, the performance index is the Integral of the Time multiplied Absolute value of the Error (ITAE).

\[ ITAE = \int_0^t |\Delta \omega| dt + \int_0^t |\Delta V_{DC}| dt \]  

(9)

Where, \( \Delta \omega \) is the frequency deviation, \( \Delta V_{DC} \) is the deviation of DC voltage and parameter \( \beta^t \) in ITAE is the simulation time and a 100 seconds time period is considered. It is clear to understand that the controller with lower ITAE is better than the other controllers. To compute the optimum parameter values, a 0.1 step change in mechanical torque \( (\Delta T_m) \) is assumed and the performance index is minimized using SA. The optimum values of \( K_{DC}, T_1 \) and \( T_2 \), resulting from minimizing the performance index is presented in Table 2. Also in order to show effectiveness of SA method, the parameters of stabilizer controller are tuned using the other optimization method, GA. In continuous GA case, the performance index is considered as SA case and the optimal parameters of stabilizer controller are obtained as shown in Table 3.

The search limits are as follows:

- 1 \( K_{DC} < 1000 \), 0.01 \( T < 1 \).

Simulation results

In this section the designed SA and GA based stabilizer controllers are applied to damping LFO in the under study system. In

| Table 2. Optimum values of stabilizer controller parameters using SA |
|------------------------|------------------------|
| \( K_{DC} \)   | 561.443               |
| \( T_1 \)    | 42.933                |
| \( T_2 \)    | 0.0219                |

| Table 3. Optimum values of stabilizer controller parameters using GA |
|------------------------|------------------------|
| \( K_{DC} \)   | 622.78                 |
| \( T_1 \)    | 0.2819                 |
| \( T_2 \)    | 0.01                   |
order to study and analysis system performance under system uncertainties (controller robustness), two operating conditions are considered as follow:
Case 1: Nominal operating condition
Case 2: Heavy operating condition
The parameters for two cases are presented in appendix. SA and GA stabilizer controllers have been designed for the nominal operating condition. In order to demonstrate the robustness performance of the proposed method, The ITAE is calculated following 10% step change in the reference torque ($\Delta T_m$) at all operating conditions (Nominal and Heavy) and results are shown at Tables 4. Following step change, the SA based stabilizer has better performance than the GA based stabilizer at all operating conditions.

<table>
<thead>
<tr>
<th>Case</th>
<th>Nominal operating condition</th>
<th>Heavy operating condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>SA stabilizer</td>
<td>0.0019</td>
<td>0.0033</td>
</tr>
<tr>
<td>GA stabilizer</td>
<td>0.0021</td>
<td>0.0045</td>
</tr>
</tbody>
</table>

Table 4. 10% Step increase in the reference torque ($\Delta T_m$)

Also for case 1 the simulation results are shown in Figs. 4 and 5. The simulation results show that applying the supplementary control signal greatly enhances the damping of the generator angle oscillations and therefore the system becomes more stable. The SA stabilizer performs better than the GA controller. For case 2, the simulation results are shown in Figs. 6 and 7. Under this condition, while the performance of GA supplementary controller becomes poor, the SA controller has a stable and robust performance. It can be concluded that the SA supplementary controller have suitable parameter adaptation in comparing with the GA supplementary controller when operating condition changes.

### References