Damping of Power System Oscillations using Unified Power Flow Controller (UPFC)

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Abstract--This paper presents a systematic approach for designing Unified Power Flow Controller (UPFC) based damping controllers for damping low frequency oscillations in a power system. Detailed investigations have been carried out considering four alternative UPFC based damping controllers. The investigations reveal that the damping controllers based on UPFC control parameters $\delta_E$ and $\delta_B$ provide robust performance to variations in system loading and equivalent reactance $X_e$.

Keywords-- Power system Stability, Damping of power system oscillations, UPFC, FACTS controllers.

I. INTRODUCTION

The power transfer in an integrated power system is constrained by transient stability, voltage stability and small signal stability. These constraints limit a full utilization of available transmission corridors. Flexible AC Transmission System (FACTS) is the technology that provides the needed corrections of the transmission functionality in order to fully utilize the existing transmission facilities and hence, minimizing the gap between the stability limit and thermal limit.

Unified Power Flow Controller (UPFC) is one of the FACTS devices, which can control power system parameters such as terminal voltage, line impedance and phase angle. It can also be used for damping power system oscillations. Recently researchers have presented dynamic models of UPFC in order to design power flow, voltage and damping controllers [4-10]. Wang [8-10], has presented a modified linearised Heffron-Phillips model of a power system installed with UPFC. He has addressed the basic issues pertaining to the design of UPFC damping controller, i.e., selection of robust operating condition for designing damping controller; and the choice of parameters of UPFC (such as $m_B$, $m_E$, $\delta_B$ and $\delta_E$) to be modulated for achieving desired damping. No effort seems to have been made to identify the most suitable UPFC control parameter, to be modulated for achieving robust dynamic performance of the system following wide variations in loading condition.

In view of the above, the main objectives of the research work presented in the paper are,

1. To present a systematic approach for designing UPFC based damping controllers.
2. To examine the relative effectiveness of modulating alternative UPFC control parameters (i.e. $m_B$, $m_E$, $\delta_B$ and $\delta_E$), for damping power system oscillations.
3. To investigate the performance of the alternative damping controllers, considering wide variations in loading conditions and system parameters in order to arrive at most effective damping controller.

II. SYSTEM INVESTIGATED

A single-machine-infinite-bus (SMIB) system installed with UPFC is considered (Fig. 1). A static excitation system model type IEEE-ST1A has been considered. The UPFC considered here is assumed to be based on pulse width modulation (PWM) converters. The nominal loading condition and system parameters are given in Appendix-1.

![Fig. 1. UPFC installed in a SMIB system.](image)

III. UNIFIED POWER FLOW CONTROLLER

Unified power flow controller (UPFC) is a combination of static synchronous compensator (STATCOM) and a static synchronous series compensator (SSSC) which are coupled via a common dc link, to allow bi-directional flow of real power between the series output terminals of the SSSC and the shunt output terminals of the STATCOM and are controlled to provide concurrent real and reactive series line compensation without an external electric energy source. The UPFC, by means of angularly unconstrained series voltage injection, is able to control, concurrently or selectively, the transmission line voltage, impedance and angle or alternatively, the real and reactive power flow in the line. The UPFC may also provide independently controllable shunt reactive compensation. Viewing the operation of UPFC from the standpoint of conventional power transmission based on reactive shunt compensation, series compensation and phase shifting, the UPFC can fulfill all these functions and thereby meet multiple control objectives.
IV. MODIFIED HEFFRON-PHILLIPS SMALL PERTURBATION TRANSFER FUNCTION MODEL OF A SMIB SYSTEM INCLUDING UPFC

Fig. 2 shows the small perturbation transfer Function block diagram of a machine-infinite bus system including UPFC relating the pertinent variables of electric torque, speed, angle, terminal voltage, field voltage, flux linkages, UPFC control parameters, and dc link voltage. This model has been developed by Wang [8], by modifying the basic Heffron-Phillips model including UPFC. This linear model has been developed by linearising the nonlinear model around a nominal operating point. The constants of the model depend on the system parameters and the operating condition.

In the above transfer function model \([\Delta u]\) is the column vector while \([Kpu]\), \([Kqu]\), \([Kvu]\) and \([Kcu]\) are the row vectors as defined below,

\[
[\Delta u] = [\Delta m_E, \Delta \delta_E, \Delta m_B, \Delta \delta_B]^T, \quad [Kpu] = [Kp e, Kp \delta_e, Kp \delta_b, Kp], \quad [Kqu] = [Kq e, Kq \delta_e, Kq \delta_b, Kq], \quad [Kvu] = [Kv e, Kv \delta_e, Kv \delta_b, Kv], \quad [Kcu] = [Kc e, Kc \delta_e, Kc \delta_b, Kc]
\]

The control parameters of the UPFC are:
1. \(m_B\) – pulse width modulation index of series inverter. By controlling \(m_B\), the magnitude of series injected voltage can be controlled.
2. \(\delta_B\) – Phase angle of series inverter which when controlled results in the real power exchange.
3. \(m_E\) – pulse width modulation index of shunt inverter. By controlling \(m_E\), the voltage at a bus where UPFC is installed, is controlled through reactive power compensation.
4. \(\delta_E\) – Phase angle of the shunt inverter, which regulates the dc voltage at dc link.

V. ANALYSIS

1) Computation of Constants of the Model

The initial d-q axes voltage and current components and torque angle for the nominal operating condition needed for computing constants of the model are calculated and are given below:

\[
\begin{align*}
Q &= 0.1670 \text{ pu} & E_{bdo} &= 0.7331 \text{ pu} \\
\varepsilon_{do} &= 0.3999 \text{ pu} & E_{bqo} &= 0.6801 \text{ pu} \\
\varepsilon_{qo} &= 0.9166 \text{ pu} & i_{bdo} &= 0.4729 \text{ pu} \\
\delta_o &= 47.13^\circ & i_{qo} &= 0.6665 \text{ pu}
\end{align*}
\]
2). Design of Damping Controllers

For this operating condition, the eigen-values of the system are obtained (Table 1) and it is clearly seen that the system is unstable.

The damping controllers are designed to produce an electrical torque in phase with speed deviation. The four control parameters of the UPFC (i.e. \( m_B, m_E, \delta_B \) and \( \delta_E \)) can be modulated in order to produce the damping torque. The speed deviation \( \Delta \omega \) is considered as the input to the damping controllers. The four alternative UPFC based damping controllers are examined in the present work.

Damping controller based on UPFC control parameter \( m_B \) shall henceforth be denoted as Damping controller \((m_B)\). Similarly damping controllers based on \( m_E \), \( \delta_B \) and \( \delta_E \) shall henceforth be denoted as Damping controller \((m_E)\), Damping controller \((\delta_B)\), and Damping controller \((\delta_E)\) respectively.

\[ G_c(s) = \frac{1 + s T_1}{1 + s T_2} \]

\[ \Delta \omega \]

\[ \text{Gain} \]

\[ \text{Signal Washout} \]

\[ \text{Phase compensation} \]

\[ s T_w \]

\[ 1 + s T_w \]

\[ 1 + s T_e \]

\[ 1 + s T_e \]

Fig. 3. Structure of UPFC based damping controller.

The structure of UPFC based damping controller is shown in Fig. 3. It consists of gain, signal washout and phase compensator blocks. The signal washout is the high pass filter that prevents steady changes in the speed from modifying the UPFC input parameter. The value of the washout time constant \( T_w \) should be high enough to allow signals associated with oscillations in rotor speed to pass unchanged. From the viewpoint of the washout function, the value of \( T_w \) is not critical and may be in the range of 1 to 20 seconds. \( T_w \) equal to 10 seconds is chosen in the present studies. The parameters of the damping controllers are obtained using the phase compensation technique [11].

The transfer function of the system relating the electrical component of torque \((\Delta T_e)\) and UPFC control parameter is denoted as GEPA. The time constants of the phase compensator are chosen so that the phase lag/lead of the system is fully compensated. For the nominal operating condition, the natural frequency of oscillation \( \omega_n = 4.0974 \) rad./sec. The transfer function relating \( \Delta T_e \) and \( \Delta m_B \) is denoted as GEPA. For the nominal operating condition, phase angle of GEPA i.e. \( \angle \text{GEPA} = 12.03^\circ \) lagging. The magnitude of GEPA i.e. \( |\text{GEPA}| = 0.1348 \). To compensate the phase lag, the time constants of the lead compensator are computed [11] and are obtained as \( T_1 = 0.3016 \) sec. and \( T_2 = 0.1975 \) sec.

Following the same procedure, the phase angle to be compensated by the other three damping controllers are computed and are given in Table 2. The critical examination of Table 2 reveals that the phase angle of the system i.e. \( \angle \text{GEPA} \), is negative for control parameter \( m_B \) and \( m_E \). However, it is positive for \( \delta_B \) and \( \delta_E \). Hence the phase compensator for the Damping controller \((m_B)\) and Damping controller \((m_E)\) is a lead compensator while for Damping controller \((\delta_B)\) and Damping controller \((\delta_E)\) is a lag compensator. The gain settings \((K_{dc})\) of the controllers are computed assuming a damping ratio \( \xi = 0.5 \).

| GEPA | \( |\text{GEPA}| \) | \( \angle \text{GEPA} \) (degrees) |
|-------|-----------------|------------------|
| \( \Delta T_e / \Delta m_B \) | 0.3168 | -18.4017 |
| \( \Delta T_e / \Delta \delta_E \) | 1.8919 | 0.6357 |
| \( \Delta T_e / \Delta m_E \) | 0.1348 | -12.0273 |
| \( \Delta T_e / \Delta \delta_B \) | 0.0958 | 8.8143 |

Table 3 shows the parameters (Gain and Time constants) of the four alternative damping controllers. Table 3 clearly shows that the gain setting of the Damping controller \((m_B)\) and Damping controller \((m_E)\) are much higher as compared to gain setting of Damping controller \((\delta_B)\) and Damping controller \((\delta_E)\).

Table 1. Eigen-values of the closed loop system.

<table>
<thead>
<tr>
<th>Eigen-values</th>
<th>( \omega_n ) of the oscillatory mode</th>
<th>( \zeta ) of the oscillatory modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>- 19.1186</td>
<td>0.171 ± 4.06i</td>
<td>4.06 rad/sec</td>
</tr>
<tr>
<td>System without any damping controller</td>
<td>- 0.765 ± 0.407i</td>
<td>0.866 rad / sec</td>
</tr>
</tbody>
</table>
Table 3. Parameters of the UPFC based Damping controllers.

<table>
<thead>
<tr>
<th>Damping Controller (mE)</th>
<th>K_{dc}</th>
<th>T_1 (seconds)</th>
<th>T_2 (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damping Controller (δE)</td>
<td>74.6089</td>
<td>0.3384</td>
<td>0.1760</td>
</tr>
<tr>
<td>Damping Controller (δB)</td>
<td>17.5203</td>
<td>0.2214</td>
<td>0.2468</td>
</tr>
<tr>
<td>Damping Controller (mB)</td>
<td>196.7449</td>
<td>0.3016</td>
<td>0.1975</td>
</tr>
<tr>
<td>Damping Controller (δB)</td>
<td>399.3160</td>
<td>0.2091</td>
<td>0.2848</td>
</tr>
</tbody>
</table>

Table 4. Eigenvalues of the system with UPFC Damping controllers.

<table>
<thead>
<tr>
<th>Eigenvalues</th>
<th>Damping ratio</th>
<th>Natural frequency of oscillation (ω_n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.61 ± 3.46i</td>
<td>0.421</td>
<td>3.82</td>
</tr>
<tr>
<td>-1.92 ± 3.23i</td>
<td>0.511</td>
<td>3.76</td>
</tr>
<tr>
<td>-1.60 ± 3.37i</td>
<td>0.429</td>
<td>3.74</td>
</tr>
<tr>
<td>-2.27 ± 3.68i</td>
<td>0.524</td>
<td>4.33</td>
</tr>
</tbody>
</table>

Table 4 shows eigenvalues of the system at nominal operating condition with the above alternative damping controllers. Table 4 clearly shows that damping ratios obtained with Damping controllers (δE) and (δB) are higher than those obtained with Damping controllers (mE) and (mB).

3). Dynamic Performance of the system with Damping Controllers

Fig. 4 shows the dynamic responses for Δω obtained considering a step load perturbation ΔT_m = 0.01 p.u. with the four alternative damping controllers (Table 3).

Fig. 4 clearly shows that the dynamic responses of the system obtained with the four alternative damping controllers are virtually identical. At this stage it can be inferred that any of the UPFC based damping controllers provide satisfactory dynamic performance at the nominal operating condition.

Further investigations are carried out to assess the robustness of these four alternative damping controllers to wide variation in loading conditions and line reactance X_e.

4). Effect of Variation of loading condition and system parameters on the dynamic performance of the system

In any power system, the operating load varies over a wide range. It is extremely important to investigate the effect of variation of the loading condition on the dynamic performance of the system.

In order to examine the robustness of the damping controllers to wide variation in the loading condition, loading of the system is varied over a wide range (Pe = 0.2 to Pe = 1.2 p.u.) and the dynamic responses are obtained for each of the loading condition considering parameters of the damping controllers computed at nominal operating condition for the step load perturbation in mechanical torque (i.e. ΔT_m = 0.01 p.u.)

Figs. 5 and 6 show the dynamic responses of Δω with nominal optimum Damping controller (mB) and Damping controller (mE) at different loading conditions. It is clearly seen that the dynamic performance of the system is degraded significantly as the system loading is reduced from the nominal loading. Further it is seen that system becomes unstable.
Examining Figs. 10 and 11, it can be inferred that Damping controller (δ_B) and Damping controller (δ_E) are quite robust to variations in Xe also. It may thus be concluded that Damping controller (δ_B) and Damping controller (δ_E) are quite robust to wide variation in loading condition and system parameters. The reason for the superior performance of Damping controller (δ_B) and Damping controller (δ_E) may be attributed to the fact that modulation of δ_B and δ_E results in exchange of real power.

VI. CONCLUSIONS

The significant contributions of the research work presented in this paper are as follows:

1. A systematic approach for designing UPFC based controllers for damping power system oscillations has been presented.

2. The performance of the four alternative damping controllers, (i.e. Damping controller (m_H), Damping controller (m_B), and Damping controller (δ_H)) has been examined considering wide variation in the loading conditions and line reactance Xe.
3. Investigations reveal that the Damping controller ($\delta_E$) and Damping controller ($\delta_B$) provide robust performance to wide variation in loading conditions and line reactance $X_e$. It may thus be recommended that the damping controllers based on UPFC control parameters $\delta_E$ and $\delta_B$ may be preferred over the damping controllers based on control parameters $m_B$ or $m_E$.

APPENDIX 1

The nominal parameters and the operating condition of the system are given below.

Generator : $M = 2H = 8.0\text{MJ} / \text{MVA}$  
D = 0.0  Td0' = 5.044 sec.  
$X_q = 1.0 \text{p.u.}$  $X_q = 0.6 \text{p.u.}$  
$X'_{d} = 0.3 \text{p.u.}$

Excitation system : $K_a = 10.0$  $T_a = 0.01 \text{sec.}$  
$X_{di} = 0.1 \text{p.u.}$

Transformer : $X_{tE} = 0.1 \text{p.u.}$  $X_E = X_B = 0.1 \text{p.u.}$

Transmission line : $X_{Bv} = 0.3 \text{p.u.}$  $X_e = 0.5 \text{p.u.}$  
$V_b = 1.0 \text{p.u.}$  $f = 60 \text{Hz}$

Operating condition : $P_e = 0.8 \text{p.u.}$  $V_t = 1.0 \text{p.u.}$

UPFC Parameters : $m_E = 0.4013$  $m_B = 0.0789$  
$\delta_E = -85.3478^\circ$  $\delta_B = -78.2174^\circ$

DC Link Parameters : $V_{dc} = 2 \text{p.u.}$  $C_{dc} = 1 \text{p.u.}$

REFERENCES