Damping of power system oscillations with unified power flow controller (UPFC)

N. Tambey and M.L. Kothari

Abstract: A comprehensive approach to the design of UPFC controllers (power-flow controller, DC-voltage regulator and damping controller) is presented. Studies reveal that damping is adversely affected by the incorporation of a DC-voltage regulator. Investigations were carried out to understand the relative effectiveness of modulation of the UPFC control signals $m_a$, $m_b$, $m_e$ and $\omega_s$ on damping of the system oscillations, using a controllability index. A dual damping controller based on simultaneous modulation of UPFC control signals $m_a$, $m_b$ and $m_e$ is proposed. Investigations reveal that alternative damping controllers (damping controller $m_a$, damping controller $m_b$ and dual damping controller) provide robust dynamic performance under wide variations in loading condition and system parameters.

List of symbols

$H$  inertia constant ($M = 2 H$)
$\omega_n$  natural frequency of oscillation, rad s$^{-1}$
$X_e$  equivalent reactance of the system
$X_T$  reactance of transmission line 1
$X_B$  reactance of transmission line 2
$X_E$  reactance of excitation transformer (ET)
$X_B$  reactance of boosting transformer (BT)
$X_{qi}$  direct axis steady-state synchronous reactance of the generator
$X_{qj}$  quadrature axis steady-state synchronous reactance of the generator
$T_a$  direct axis open-circuit time-constant of the generator
$P_e$  electrical power of the generator
$P_{m}$  mechanical power input to the generator
$P_{Z_{ref}}$  modified reference power on transmission line 2
$V_e$  generator terminal voltage
$V_\infty$  infinite bus voltage
$V_{up}$  voltage at UPFC bus
$V_{sh}$  initial voltage of series-injected voltage
$V_{sh}$  initial value of shunt-injected voltage
$I_f$  current through transmission line 1
$I_g$  current through transmission line 2
$I_{sh}$  current through shunt converter
$V_d$  voltage at DC link
$Q_D$  DC link capacitor
$m_e$  modulation index of shunt converter
$m_a$  modulation index of series converter
$K_{DC}$  gain of damping controller
$T_1, T_2$  time constants of phase compensator

$J_g$  phase angle of shunt-converter voltage
$T_h$  phase angle of series-converter voltage

1 Introduction

The power transfer in an integrated power system is constrained by transient stability, voltage stability and small-signal stability. These constraints limit the full utilisation of the available transmission corridors. The flexible AC transmission system (FACTS) is the technology that provides the corrections to the transmission functionality required in order to fully utilise the existing transmission facilities, hence minimising the gap between the stability and thermal-loading limits.

The unified power flow controller (UPFC) is a FACTS device which can control power-system parameters such as terminal voltage, line impedance and phase angle [1-3]. The primary function of the UPFC is to control power flow on a given line and voltage at the UPFC bus. This is achieved by regulating the controllable parameters of the system: line impedance, phase angle and voltage magnitude. The UPFC can also be utilised for damping power-system oscillations by judiciously applying a damping controller. Unlike the PSS at a generator location, the speed deviations of the machines of interest are not readily available to a FACTS controller located on a transmission path. For a UPFC-based damping controller, we wish to extract an input signal to the damping controller from the locally measurable quantities at the UPFC location. The electrical power flow can be easily measured at the UPFC location and hence may be used as an input signal to the damping controller.

Recently, steady-state and dynamic models of UPFC have been developed by several researchers [8,9,10]. Wang [9-11] has developed modified linearised Heffron-Phillips models for an SMIB system and a multi-machine system with UPFC installed. He has proposed criteria for the selection of operating condition and control signal in order to design a robust UPFC-based damping controller. For a multi-machine system, he has proposed a controllability-index approach to selecting the control signal. He has also considered proportional-type power-flow controllers, AC-voltage and DC-voltage regulators and also damping...
controllers. However, he has not presented a comprehensive approach to obtaining optimum parameters for the power-flow controller and DC-Voltage regulator. Padiyar and Kulkami [12] have proposed a UPFC control strategy based on local measurements, in which real power flow through the line is controlled by reactive voltage injection and reactive power flow is controlled by regulating the magnitude of voltages at the two UPFC ports. They have also included an auxiliary controller for improving the transient stability of the system. However, they have not presented an approach for obtaining the optimum parameters of the power-flow and auxiliary controllers. In view of the above, the main objectives of the research work presented here are as follows. Firstly, to present a comprehensive approach to designing power-flow and DC-voltage UPFC regulators. Secondly, to design and study the performance of the UPFC-based damping controllers taking into account alternative UPFC: control parameters. Lastly, to investigate the performance of alternative damping controllers under wide variations in loading condition and in system parameters.

2 System investigated

We consider a single machine infinite bus (SMIB) system with UPFC installed [13]. The UPFC is installed in one of the two parallel transmission lines (Fig. 1). This configuration, comprising two parallel transmission lines, permits the control of real and reactive power flow through a line. The static excitation system, model type IEEE-STIA, has been considered. The UPFC is assumed to be based on pulse width modulation (PWM) converters. The conventional PSS is considered. The nominal loading condition and system parameters are even in Appendix I.

3 Unified power flow controller

The unified power flow controller (UPFC) was devised for the real-time control and dynamic compensation of AC transmission systems, providing the multifunctional flexibility required to solve many of the problems facing the power-supply industry. The UPFC is a combination of a static synchronous compensator (STATCOM) and a static synchronous series compensator (SSSC) coupled via a common DC voltage link. It is capable of controlling simultaneously or selectively, all the parameters affecting the power flow in a transmission line (voltage, impedance and phase angle). Alternatively, it can control both the real and the reactive power flow in the line independently. The UPFC may also provide an independent, controllable, shunt reactive compensation.

4 Dynamic model of the system with UPFC

4.7 Non-linear dynamic model

A non-linear dynamic model of the system is derived by disregarding the resistances of all the components of the system (generator, transformer, transmission lines, shunt and series converter transformers) and the transients of the transmission lines and transformers of the UPFC. The non-linear dynamic model of the system using UPFC is given below:

$$\frac{d}{dt} \begin{pmatrix} \Delta P_n \\ \Delta Q_n \end{pmatrix} = \begin{pmatrix} \frac{1}{M} \frac{\partial M}{\partial \Delta P_n} \\ \frac{1}{M} \frac{\partial M}{\partial \Delta Q_n} \end{pmatrix}$$

$$\frac{d}{dt} \begin{pmatrix} \Delta V_n \\ \Delta I_n \end{pmatrix} = \begin{pmatrix} \frac{1}{L_n} \frac{\partial L_n}{\partial \Delta V_n} \\ \frac{1}{L_n} \frac{\partial L_n}{\partial \Delta I_n} \end{pmatrix}$$

$$\frac{d}{dt} \begin{pmatrix} \Delta \theta_n \end{pmatrix} = \begin{pmatrix} \frac{1}{C_n} \frac{\partial C_n}{\partial \Delta \theta_n} \end{pmatrix}$$

where$$V_{n+1} = V_{n} + \int \left( \Delta \Delta P_n \right) dt$$

$$V_{n+1} = V_{n} + \int \left( \Delta \Delta Q_n \right) dt$$

$$\Delta \theta_n = \Delta \theta_n + \int \left( \Delta \Delta \theta_n \right) dt$$

Fig. 1 A Single machine infinite bus (SMIB) power system installed with an UPFC in one of the lines

width modulation (PWM) converters. The conventional PSS is considered. The nominal loading condition and system parameters are even in Appendix I.
The equation for the real power balance between the series and shunt converters is given as

\[ Re(V_r - I_s) = 0 \]  \hspace{1cm} (6)

4.2 Linear dynamic model (modified Heffron-Phillips model of an SMIB system including UPFC)

A linear dynamic model is obtained by linearising the non-linear model around an operating condition. The linearised model is given below:

\[ A \dot{W} = -(AP, - AP, - D) \]

\[ AS = a > Aa > \]

where

\[ (-AE_q) \]

\[ A_{tfd} = \]

\[ AE_q = K_d AS + K_p AE_p, \]

\[ + K_d A \dot{e} + K_d Am_s A V_s = K_d A_6 + \]

\[ Khq Aq E + K_d Am_s e, \]

and

\[ + \]

Fig. 2 shows the modified Heffron-Phillips transfer-function model of the system including UPFC. The modified Heffron-Phillips model has 28 constants as opposed to 6 constants in the Heffron-Phillips model. These constants are functions of the system parameters and the initial operating condition. The equations for computing the constants of the model are given in Appendix 2. The control vector \( u \) is defined as follows:

\[ u = \begin{bmatrix} Am_B^d \end{bmatrix} \]

\[ \text{deviation in pulse width modulation index of series inverter. By controlling } m_b, \text{ the magnitude of series-injected voltage can be controlled. deviation in } Ad_\theta \text{ phase angle of the injected voltage deviation in pulse-width-modulation index of shunt inverter. By controlling } i_{sab}, \text{ the output voltage of the shunt converter is controlled, deviation in phase angle of } Ad, \text{ the shunt-inverter voltage. The series and shunt converters are controlled in a coordinated manner to ensure that the real power output of the shunt converter is equal to the real power input to the series converter. The fact that the DC voltage remains constant ensures that this equality is maintained.} \]

It may be noted that \( IC_{pu}, K_q, K_p \), and \( K_s \) in Fig. 2 are the row vectors defined below:

\[ \begin{bmatrix} K_{pu} \end{bmatrix} \]

\[ \begin{bmatrix} K_{po} \end{bmatrix} \]

\[ \begin{bmatrix} K_{p,1} \end{bmatrix} \]

where \( u = [Am_B A_5 E Am_B A_6 E]^T \) is a column vector.

4.3 Dynamic model in state-space form

The dynamic model of the system in state-space form is obtained from the transfer-function model as

\[ X = AX + Bu \]  \hspace{1cm} (13)
Fig. 2  Modified Heffron-Phillips model of SMIB System with UPFC
where
\[ X = \begin{bmatrix} A_5 & A_w & A_E'q \\ \end{bmatrix}, \quad \begin{bmatrix} A_E \\ \end{bmatrix} u = \begin{bmatrix} Am_1 \\ AS_2 \\ Am_2 \\ \end{bmatrix} \]

\[ A = \begin{bmatrix} 0 & 0 \\ -^t & 0 \\ K_A & 0 \\ 0 & 1 & K_{pd} \end{bmatrix} \]

\[ n = \begin{bmatrix} K_{qh} & I_{d} & J_{sh} \\ T_A & T_1 & T_a \end{bmatrix} \]

\[ \begin{bmatrix} 0 & 0 & 0 \\ \end{bmatrix} \]

UPFC controllers

Fig. 3 shows a schematic diagram of a UPFC control system. The UPFC control system comprises two controllers:

(i) power-flow controller
(ii) power-system oscillation-damping controller

5.1 Power-flow controller

The UPFC is installed in one of the two lines of the SMIB system. Fig. 4 shows the transfer function of the 12-1 type power-flow controller. The power-flow controller regulates the power flow on this line. \( k_{pd} \) and \( k_{qh} \) are the proportional and integral gain settings of the power-flow controller.

The real power output of the shunt Converter must be equal to the real power input 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 repulsed by modulating the phase angle of the shunt-converter voltage. Thus, the DC-voltage regulator forms part of the power-flow controller. A P-I type DC-voltage regulator is considered (Fig. 5). \( k_{pd} \) and \( k_{qh} \), are the proportional and integral gain settings of the DC regulator.

5.2 Power-system oscillation damping controller

A damping controller is provided to improve the damping of power system-oscillations. The damping controller may be considered as comprising two cascade-connected blocks. Block I is provided to derive a speed-deviation signal from the electrical power, \( P_e \). The total electrical power is measured at the UPFC location. It is then compared with the set point (mechanical power). The error is integrated and multiplied by \( jM \) to derive a speed-deviation signal. It may be noted that the speed-deviation signal derived is used instead of the speed-deviation signal which has been measured, since the speed-deviation signal, in general, may not be available at the UPFC location. The second block comprises a lead-lag compensator. An electrical torque in phase with the speed deviation is to be produced in order to improve the damping of the system oscillations. The parameters of the lead-lag compensator are chosen so as to compensate for the phase shift between the control signal and the resulting electrical power deviation. In this way an additional electrical power output is obtained in phase with the speed deviation. The gain setting of the damping controller is chosen so as to achieve the desired damping ratio of the electromechanical mode. The output of the damping controller modulates the reference setting of the power-flow controller (Fig. 3).
Fig. 3 Schematic Diagram of an UPFC control system
6 Analysis

6.1 Computation of constants of the transfer function model (Fig. 2)
The initial d-q axes voltage and current components and torque angle are computed for the nominal operating condition \( P = 0.912 \text{p.u.}, Q = 0.277 \text{p.u.}, V_i = 1.032 \text{p.u.}, V_h = 0.6736 \text{p.u.} \) These data are needed for computing the constants of the system model and are even below:

- **E \( \text{dc} \) = 0.4041 \text{p.u.} \)
- **V \( \text{dc} \) = 0.9493 \text{p.u.} \)
- **V \( \text{eq} \) = 1.0 \text{p.u.} \)

The parameters of the DC-voltage regulator are now optimised using the gradient-type Newton algorithm. When optimising the DC-voltage regulator, power-flow Wntrokr parameters are set at their optimum values. The optimum gain settings of the P-I type DC-voltage regulator are \( k_{ip} = 0.25 \) and \( k_{id} = 0.35 \).

6.2 Optimisation of UPFC damping controllers The UPFC damping controllers are designed taking into account the power-flow-controller and DC-Voltage-regulator parameters obtained earlier. The damping controllers are designed so as to produce an electrical torque in phase with the speed deviation. The UPFCs controllable parameters \( (m_n, m_e, S_B \text{ and } S_E) \) can be modulated in order to produce a damping torque. However, the UPFC bus: bus 2 (Fig. 1), is assumed to be a voltage-controlled bus, and so the magnitude of this bus voltage cannot be modulated. Therefore, the remaining three parameters are considered when designing damping controllers. In order to select the UPFC control parameter most suitable for modulation, by

\[ k_{ip} \text{ and } k_{ip} \text{ are optimised using a gradient-type Newton algorithm [14, 15]. A brief description of the gradient-type Newton algorithm is presented in Appendix 3. The parameters of the power-flow controller are optimised while neglecting the DC-voltage regulator. Optimum values of the proportional and integral gain settings of the power-flow controller are obtained as \( k_{ip} = 2 \) and \( k_{id} = 0 \).

The parameters of the DC-voltage regulator are now optimised using the gradient-type Newton algorithm. When optimising the DC-voltage regulator, power-flow Wntrokr parameters are set at their optimum values. The optimum gain settings of the P-I type DC-voltage regulator are \( k_{ip} = 0.25 \) and \( k_{id} = 0.35 \).

6.2.2 Dynamic performance of the system using power-flow controller and DC-voltage regulator: The dynamic performance of the system is obtained with:

(a) a power-flow controller only and
(b) a power-flow controller and DC-voltage regulator operating simultaneously

Fig. 6 shows the dynamic responses for \( \Delta P \text{, i.e., transient deviation in the power flow on line 2 following a 5% step change in reference power on line 2} \) (i.e. \( \Delta P_{eq} = 0.05 \text{p.u.} \)), with power-flow controller alone and also with power-flow controller and DC-voltage regulator operating simultaneously, Fig. 6 shows clearly that the power-flow on line 2 is regulated to the desired value, i.e., under steady-state condition the power flow on line 2 is increased by 5%. However, with the addition of a DC-voltage regulator, the response becomes somewhat oscillatory.

Fig. 7 shows the dynamic responses for a deviation in DC link voltage for the two conditions defined above. The responses clearly show that the deviation in DC link voltage \( A V_{dc} \) is regulated to zero when the DC-voltage regulator is operating simultaneously with the power-flow controller.

In order to examine the effect of a DC-voltage regulator on the dynamic performance of the system, the dynamic responses for Acu (Fig. 8) are obtained by making a 5% step increase in \( P_{eq} \) i.e., AP.Zcren = 0.05 p.u.

- (a) power-flow controller only and
- (b) power-flow controller and DC-Voltage regulator operating simultaneously

An examination of Fig. 8 reveals the following:

1. The dynamic response for Am of the system with just the power-flow controller is well damped.
2. The damping of the dynamic response is adversely affected by the incorporation of a DC-Voltage regulator.

6.3 Design of UPFC damping controllers The UPFC damping controllers are designed taking into account the power-flow-controller and DC-Voltage-regulator parameters obtained earlier. The damping controllers are designed so as to produce an electrical torque in phase with the speed deviation. The UPFCs controllable parameters \( (m_n, m_e, S_B \text{ and } S_E) \) can be modulated in order to produce a damping torque. However, the UPFC bus: bus 2 (Fig. 1), is assumed to be a voltagecontrolled bus, and so the magnitude of this bus voltage cannot be modulated. Therefore, the remaining three parameters are considered when designing damping controllers. In order to select the UPFC control parameter most suitable for modulation, by
Fig. 6  Dynamic responses for $\Delta P_{c2}$ following 5\% step increase in $P_a(nf)/P_{c2}(ref) = 0.05 \text{ p.u.}$

Fig. 7  Dynamic responses for $dV^-$ following 5\% step increase in $P_2(f)/P_{c2}(ref) = 0.05 \text{ p.u.}$

Fig. 8  Dynamic responses for $\Delta m$ following 5\% step increase in $P_{c2}(ref)/P_{c2}(ref) = 0.05 \text{ p.u.}$
the damping controller, the concept of a controllability index [16, 171 is used.

6.3.7 Controllability index: According to the modal control theory, the modal controllability index of the ith oscillation mode $L_i$ of the power system is:

$$\text{MD}(i,j) = \kappa_{i,j} A_{i,j} W$$

where $WT$ is the left eigenvector (row vector) of the state matrix $A$ corresponding to mode $A_i$, $B_i$, the $k$th column vector of the $B$ matrix, $k$ is the $k$th element of control vector $u$ and $MD(i,j)$ is a measure of the influence of the stabilisers on oscillation mode $L_i$. Consequently, this index can be used to assess the damping effect of the stabilisers on the oscillation mode. The procedure for calculating the controllability index is given in Appendix 4. It has been proved in [16, 11 that $\kappa_{i,j} A_{i,j} W$ where $W$ is the second element of $A_i$, and its module does not change with the different selection of the UPFC input control signals. Hence $\kappa_{i,j} A_{i,j} W$ can replace $MD(i,j)$ as a controllability index. The controllability index is computed for the electromechanical mode to be damped, taking into account control parameters $m_R$, $m_B$, $S_B$, and $S_C$, one at a time (Table 1). An examination of Table 1 reveals that the controllability index corresponding to UPFC control parameter $A_{i,j}$ is insignificant compared to control parameters $\kappa_{i,j}$ and $A_{i,j}$. Hence, modulating control parameter $A_{i,j}$ has relatively little effect on damping the oscillations compared to parameters $\kappa_{i,j}$ and $A_{i,j}$.

In view of the above, if the damping controller based on $A_{i,j}$ is not considered for further studies.

The damping controllers are designed taking $A_{i,j}$ and $A_{i,j}$ as their output signals. From now on, the damping controllers based on $m_R$ and $d_L$ shall be denoted as damping controller $in_D$ and damping controller $in_E$, respectively. It may be noted that the speed deviation signal $d_j$ which has been derived is used as an input to the damping controller. The transfer-function block diagram of the damping controller is shown in Fig. 9. It comprises gain block, signal-washout block and lead-lag compensator. The signal washout is the high-pass filter that prevents the steady changes in speed from modifying the UPFC control parameters. The value of washout time constant $T_w$ is not critical and may be in the range of 1 to 20 seconds. A $T_w$ equal to 10 seconds is chosen in the present studies.

The optimum parameters for the damping controllers are determined using the phase compensation technique [15].

Table 1: Controllability indices with different UPFC controllable parameters

<table>
<thead>
<tr>
<th>UPFC control parameters</th>
<th>Controllability index</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{i,j}$</td>
<td>0.0133</td>
</tr>
<tr>
<td></td>
<td>0.0196</td>
</tr>
<tr>
<td></td>
<td>3.6 x 10^-~</td>
</tr>
</tbody>
</table>

The time constants of the phase compensator are chosen such that the phase angle of the system is fully compensated for. For the nominal operating condition, the magnitude and phase angle of transfer functions $AP_{/A_i}$ and $AP_{/A_l}$ are computed (Table 2) for $s=jw$, where $\omega = \omega_C$ is the undamped natural frequency of the electromechanical mode.

An examination of Table 2 reveals that the phase angle is negative for transfer function $AP_{/A_i}$ and positive for transfer function $AP_{/A_l}$. The gain setting of the damping controller is chosen such that the required damping ratio of the electromechanical mode is achieved. However, it should be noted that, when choosing the gain setting of the damping controller, it must be ensured that this does not have any adverse effects on other modes of oscillations.

Table 3 shows the time constants ($T_1$ and $T_2$) of the phase compensators and the gain settings for damping controller $m_R$ and damping controller $S_C$. The gain settings of the controllers are computed assuming a damping ratio $\zeta = 0.5$.

It is extremely important to highlight the fact that damping controllers with a low controllability index require a high gain setting (compare Tables 1 and 3).

6.4 Dynamic performance of the system using damping controllers

The dynamic performance of the system is now examined using alternative damping controllers. The dynamic responses are obtained for $AP_{/A_i}$ and $AP_{/A_l}$ without damping controller are also shown in Figs. 10 and 11. It is evident from Figs. 10 and 11 that the desired dynamic performance of the system is obtained using both of these damping controllers.

It may thus be inferred that identical damping characteristics can be obtained either by controlling the magnitude of the voltage injected in series with the line or by modulating the phase angle of the shunt-converter voltage.

The dynamic performance of the system is further examined considering a case in which both of the damping controllers cooperate with each other. From now on, the simultaneous operation of both damping controllers will be referred to as 'dual damping controller'.

Fig. 12 shows the dynamic responses for Aw with:

(a) damping controller $d_L$

(b) damping controller $nig$

(c) dual damping controller

An examination of Fig. 12 clearly shows that the dynamic performance of the system using the dual damping controller is superior to that obtained by the individual damping controllers. This shows that the damping controllers based on $in_D$ and $in_E$ cooperate with each other. The performance of the dual damping controller shall now be examined in detail.

Fig. 9: Transfer function block diagram of the UPFC based damping controller
6.5 Effect of variation of loading condition on dynamic performance of the system

In any power system, there is a wide variation in operating load. It is extremely important to investigate the effect which varying the loading condition has on the dynamic performance of the system.

In order to examine the robustness of the UPFC-based dual damping controller in the presence of wide variations in loading condition, the system load is varied over a wide range. Dynamic responses are obtained for the following three typical loading conditions for $AP_2, \omega = 0.05 \text{ p.u.}$

(a) $P_1 = 1.031 \text{ p.u.}, Q_1 = 0.364 \text{ p.u. (heavy load)}$
(b) $P_1 = 0.912 \text{ p.u.}, Q_1 = 0.277 \text{ p.u. (nominal load)}$
(c) $P_1 = 0.651 \text{ p.u.}, Q_1 = 0.135 \text{ p.u. (light load)}$

Fig. 13 shows the dynamic performance of the system with a dual damping controller for the above loading conditions. A critical examination of Fig. 13 reveals that the dual damping controller provides a robust dynamic performance in the presence of variations in loading condition.

6.6 Effect of variation of line reactance $X_1$ on dynamic performance of the system with a UPFC-based dual damping controller

In order to examine the performance of the UPFC-based dual damping controller in the presence of variation in the

Table 2: Magnitude and phase angle of transfer functions for the system

<table>
<thead>
<tr>
<th>Transfer function</th>
<th>Magnitude</th>
<th>Phase angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>$5,$</td>
<td>0.1067</td>
<td>-13.65°</td>
</tr>
<tr>
<td>$AP,$</td>
<td>1.5325</td>
<td>2.62°</td>
</tr>
</tbody>
</table>

Table 3: Optimum parameters for the damping controllers

<table>
<thead>
<tr>
<th>Damping controller</th>
<th>$K_{oc}$</th>
<th>$T_{rs}$</th>
<th>$W_1$</th>
<th>$W_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>m</td>
<td>144.67</td>
<td>0.5185</td>
<td>0.2213</td>
<td></td>
</tr>
<tr>
<td>&amp;</td>
<td>16.13</td>
<td>0.3235</td>
<td>0.3547</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 10  Dynamic responses for $A_w$ with and without damping controller (m) $Jh AP_2, \omega = 0.05 \text{ p.u.}$
Fig. 11  Dynamic responses for zlo) with and without damping controller (S_d) for AP^fre/j = 0.05 p.u.
1.0
-2.0

-1.5

a damping controller
b damping controller
c damping controller

Aкс (p.u.) (x 10^-4)
Fig. 12  Dynamic responses for Am with different clamping controllers for AP, 2(μf) — 0.05 p.u.
equivalent line reactance, we vary \( X \) over the range *25% from its nominal value. Fig. 14 shows the dynamic responses for \( Aw \) with a dual damping controller for:

(a) \( X = 0.850 \) p.u. (25% increase in \( X \) from its nominal value)
(b) \( X = 0.683 \) p.u. (nominal value)
(c) \( X = 0.512 \) p.u. (25% decrease in \( X \), from its nominal value)

It can be clearly seen from Fig. 14 that the dual damping controller damps oscillations effectively for all the values of \( X \). However, responses deteriorate slightly with an increase in \( X \).

The above investigations reveal that the dual damping controller provides the most robust performance when subject to wide variations in loading condition and in system parameters.

Dynamic performances of the system with damping controller \( n_{\omega} \) and \( \delta_{\omega} \) were examined under wide variations in loading condition and in line reactance \( X \). Investigations revealed that these controllers also exhibit robust dynamic performance over a wide range of loading and of line reactance \( A \). However, the performance of the dual damping controller is somewhat superior to these damping controllers.

6.7 Performance of damping controllers under large perturbations

In order to understand the dynamic performance of the system under large perturbations, a transitory 3-phase fault of 4-cycle duration at the generator terminals is considered. Dynamic performance is obtained using the non-linear model of the system at the nominal loading condition with optimal settings of the UPFC controllers (power-Row controller, DC-voltage regulator and damping controller). Fig. 15 shows the dynamic responses for \( o \) of the systems using damping controller \( n_{\omega} \), damping controller \( \delta_{\omega} \), and dual damping controller, considering a 3-phase transitory fault of 4-cycle duration at generator terminals.
7 Conclusions

The significant contributions of the research work presented are as follows.

A comprehensive approach to designing UPFC controllers (power-flow controller, DC-voltage regulator and damping controllers) has been presented. The relative effectiveness of UPFC control signals ($Am$, $Ad$ and $As$) in damping low-frequency oscillations has been examined, using a controllability index. Investigations have revealed that UPFC control signal $dm$ is ineffective in damping oscillations. Dynamic-simulation results have revealed that the damping controllers based on control parameters $m_B$ and $J_E$ cooperate with each other.

The dual damping controller, which modulates control signals $dm_B$ and $Ad$ (simultaneously), has been proposed. Our investigations reveal that alternative damping controllers (damping controller $m_B$, damping controller $J_E$ and dual damping controller) provide robust dynamic performance under wide variations in loading condition and system parameters. The dual damping controller provides a significant improvement in dynamic performance in terms of peak deviations.

8 References

8 MORIoka, Y., and NAKACHI, Y. et al.: Implementation of unified power flow controller and verification for transmission
9 Appendix

9.1 Appendix 7
The nominal parameters and the operating conditions of the system are given below:

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator</td>
<td>M = 3000 MVA</td>
</tr>
<tr>
<td></td>
<td>D = 0.05 s</td>
</tr>
<tr>
<td></td>
<td>Xn = 1.0 p.u.</td>
</tr>
<tr>
<td></td>
<td>Xd = 0.1 p.u.</td>
</tr>
<tr>
<td>Transformers</td>
<td>Xgi = 1.0 p.u.</td>
</tr>
<tr>
<td></td>
<td>Xe = 0.1 p.u.</td>
</tr>
</tbody>
</table>

9.2 Appendix 2: Computation of constants of the model
The constants of the modified Heffron-Phillips model are computed from the expressions given below:

\[ K_{c1} = V5567 + yfifi + yidi + y\frac{\phi}{\delta}i + y; \]

\[ ygh_i + y\phi \]

\[ K_{c1} = \frac{ygh_i + y\phi}{ygh_i + y\phi} \]

\[ K_{c3} = \frac{s}{s} \]

\[ K_{c4} = \frac{s}{s} \]

\[ b_i = 4K_{c6}\cos(\phi_i)/2; \]

\[ b_f = -a_mV_{dc}\sin(\delta)/2; \]

\[ b_f = (a_mV_{dc}\sin(\delta))/2; \]

where

\[ x_{ef} \]

\[ a_1 = \ldots; a_2 = \ldots \]

\[ c_i \]

\[ c_i \]

\[ d_i \]

\[ d_i = c_i \]

\[ d_i = c_i \]

\[ f_i = 2; f_i = c_i + e_0m_0 \]

\[ 0f = \sin(\phi_0)/2; \]

\[ h_i = g \]

\[ \sin(\phi_0)/2; A 5 = \]

\[ = g_0m_0 \sin \]

\[ \cos \sin(\phi_0)/2 \]

\[ 4 = 0 \cos(\phi_5) \]

\[ f_i = 1 \]

\[ h_i = h_i + x_i \]

\[ x_T \]

\[ x_T \]

\[ 75 = x_T \]

\[ 76 = x_T \]

\[ x_T \]

\[ x_T \]

\[ x_T \]
\[ x = A x + B u \]

\[ p = [A P_{v1}, AV_{v1}, AP_{v2}, AV_{v2}] \]

where the state vector \( x \) and perturbation vector \( p \) are defined as:

\[ x = [A^T, \frac{dO}{dt}, A E^T, A E] \]

\[ p = [A P_{v1}, AV_{v1}, AP_{v2}, AV_{v2}] \]

\( A \) and \( B \) are matrices of compatible dimensions.

A vector \( A \) is defined as \( I - [k_p, k_i] \), where \( k_p \) is the proportional gain setting and \( k_i \) is the integral gain setting.

The algorithm is given as:

1. Initialise \( A \), i.e.,
2. Solve the system (2) to obtain \( I \)
3. Obtain the gradient vector of cost function as:

\[ VC(I) = \frac{dc}{ac} \]

where

\[ -x'_{n y}, q 4 = \]

4. Compute the Hessian of the cost function as

\[ H_{c}(k) = \frac{ac}{ \Gamma^T } \]

The Hessian is computed from the gradient vector by numerical differentiation.

5. Update the parameter vector \( A \) using Newton iterations:

\[ A_{n+1} = A_n - \frac{1}{E} \cdot VC(2.n) \]

6. If \( ||A_{n+1} - A|| < E \) go to step 7. If not go to step 2. \( E \) is the small positive number which defines the convergence criterion.

7. END.

9.3 Appendix 3

The gradient-type Newton algorithm can be given as

The cost function \( C \) is defined as

\[ e = \int (A \alpha) \cdot 2 \, dt \quad (14) \]

7. The dynamic model of the closed-loop system with a P-I controller in state-space form is given below:

\[ X = AX + B u \quad \text{(15)} \]