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Discussion on Effective Control of Inter-Area Oscillations by UPFCs

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Abstract—The paper discusses an effective method for damping inter-area oscillations in a power network using UPFCs. This two stage method controls voltage magnitudes/angles of the two sides of the UPFC based on a linearized approach, which in turn will command modulation amplitudes and angles of the UPFC. The method is compared to a one stage linearized approach which directly commands modulation amplitudes and angles of the UPFC. Discussion on the feasibility of the method and its relation to the steady-state operation of the UPFC is also addressed.

Index Terms—UPFC, Inter-Area Oscillations

I. INTRODUCTION

Damping inter-area oscillations in a power network is one of the important applications of a Unified Power Flow Controller [1]-[6]. These oscillations can occur in a system because of contingencies such as sudden load changes or power system faults. Fig. 1 shows a schematic diagram of a UPFC, which is a series-shunt FACTS device. Controlling power oscillations can be done by rapidly changing the power flow through the series part of the UPFC. The needed electrical power to do this action comes from the UPFC’s capacitor, which can be discharged temporarily during the control. This in turn brings up the issue of control and maintaining the capacitor dc voltage. There has been numerous work reported in the area of damping inter-area oscillations, some of which are based on linear control analysis of the UPFC and power system [1, 3 and 5], and others are based on nonlinear control systems theory and Lyapunov Energy Functions [2, 4 and 6]. Whichever method is used for the problem, the controller does its action by commanding the modulation amplitudes \((k_1, k_2)\) and angles \((\alpha_1, \alpha_2)\) of the UPFC.

Despite all the work done so far, authors have rarely found thorough work which not only shows results of the control in a complex multi-machine network with numerous oscillating modes, but also takes into account the dynamics of the UPFC capacitor and its shunt part in the studies.

In the present work, two control schemes for damping inter-area oscillations have been considered. In the first scheme, a one stage controller has been designed which directly commands the modulation amplitudes and angles of the UPFC. In the second scheme a two stage controller is devised. The first stage calculates the needed voltage magnitudes and angles at the two buses of the UPFC and the second stage commands the values of modulation amplitudes and angles of the UPFC based on the calculated values in the first stage. Both methods are based on the linear control theory and linearization of the state space model of the power system and they both take into account the dynamics of the shunt part and capacitor of the UPFC in the design. However, nonlinear simulations have been carried out to show the capability of the controllers in damping multiple inter-area oscillations. Studies show that the two stage controller shows remarkably better results on the IEEE 118 bus test system. In the following sections, modeling of the power system as well as the design of the controllers will be explained in detail. Then simulation results will be shown and comparison between the operations of the mentioned controllers will be presented. In the end, feasibility of the two stage controller as well as its relation to the steady-state operation of the UPFC will be discussed.

II. SYSTEM MODELING FOR CONTROLLER DESIGN

This section describes the process for modeling the power system from the controller's point of view. The goal is to
describe the system by a pure nonlinear differential equation set. The resulted state space model can be linearized for the purpose of the present work. In the work, the system is assumed to have \( n_g \) generators, \( n_l \) load buses and \( n_{UPFC} \) UPFCs. This results the system admittance matrix to have an order of \( n_g + n_l + 2n_{UPFC} \). If we assume all loads of the system to have constant admittance, and if we consider classical model for the generators, it would be possible to get a reduced admittance matrix of order \( n_g + 2n_{UPFC} \), where \( n_g \) internal machine buses are connected to \( 2n_{UPFC} \) UPFC buses as shown in Fig. 2. This comes from the fact that there would be no current injection at load buses or generator terminal buses if we assume the loads to be of constant admittance type and hence it would be possible to reduce the order of the system by Cron reduction when the load admittances are taken into the new bus admittance matrix. This method would also take the generators' transient \( d \)-axis reactances into the new admittance matrix so that the equivalent system would be viewed from the injection points of (a) Generator internal buses (b) UPFC sending buses and (c) UPFC receiving buses as shown in Fig. 2.

![Fig. 2. Equivalent Power System from the Controller's View](image)

The resulted state space system would be of the following format for the generators:

\[
\delta_j = \omega_j - \omega_i \tag{1}
\]

\[
\omega_j = (1/M_j)(P_{M,j} - E_j \sum_{k=1}^{n_{UPFC}} E_k \cos(\delta_j - \delta_k - \Phi_k)) \tag{2}
\]

Where:
- \( \omega_i \): Synchronous speed (rad/s)
- \( \omega_j \): Speed of machine j (rad/s) \( j = 1, ..., n_g \)
- \( P_{M,j} \): Mechanical input at machine j (pu) \( j = 1, ..., n_g \)
- \( \delta_j \): Angle at bus i (Radians) \( i = 1, ..., n_g + 2n_{UPFC} \)
- \( E_j \): Bus magnitude at bus i (pu) \( i = 1, ..., n_g + 2n_{UPFC} \)

\( Y_j \): Admittance matrix of the equivalent reduced system for \( j, k = 1, ..., n_g + 2n_{UPFC} \)

For UPFCs we use a power injection model schematically shown in Fig. 3.

![Fig. 3. Power Injection Model for UPFC](image)

According to [7], the dynamical equations for UPFC's power injection model could be written as:

\[
\frac{1}{\omega_i} i_{d0} = \frac{R_{d0}}{L_{d0}} i_{d0} + \frac{1}{L_{d0}} i_{q0} + \frac{k_{d1}}{L_{d0}} \cos(\delta_{j,i} + \alpha_{j,i}) v_{d0} - \frac{V_{d0}}{L_{d0}} \tag{3}
\]

\[
\frac{1}{\omega_i} i_{q0} = \frac{R_{q0}}{L_{q0}} i_{q0} - \frac{1}{L_{q0}} i_{d0} + \frac{k_{q1}}{L_{q0}} \sin(\delta_{j,i} + \alpha_{j,i}) v_{q0} - \frac{V_{q0}}{L_{q0}} \tag{4}
\]

\[
\frac{1}{\omega_{i,j}} i_{d0,k} = \frac{R_{d0,k}}{L_{d0,k}} i_{d0,k} + \frac{1}{L_{d0,k}} i_{q0,k} + k_{d1,k} \cos(\delta_{j,i} + \alpha_{j,i}) v_{d0,k} - \frac{V_{d0,k}}{L_{d0,k}} \tag{5}
\]

\[
\frac{1}{\omega_{i,j}} i_{q0,k} = \frac{R_{q0,k}}{L_{q0,k}} i_{q0,k} - \frac{1}{L_{q0,k}} i_{d0,k} + k_{q1,k} \sin(\delta_{j,i} + \alpha_{j,i}) v_{q0,k} - \frac{V_{q0,k}}{L_{q0,k}} \tag{6}
\]

\[
\frac{C}{\omega_{i,j}} v_{d0,k} = -k_{d1,k} \cos(\delta_{j,i} + \alpha_{j,i}) i_{d0,k} - k_{q1,k} \sin(\delta_{j,i} + \alpha_{j,i}) i_{q0,k} + \frac{v_{d0,k}}{R_{d0,k}} \tag{7}
\]

Where:
- \( j = 1, ..., n_g \)
- \( k_{d1,k} = l_{d0,k} + j_l_{d0,k} \): Shunt injection current in UPFC j (pu)
$i_{d,j} = i_{q,j} + jf_{d,j}$: Series injection current in UPFC j (pu)

$R_{d,j}$: Equivalent shunt resistance in UPFC j (pu)

$L_{d,j}$: Equivalent shunt inductance in UPFC j (pu)

$R_{q,j}$: Equivalent series resistance in UPFC j (pu)

$L_{q,j}$: Equivalent series inductance in UPFC j (pu)

$v_{dc,j}$: DC bus voltage in UPFC j (pu)

$C_{j}$: Equivalent capacitance in UPFC j (pu)

$k_{d,j}$, $\alpha_{d,j}$: Modulation amplitude and angle of the shunt part of UPFC j

$k_{q,j}$, $\alpha_{q,j}$: Modulation amplitude and angle of the series part of UPFC j

\[ V_{d,j} = E_{s} \cos \theta_{d,j} \] (8)

\[ V_{q,j} = E_{s} \sin \theta_{d,j} \] (9)

\[ V_{d,j} = V_{d,j} \cos \theta_{d,j} \] (10)

\[ V_{q,j} = V_{q,j} \sin \theta_{d,j} \] (11)

If the buses of the new system are numbered as $1$ to $n_{g}$ for generators, $n_{g} + 1$ to $n_{g} + n_{q}$ for UPFCs' sending buses and $n_{g} + n_{q} + 1$ to $n_{g} + 2n_{q}$ for UPFCs' receiving buses, then we will have:

\[ j = 1, \ldots, n_{g} \]

\[ V_{d,j} = E_{s} \sin \theta_{d,j} \] (12)

\[ \theta_{d,j} = \delta_{d,s} + \gamma_{d,j} \] (13)

\[ V_{q,j} = E_{s} \cos \theta_{d,j} \] (14)

\[ \theta_{q,j} = \delta_{q,s} + \gamma_{d,j} \] (15)

Writing up KCL at the sending and receiving buses of the UPFC and doing some math one can get the following equations:

\[ i = 1, \ldots, n_{g} \]

\[ V_{d,i} = -\sum_{j=1}^{n_{g}} \sum_{k=1}^{n_{q}} Z_{m_{d,j}k_{q}} E_{k} \sin(\Psi_{m_{d,j}k_{q}} + \Phi_{k} + \delta_{d,j}) \]

\[ + \sum_{j=1}^{n_{q}} Z_{m_{d,j}k_{q}} [i_{d,j} \cos(\Psi_{m_{d,j}k_{q}}) - i_{q,j} \sin(\Psi_{m_{d,j}k_{q}})] \] (16)

\[ + \sum_{j=1}^{n_{q}} Z_{m_{d,j}k_{q}} [-i_{d,j} \cos(\Psi_{m_{d,j}k_{q}}) + i_{q,j} \sin(\Psi_{m_{d,j}k_{q}})] \]

\[ + \sum_{j=1}^{n_{q}} Z_{m_{d,j}k_{q}} [i_{d,j} \cos(\Psi_{m_{d,j}k_{q}}) - i_{q,j} \sin(\Psi_{m_{d,j}k_{q}})] \]

\[ V_{q,i} = -\sum_{j=1}^{n_{g}} \sum_{k=1}^{n_{q}} Z_{m_{q,j}k_{q}} E_{k} \sin(\Psi_{m_{q,j}k_{q}} + \Phi_{k} + \delta_{q,j}) \]

\[ + \sum_{j=1}^{n_{q}} Z_{m_{q,j}k_{q}} [i_{d,j} \cos(\Psi_{m_{q,j}k_{q}}) + i_{q,j} \sin(\Psi_{m_{q,j}k_{q}})] \]

\[ + \sum_{j=1}^{n_{q}} Z_{m_{q,j}k_{q}} [-i_{d,j} \cos(\Psi_{m_{q,j}k_{q}}) + i_{q,j} \sin(\Psi_{m_{q,j}k_{q}})] \]

\[ + \sum_{j=1}^{n_{q}} Z_{m_{q,j}k_{q}} [i_{d,j} \cos(\Psi_{m_{q,j}k_{q}}) + i_{q,j} \sin(\Psi_{m_{q,j}k_{q}})] \] (17)

Where:

\[ [Z_{d} \in j \Psi_{j} = \left[ I_{d} \in j \Phi_{j} \right]^{T}] \quad i, j = n_{g} + 1, \ldots, n_{g} + 2n_{q} \] (20)

Equations (1) to (20) could fully describe the model used in this work for controller design.

III. ONE STAGE CONTROLLER DESIGN

Using the full state space model described in the previous section and considering the following $4n_{q}$ inputs:

\[ j = 1, \ldots, n_{g} \]

\[ u_{2(j-1)+1} = k_{1,j} \cos(\alpha_{1,j}) \]

\[ u_{2(j-1)+2} = k_{1,j} \sin(\alpha_{1,j}) \] (21)

\[ u_{2(j-1)+3} = k_{2,j} \cos(\alpha_{2,j}) \]

\[ u_{2(j-1)+4} = k_{2,j} \sin(\alpha_{2,j}) \]
It would be possible to get a linearized state space system of the form:

\[ X = AX + BU \]

\[ X = [\delta_{c}, \delta_{s}, \delta_{e}, \delta_{t}, \alpha_{c}, \alpha_{s}, \alpha_{e}, \alpha_{t}, V_{d}, V_{q}]^{T} \]  \hspace{1cm} (22)  

\[ U = [a_{1}, \ldots, a_{n}]^{T} \]

Where \( A \) and \( B \) are constant matrices. As it is seen in (22), the order of the system is \( 2n_{g} + 5n_{l} - 1 \). This is because instead of the equation set (1), the following modified equation set has been used in the linearization process:

\[
\begin{align*}
\delta_{j} &= \omega_{j} - \omega_{l} \\
J &= 2, \ldots, n_{g} \hspace{1cm} (1)
\end{align*}
\]

The reason for the above manipulation and calculating generators' speed deviations with respect to the first generator is to get a linear system which is controllable. Using (22) and applying an optimal control scheme of the LQR format, it is possible to find an optimal \( K \) matrix to account for updated modulation amplitudes and angles from \( U - KX \) during the control process. This approach is called the one stage method because it directly calculates the controlling modulation amplitudes and angles.

IV. TWO STAGE CONTROLLER DESIGN

Rewriting (2) as:

\[
J = 1, \ldots, n_{l}
\]

\[
\omega_{l} = \frac{1}{M_{j}} [J E_{p} - E \sum_{j} \delta_{j} \cos(\delta_{j} - \delta_{l})]
\]

\[
E_{d} = E \sum_{j} \cos(\delta_{j} - \delta_{l}) v_{2j_{d}} + E \sum_{j} \sin(\delta_{j} - \delta_{l}) v_{2j_{q}}
\]

\[
E_{q} = E \sum_{j} \cos(\delta_{j} - \delta_{l}) v_{2j_{q}} - E \sum_{j} \sin(\delta_{j} - \delta_{l}) v_{2j_{d}}
\]

Where:

\[
J = 1, \ldots, n_{l}
\]

\[
r_{x, j} = V_{id_{j}}
\]

\[
r_{x, j} = V_{id_{j}}
\]

\[
r_{x, j} = V_{id_{j}}
\]

\[
r_{x, j} = V_{id_{j}}
\]

\[
r_{x, j} = V_{id_{j}}
\]

\[
J = 1, \ldots, n_{l}
\]

and considering (1)' and (2)', one can get a nonlinear state space equation of the order \( 2n_{g} - 1 \) with intermediate control inputs defined by (23). This state space set, which describes the first stage of the control process, is independent of the UPFC dynamics and seems to be mathematically much less complicated than the system defined in III. Linearizing this system and applying an optimal linear control based on LQR would result in optimal values of voltages at both sending and receiving buses of a UPFC at every time step of the control process. The resulting control tries to minimize speed and angle deviations of the machines. Considering UPFC voltages as intermediate inputs of the control problem would decouple them from the power network and one can independently solve the dynamical equations of a UPFC for its modulation amplitudes and angles once its bus voltages are known. This is called the second stage of the control. Fig. 4 shows a flowchart which describes this two stage control schematically.

V. EXAMPLE AND DISCUSSION

As an example, IEEE 118 bus test system has been considered [8]. This system has 20 machines, where the order of each machine is 10, containing the two-axis generator model, Type I Exciter/AVR model and turbine and governor models. The diagram of the network is shown in Fig. 5.

The above system has been nonlinearly simulated using MATLAB with a fault having an admittance of 1 pu occurring on bus 43 at 0.2 s and removed at 0.4 s. Two UPFCs have been installed in the system in lines 30-26 and 64-65 respectively. They operating points of the UPFCs have
been initialized using the method discussed in [9]. The characteristics of the UPFCs along with their pre-fault steady state operating points are as follows:

- **UPFC$_1$**
  - $R_1 = 0.01 \text{ pu}$, $I_1 = 0.15 \text{ pu}$
  - $R_2 = 0.001 \text{ pu}$, $L_1 = 0.015 \text{ pu}$
  - $R_3 = 500 \text{ pu}$
  - $C = 2 \text{ pu}$
  - $P_{Loss} = 0.08 \text{ pu}$
  - $k_1 = 0.1545$, $\alpha_1 = 359.2175$
  - $k_2 = 0.0059$, $\alpha_2 = 254.9898$
  - $v = 6.1098 \text{ pu}$
  - $i_{d1} = -0.0882 \text{ pu}$, $i_{q1} = 0.0031 \text{ pu}$
  - $i_{d2} = 1.1926 \text{ pu}$, $i_{q2} = 1.1926 \text{ pu}$

- **UPFC$_2$**
  - $R_1 = 0.01 \text{ pu}$, $I_1 = 0.10 \text{ pu}$
  - $R_2 = 0.001 \text{ pu}$, $L_1 = 0.010 \text{ pu}$
  - $R_3 = 500 \text{ pu}$
  - $C = 2 \text{ pu}$
  - $P_{Loss} = 0.08 \text{ pu}$
  - $k_1 = 0.1582$, $\alpha_1 = 359.4904$
  - $k_2 = 0.0018$, $\alpha_2 = 238.9933$
  - $v = 6.1748 \text{ pu}$
  - $i_{d1} = -0.0861 \text{ pu}$, $i_{q1} = 0.0094 \text{ pu}$
  - $i_{d2} = 1.6997 \text{ pu}$, $i_{q2} = 0.8824 \text{ pu}$

Two controllers have been designed using the One Stage and Two Stage schemes respectively. Simulations have been compared with the case where no UPFC exists in the system and the results have been shown in the following figures. The weighting matrices for both controllers have been chosen such that the most possible damping of inter-area oscillations can be obtained. Fig. 6 shows the speed of generators. The dashed plots show the simulations with no UPFC and the thin and bold plots show the results with the One Stage and Two Stage controllers, respectively. As it is seen, speed deviations have been controlled using the Two Stage controller effectively. Also note that for both the uncontrolled and the One Stage controller there exist low frequency components which have not been damped out completely by the end of the simulation. The results of the Two Stage controller do not show this low frequency component at all. The One Stage controller shows qualitatively compatible results with [10]. In [10], the differential-algebraic equations of the power system have been directly linearized for designing the controller.

![Fig. 6. Speed Deviations (No Control: thin, One Stage: bold, Two Stage: boldest)](image-url)
continued Fig. 6. Speed Deviations (No Control: thin, One Stage: bold, Two Stage: boldest)

Fig. 7 shows the controlling modulation amplitudes and angles of the UPFCs during the control process. Fig. 8 depicts UPFC currents in d-q format and Fig. 9 shows UPFC ac and dc voltages.
This sensitivity does not hold for the One Stage controller, where the simulations were repeated with a broad range of $C_p$, $P_{in}$ and $R_p$ and the simulation results were generally successful.

VI. Conclusion

Two control schemes for damping inter-area oscillations using multiple UPFCs have been introduced in this paper, which are both based on the linear control theory. They are both state-feedback controllers and assume that global data of the power system is available to the controllers. The Two Stage controller shows more effective and quicker results than the One Stage controller. However, certain operating conditions must be provided for the Two Stage controller to do its job effectively. These conditions are mostly affected by UPFC dc capacitance and its ac and dc losses, where more capacitance and ac losses from one hand and less dc losses from the other hand can enhance the operation of the controller. Simulations show that a compromise between these three parameters could be gained for practical purposes.

Further work includes designing decentralized controllers which depend on only local data. Further investigation could be made on designing nonlinear controllers based on the proposed nonlinear modeling. Robustness and dependency of the designed controllers on the topology changes of the power system is also a matter of concern.

VII. References