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A New Control Strategy for the Unified Power Flow Controller

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Abstract: The Unified Power Flow Controller (UPFC) is the most versatile among a variety of Flexible AC Transmission System (FACTS) devices, which can be used for power flow control, enhancement of transient stability, damping system oscillations and voltage regulation. In this paper, we propose a new PI based approach for the dynamic control of UPFC. With the new control strategy, not only the active and reactive power flow control but also the system oscillations damping can be achieved. The digital simulation results developed in MATLAB and PSCAD/EMTDC environments are presented to verify the efficiency of the proposed control algorithm.

2 A Dynamic Model for the UPFC

Fig. 1 shows the system configuration of a UPFC, installed between two machines through a transmission line. The UPFC consists of a combination of a shunt and series branches, which take the form of two transformers and two voltage-source inverters sharing a common DC link with a DC storage capacitor [1]. The series connected inverter injects a voltage with controllable magnitude and phase angle in series with the transmission line, therefore providing real and reactive power to the transmission line. The shunt-connected inverter provides the real power drawn by the series branch and the losses. In addition, it can independently provide reactive compensation to the system by the reactive current.

To simplify the control analysis, improve the performance and reduce the interaction between the real and reactive power flow, we convert the instantaneous three-phase variables to vectors with orthogonal d-axis and q-axis components in a synchronously rotating dq frame by using Park's transformation [3][6]. So the dq reference transient stability model for UPFC shunt input and series output circuits is as follows:

\[
\frac{di_{pd}}{dt} = \left[ \frac{R_{L1}\omega}{L_{L1}} \right] + \omega \frac{R_{L1}\omega}{L_{L1}} \left[ i_{pd} + \frac{\omega}{L_{L1}} \left[ E_{pd} - \frac{1}{2} |V| \right] \right] \tag{1}
\]

\[
\frac{di_{pd}}{dt} = \left[ \frac{R_{L2}\omega}{L_{L2}} \right] + \omega \frac{R_{L2}\omega}{L_{L2}} \left[ i_{pd} + \frac{\omega}{L_{L2}} \left[ E_{pd} - \frac{1}{2} |V| \right] \right] \tag{2}
\]
where the inductance at the shunt input \( L_{s1} \) represents the leakage reactance of the shunt transformer, and the resistance \( R_{s1} \) represents the conduction losses of the shunt transformer. \( L_{s2} \) and \( R_{s2} \) denote the leakage of transformer, inverter conduction, switching and transmission line losses at the series output of UPFC.

The inverters can be assumed to be lossless because two equivalent resistors represent the losses of the inverters. Therefore the instantaneous active power on the AC sides of the inverters should be the same. The DC-link circuit can be derived as:

\[
\frac{dV_{dc}}{dt} = \frac{1}{V_{dc}}(E_{pd}I_{pd} + E_{pq}I_{pq} + E_{d}(I_{d} + I_{q})) - \frac{V_{dc}}{R_{dc}} \tag{3}
\]

where \( R_{dc} \) represents the inverter harmonics losses.

Neglecting the inverter voltage harmonics, the fundamental component of inverter output voltage \( E_{pd} \) and \( E_{pq} \) at the shunt input side can be defined as:

\[
E_{pd} = K_{pd}V_{dc}\cos\alpha, \quad E_{pq} = K_{pq}V_{dc}\sin\alpha \tag{11}
\]

Similarly the series injected voltage component \( E_{d} \) and \( E_{q} \) can be described as:

\[
E_{d} = K_{d}V_{dc}\cos\alpha_{d}, \quad E_{q} = K_{q}V_{dc}\sin\alpha_{q} \tag{12}
\]

where \( K_{1} \) and \( K_{2} \) are the modulation index of the inverter, and \( \alpha_{1} \) and \( \alpha_{2} \) are the phase shift between the inverter output voltage and the synchronous reference voltage.

3 The UPFC Control System

In general, the UPFC has three control parameters: magnitude and angle of series injected voltage and shunt reactive current [4]. We can achieve real and reactive power flow control independently by injecting series voltage with appropriate magnitude and angle. In the synchronous rotating dq frame, the injected voltage can be split into \( E_{d} \) and \( E_{q} \). By controlling \( E_{d} \) and \( E_{q} \) properly, different active and reactive power flow objectives can be accomplished. It is well known that shunt reactive current can provide reactive power support and shunt active current provides the DC-link capacitor voltage regulation.

3.1 Shunt Inverter and DC Voltage Control

The shunt real and reactive current can be regulated by varying the shunt inverter voltage real and reactive components \( E_{pd} \) and \( E_{pq} \) appropriately. Assuming that \( R_{s1} \ll L_{s1} \), we can rewrite the eqn. (1) in the steady state:

Thus reactive power supply and shunt input voltage can be regulated by active voltage component \( E_{pd} \) and the reactive voltage component \( E_{pq} \). The output of the PI controllers are phase shift \( \alpha_{1} \) and modulation index \( K_{1} \).

\[
i_{pq} = \frac{\alpha_{s}}{\alpha_{s}L_{s1}}(E_{pd} - V_{d})
\]

\[
i_{pd} = \frac{\alpha_{s}E_{pq}}{\alpha_{s}L_{s1}}
\]

3.2 Series Inverter Control

In this section, two series inverter control strategies are proposed. The first one is directly using active and reactive power flow control objectives to realize PQ decoupled control, the second one is converting active and reactive power flow control objectives to the series output current control objectives.

3.2.1 PQ decoupled control

Neglecting inverter losses, the injected active power \( P_{inj} \), injected reactive power \( Q_{inj} \), output active power \( P_{out} \), and output reactive power \( Q_{out} \), are calculated as follows:

\[
P_{inj} = \frac{V(E_{q} - E_{q}\cos\delta + E_{d}\sin\delta)}{X}
\]

\[
Q_{inj} = \frac{VE_{d}\cos\delta + VE_{q}\sin\delta - VE_{d} + E_{q}^{2} + E_{q}^{2}}{X}
\]

\[
P_{out} = \frac{V^{2}\sin\delta + VE_{q}}{X}
\]

\[
Q_{out} = \frac{2VE_{d}\cos\delta + 2VE_{q}\sin\delta + E_{d}^{2} + E_{q}^{2}}{2X}
\]

where

\[
V_{inj} = \sqrt{E_{d}^{2} + E_{q}^{2}}, \quad E_{q} = V_{inj}\sin\theta_{inj}, \quad E_{d} = V_{inj}\cos\theta_{inj}
\]
Equation (5) shows that $P_{\text{out}}$ is mainly affected by $E_q$, whereas $Q_{\text{out}}$ is affected by both $E_q$ and $E_d$. In incremental form, the line active and reactive power can be expressed in terms of $\Delta E_q$ and $\Delta E_d$:

$$
\Delta P_{\text{out}} = \frac{V}{X} \Delta E_q
$$

$$
\Delta Q_{\text{out}} = \frac{1}{X} (V \cos \delta \Delta E_d + V \sin \delta \Delta E_q + E_d \Delta E_d + E_q \Delta E_q)
$$

In practice, the phase angle between two buses on a transmission line is typically less than 30°. Thus it is reasonable to assume that $\cos \delta$ is close to unity and $\sin \delta$ is close to 0, which leads to

$$
\Delta Q_{\text{out}} = \frac{1}{X} (V \Delta E_d + E_d \Delta E_d + E_q \Delta E_q)
$$

Combining equations (6) and (7), a decoupled reactive control can be achieved after introducing the following control variable:

$$
\Delta Q_{\text{out}} = 2 \frac{P_{\text{out}}}{V_{\text{out}}^2 + V_{\text{out}}'^2} \left( V_{\text{out}} \Omega_{\text{out}} - V_{\text{out}}' \Omega_{\text{out}}' \right)
$$

The control of the active and reactive power on the transmission line can be achieved using the decoupled algorithm. It is possible to define PI compensation for the independent control of active and reactive power as follows:

$$
\Delta E_q = K_1 P \Delta P_{\text{out}} + K_2 P \int \Delta P_{\text{out}}(\nu) \, d\nu
$$

$$
\Delta E_d = K_2 Q \Delta Q_{\text{out}} + K_2 Q \int \Delta Q_{\text{out}}(\nu) \, d\nu
$$

A block diagram of PQ decoupled series inverter controller is presented in Fig. 3.

![Fig. 3 PQ decoupled series inverter controller](image)

3.2.2 Series Current Controller

The instantaneous real power at the transmission line of the UPFC series output is given by:

$$
P_{\text{out}} = V_{\text{out}}' i_{l_d} + V_{\text{out}}' i_{l_b} + V_{\text{out}}' i_{l_c}
$$

Using the Park’s transformation, $P_{\text{out}}$ can be rewritten in terms of $d$ and $q$ quantities as follows:

$$
P_{\text{out}} = \frac{3}{2} (V_{\text{out}}' \cos \alpha \Omega_{\text{out}} - V_{\text{out}}' \sin \alpha \Omega_{\text{out}}')
$$

The instantaneous reactive power at the same point can be defined as:

$$
Q_{\text{out}} = \frac{3}{2} (V_{\text{out}}' \sin \alpha \Omega_{\text{out}} + V_{\text{out}}' \cos \alpha \Omega_{\text{out}}')
$$

The final control objective is usually the control of transmittable real and reactive power in the transmission line. By solving equation (9) and (10), the series output current dq components can be obtained in the following equations.

$$
i_d = \frac{2}{3} \frac{P_{\text{out}}}{V_{\text{out}}' V_{\text{out}}} (V_{\text{out}} - V_{\text{out}}')
$$

$$
i_q = \frac{2}{3} \frac{P_{\text{out}}}{V_{\text{out}}' V_{\text{out}}} (V_{\text{out}}' - V_{\text{out}})
$$

where $V_{\text{out}} = |V| + E_d$, $V_{\text{out}} = E_q$.

Similarly the objectives of the series output current components can be calculated by using the real and reactive power flow objectives. Therefore the power flow control is converted into series output current control.

Assuming that $R_2 << L_2$, we can rewrite the eqn. (2) in the steady state:

$$
i_d = \omega_1 \left( E_q - V_{\text{out}} \right) i(t_{w_2})
$$

$$
i_q = -\omega_1 \left( V_{\text{out}} + E_q - E_{\text{out}} \right) i(t_{w_2})
$$

Thus reactive series output current component can be regulated by active voltage component $E_d$ and the reactive voltage component $E_q$ can be regulated to achieve the active series output current component control. Fig. 4 describes a block diagram of the control system for UPFC series Inverter.

![Fig. 4 Series Current control of UPFC](image)

4. Case Study

Two case studies were carried out to test the dynamic capabilities of UPFC and the performance of the new control method. One is using a two-bus system with the UPFC inserted at the middle point of the
transmission line to test the power flow control ability of the control strategy. The second one is using a 2-generator 11-bus system to demonstrate the capability for system oscillations damping.

Case 1: Referring to Fig. 1, the system is composed of two voltage sources at the sending and receiving ends of a transmission line. The parameters of the circuit used in simulation is as follows: 
\[ L = 0.016 \text{H}, \quad R = 0.25 \Omega, \quad C = 940 \mu\text{F}, \quad R_1 = 0.6267, \quad L_2 = 0.00147 \text{H}. \] 
The transformation ratio of the series-connected transformer is 2.5:1 and the transmission angle is set at 30 degrees. Simulation results are shown in Fig. 5 and Fig. 6.

Initially the system is in steady state with the series output active and reactive power reference being 1kVA and 2kVA respectively. Fig. 5 shows the UPFC response to a step change in active power at a time of 0.4s from 1kVA to 2kVA. Fig. 6 gives the result of the UPFC response to a step change in reactive power at a time of 0.4s from 2kVA to 3kVA. From Fig. 5 and Fig. 6, both the active and reactive power respond to the change in the reference and reach the new steady state within 0.2s while with the shunt input and DC voltage controller, dc voltage and shunt input voltage remains the same value during the transient stage of the regulation.
Case 2: For this case study, a UPFC is added between bus 5 and bus 2 of a 2-Generator 11-bus system as shown in Fig. 7. By changing the active load of bus 8 at t=0.02s and t=2s, we can introduce oscillations to the system. Fig. 8 presents the simulated results under this load fluctuation condition with and without UPFC compensation.

![Fig. 7 2-Generator 11-bus System](image)

As shown in Fig. 8, with the new control approach, the power flow at the series output and the shunt input voltage of UPFC remain at the same value during the load fluctuation without exhibiting any oscillations.

![Fig. 8 Oscillation damping control result Without Control-Dash Line, With Control-Solid Line](image)

5. Conclusions

This paper investigates the new control strategy for UPFC dynamic analysis. By implementing a synchronously rotating d-q frame, a dynamic model and control system for UPFC has been derived. With the new control approach, UPFC can perform independent control of transmittable real and reactive power at series output while regulating the shunt input voltage and maintaining the DC-link Capacitor voltage constant. It can also damp the power oscillations and improve the transient stability of the system by appropriate modulation of the controller references.

6. References