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EMTP Studies of UPFC Power Oscillation Damping

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***Abstract*—This paper describes the basic operation, control and applications of a Unified Power Flow Controller (UPFC), as well as the detail model used to simulate this controller on the Electromagnetic Transient Stability Program (EMTP). To demonstrate the potential of the controller under dynamic conditions, particularly for power oscillation damping control, an 11-bus test system is used to simulate a large fault in close proximity to the UPFC. Controller design issues and EMTP simulation results are discussed in detail.**

Keywords: FACTS, UPFC, EMTP, simulation, modeling, power oscillation damping control.

I. Introduction

The future growth of power systems will rely more on increasing capability of already existing transmission systems, rather then on building new transmission lines and power stations, for economical and environmental reasons. Due to deregulation of electricity markets, the need for new power flow controllers capable of increasing transmission capability and controlling power flows through predefined corridors will certainly increase. Ideally, these new controllers should be able to control voltage levels and flow of active and reactive power on transmission lines to allow for their secure loading, to full thermal capability in some cases, with no reduction of system stability and security margins [1].

Current popular FACTS controllers such as the Static Var Compensator (SVC) and the Thyristor Controlled Series Capacitor (TCSC) basically meet the control characteristics indicated above, allowing for new approaches when designing and operating power systems. Also, the improvements on the field of power electronics, particularly on Gate Turn-Off Thyristor (GTOs) ratings, permit now to utilize voltage-source inverters in power systems applications, leading to a new family of very versatile FACTS controllers, namely, the Static Synchronous Compensator (STATCOM), the Static Synchronous Series Compensator (SSSC) and the Unified Power Flow Controller (UPFC) [2].

The STATCOM, basically a substitute for the SVC, is used to control voltage levels and thus improve dynamic stability of power systems [3]. A ± 100 Mvar, 161 kV STATCOM prototype is already in service at TVA's power system [4]. The SSSC, a substitute for the TCSC, can be used to control the power flow in a transmission line by changing the magnitude of a series injected voltage [5].

The UPFC is a device which can control transmission line impedance, voltage and phase angle in power system applications, combining the features of the STATCOM and SSSC together. The controller is capable of regulating the voltage magnitude and angles of the sending and receiving end voltages, thus controlling the power flow in the transmission line, and effectively changing the transmission line impedance; the control scheme is designed in a way that these parameters can be controlled concurrently or selectively. Although the controller offers substantial advantages for steady state and dynamic operation of power systems by controlling the power flow in the transmission line in these two states, it brings major challenges in power electronics, device control and protection design, making the actual implementation of the controller a challenging task. A ± 320 MVA, 138 kV UPFC has been recently commissioned for the American Electric Power [6].

There are several references in the technical literature that present various studies and applications of the UPFC using a variety of tools and models. Thus, the authors in [8] illustrate the operation of the UPFC under fault conditions through a TNA Study. In [9], the authors analyze the effect of the UPFC on transient stability margins of a power system; the results in this case are obtained using a simple test system modeled in NETOMAC (a simulation program). The authors in [10] illustrate the effect of a UPFC in the steady-state and dynamic operation of a simple interconnected power system using NETOMAC's stability mode. Reference [11] proposes a control strategy for the UPFC and evaluates the results by simulating in SIMULINK the UPFC in power oscillation damping control mode. With similar ideas in mind, the current paper aims at investigating the UPFC capabilities for power oscillation damping in extreme operating conditions, i.e., fault conditions at a bus in close proximity to the UPFC, using a rather detailed model implemented in the Electromagnetic Transient Stability Program (EMTP) [7].

The paper is organized as follows: Section II briefly discusses the basic operating principles and controls of the UPFC. The detailed model of the controller is explained in Section III, and Section IV presents and discusses the results obtained from an EMTP simulation of this model on an 11-bus test system. Finally, Section V summarizes the results presented in this paper and discusses future research directions.

II. Background

A. *Basic UPFC Operation*

The UPFC is made out of two voltage-source inverters; one inverter is connected to the power system through a shunt transformer, whereas the other inverter is inserted into the transmission line through a series transformer. These two voltage-source inverters are coupled on their dc sides through a common dc capacitor link. From the control perspective, the UPFC can be decoupled into two branches; the parallel branch formed by the the shunt transformer, voltage source inverter and dc capacitor operating as a STATCOM, and the series branch composed of the series transformer, a voltage source inverter and the dc capacitor which behaves as a SSSC. The basic UPFC structure is shown in Fig. 1.

The main objective of the series inverter is to produce

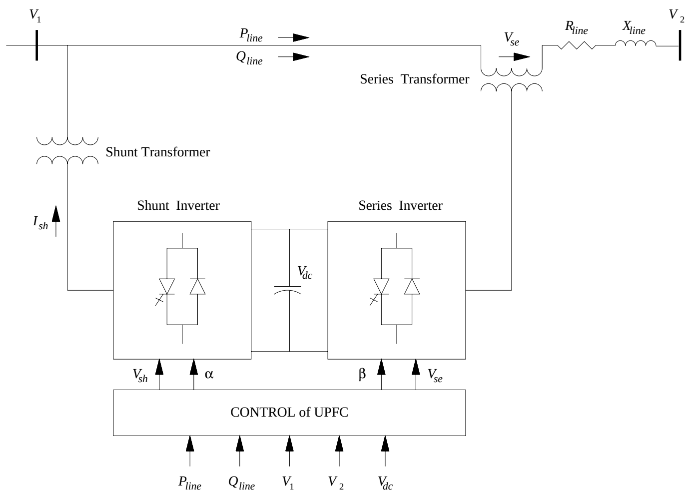

Fig. 1. UPFC functional model.

an ac voltage of controllable magnitude and phase angle, and inject this voltage of fundamental frequency into the transmission line through the series transformer. The series inverter exchanges real and reactive power at its ac terminals, while the shunt inverter provides the required real power at the dc terminals, so that real power flows freely between the controller shunt and series ac terminals through the common dc link. The reactive power is generated/absorbed independently by each inverter and does not flow through the dc link [12, 13].

Due to the inherent and unique characteristics of the UPFC to independently control the real and reactive power, the control strategies of the controller can vary widely. However, in most cases, it is anticipated that the UPFC will be used to control its bus voltage by locally generating or absorbing reactive power, as well as control power flows on the transmission line by regulating the magnitude and phase shift of the series injected synchronous voltage. This control mode is referred as Automatic Voltage Control Mode for the shunt inverter, and Automatic Power Flow Control Mode for the series inverter [8]. Since the UPFC is able to force a desired power flow through the transmission line in steady state as well as in dynamic conditions, the Automatic Power Flow Control Mode feature can be enhanced to damp power oscillation in power networks.

B. Power Oscillation Damping

The stability of a machine depends on the existence of two torque components; a synchronizing torque T_S that is in phase with the power (torque) angle perturbations $\Delta\delta$, and a damping torque T_D that is in phase with the speed deviations $\Delta\omega$. Thus, the change in electrical torque of a synchronous machine ΔT_e following a perturbation can be represented by [14]

$$\Delta T_e = T_S \Delta\delta + T_D \Delta\omega$$

For a machine to remain in synchronism after the perturbation, both torque components T_D and T_S have to be positive and sufficiently large. Lack of sufficient damping leads to oscillatory behavior of machine output quantities, and sometimes even to instability.

Since the UPFC is able to act almost instantaneously to changes in power, it is possible to improve damping and transient stability of a power system by coordinated control actions of the UPFC. Thus, power oscillations resulting from swings in rotor angles can be readily damped by using the series branch voltage of the UPFC to control the system power flow.

III. EMTP Modeling

A. Basic Structure

The UPFC simulated here is made of two six-pulse voltage source inverters with a sinusoidal Pulse Width Modulation (PWM) power controller. The typical 3-phase voltage-source inverters contain six controlled switches (GTO valves) and six uncontrolled switches (diodes). The GTO switches shape the inverter output waveforms, while the diodes provide a path for inductive output currents whenever the GTOs are switched off; two switches on the same leg cannot be on at the same time.

The EMTP provides several switching type device models such as a diode, a thyristor and a general TACS controlled switch (TACS is the part of the EMTP used to digitally simulate an analog computer). This TACS controlled switch, in conjunction with the correct TACS logic, was used to simulate a GTO valve. Each switch is also shunted with a snubber circuit to prevent numerical oscillations. The GTO's losses are modeled by a series resistance that also allow to meet a basic EMTP requirement of two switches in series having to be separated by an electrical element.

The output voltage is produced by converting the dc voltage of the capacitor into ac voltage by switching on and off the GTO switches at a sufficiently high frequency, thus synthesizing the set of three-phase fundamental frequency voltage waveforms on the inverter output terminals. The frequency modulation ratio is kept at a moderate level of 9, due to typical high switching losses of GTOs, and to prevent triplen harmonics from penetrating the network. The PWM sinusoidal reference signal is the sum of a fundamental and a sufficiently strong third harmonic so that the fundamental component of the inverter output voltage is increased [15]. Due to the low switching frequency, there is a need for some passive filters at the output terminals of the inverter to reduce the harmonic content in the voltage waveforms.

The UPFC shunt and series transformers are modeled as banks of three ideal single-phase two-winding transformers with no saturation. The transformer ratings are calculated according to the maximum permissible shunt current, maximum shunt voltage, maximum series current and maximum series inserted voltage. Except for the maximum shunt voltage, which is defined by the kV rating of the power system, e.g., 230kV in the example shown below, the other parameters are defined based on design and operating constraints. This is explained in more detail in Section IV.

B. Controls

There are two basic strategies that can be utilized to control the GTO switching. One approach involves multi-connected, out of phase inverters with a common dc source and coupled through appropriate magnetic circuits. In the only UPFC installation project so far, this control scheme is implemented to produce a nearly sinusoidal, 48-pulse output voltage waveform [4].

Another approach is to use PWM switching techniques, which permit independent control of active and reactive

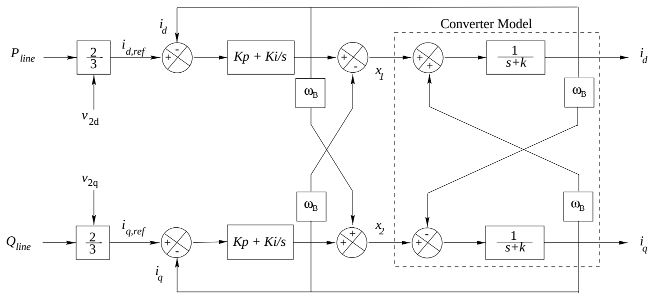

Fig. 2. Control block diagram of the UPFC's series branch [16].

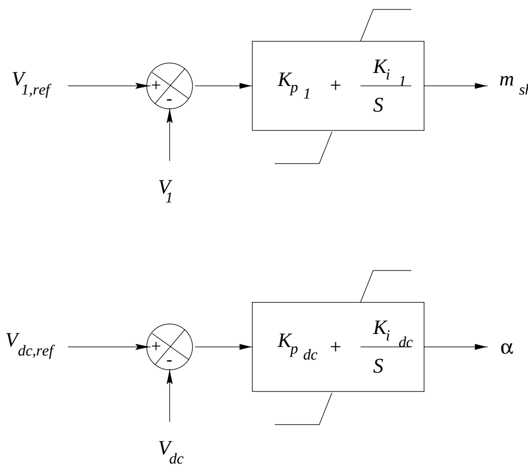

Fig. 3. Control block diagram of the UPFC's shunt branch.

power inputs into the inverters, provided that the dc capacitor voltage is kept sufficiently high. At present time, PWM is still considered uneconomical due to high switching losses and unavailability of fast switching GTOs; but with further improvements in power electronics, this technique should become more competitive.

The main objective of the UPFC is to control the power flows in the transmission line by controlling the amplitude and phase angle of the series inverter voltage. The shunt inverter controls the voltage on the ac bus and supplies the real power required by the series inverter by changing its voltage magnitude and phase angle. As proposed in [16], the control block diagram shown in Fig. 2 is used here to control the series branch of the UPFC. A similar control strategy is proposed in [16] for the shunt branch; however, for the shunt inverter the simple control depicted in Fig. 3 is used here, which is based on two PI controllers to independently control ac and dc voltage magnitudes. A more detailed explanation of these controls follows.

The decoupled watt-var control algorithm proposed in [17] is used here to control the series inverter branch. This control is based on the following d-q transformations of the ac input signals to convert these variables into dc control signals:

$$\begin{bmatrix} v_{2_{ds}} \\ v_{2_{qs}} \\ 0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} v_{2_a} \\ v_{2_b} \\ v_{2_c} \end{bmatrix}$$

$$\theta = \tan^{-1}\left(\frac{v_{2_{qs}}}{v_{2_{ds}}}\right)$$

$$\Rightarrow \begin{bmatrix} v_{2_d} \\ v_{2_q} \\ 0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin\theta & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} v_{2_a} \\ v_{2_b} \\ v_{2_c} \end{bmatrix}$$

For balanced, positive sequence voltages, $v_{2_d} = V_2$, and $v_{2_q} = 0$.

The control scheme of the series branch depicted on Fig. 2 starts with the desired set-points for active and reactive powers on the line P_{line} and Q_{line}, respectively. The values $i_{d,ref}$ and $i_{q,ref}$ are the reference values of the active and reactive current, respectively; K_p and K_i are the gains of the PI controllers; and ω_B stands for the fundamental electric frequency in rad/s. It should be noted that all signals needed for the series branch control, such as sending end voltage V_1, receiving end voltage V_2, dc voltage V_{dc} and line current I_{line} are measured and then transformed into p.u. d-q components by a synchronously rotating reference frame; the control signals obtained from this transformations are assumed to be dc.

The output variables x_1 and x_2 of the PI controllers are used to calculate the d- and q-axis components of the series converter output voltage $e_{d_{se}}$ and $e_{q_{se}}$, the amplitude modulation index m_{se}, and the phase angle β by means of the following equations:

$$\begin{aligned} e_{d_{se}} &= v_{1_d} - v_{2_d} - \frac{\omega_B}{L_{tot}}\, x_1 \\ e_{q_{se}} &= v_{1_q} - \frac{\omega_B}{L_{tot}}\, x_2 \\ m_{se} &= 2\sqrt{2}\, \frac{\sqrt{e_{d_{se}}^2 + e_{q_{se}}^2}}{V_{dc}} \\ \beta &= \tan^{-1}\left(\frac{e_{q_{se}}}{e_{d_{se}}}\right) \end{aligned}$$

where β is phase-locked to the UPFC receiving end bus voltage v_{2_a}. The term L_{tot} denotes the p.u. value of the combined series impedance of the line and transformer as follows:

$$L_{tot} = \frac{\omega_B}{Z_B}\,(L_{l_{se}} + L_{t_{se}})$$

where Z_B stands for the system base impedance.

The main objective of the shunt inverter is to control the ac voltage by controlling reactive power generation/absorption at the shunt bus, and to supply/receive active power at the dc terminals as demanded by the series inverter. Based on typical STATCOM control strategies that assume low inverter losses, the reactive power can be directly controlled by varying the magnitude of the shunt ac terminal voltage, whereas the active power can be directly controlled by the capacitor dc voltage, as any excess or deficit of active power at the dc terminals results on an increased or decreased dc voltage, respectively [18]. This is easily accomplished by varying the shunt amplitude modulation index m_{sh} to control the ac voltage magnitude, and varying the phase angle of the inverter output voltage α to control the dc voltage. Hence, shunt inverter ac and dc voltages are controlled using the two separate PI controllers depicted in Fig. 3.

Finally, the modulation controller of Fig. 4 proposed in [11] is used here to control the power oscillations. This control uses the slip of the desired machine $\Delta\omega$ to modify the active power signal reference P_{line} on the series inverter controller.

IV. Test Results

A. Test System

The 11-bus test system used for various UPFC studies is shown in Fig. 5. There are two parallel lines with the same impedance per unit length; the upper line is slightly longer than the lower parallel line. The active power flow is almost equally distributed between the two parallel lines; 45 MW per phase on the upper line and 50 MW per phase on the lower line, as depicted in Fig. 6. The voltage magnitudes in the system are within permissible limits of 0.95–1.05 p.u. for all buses.

A 3-phase fault with impedance to ground occurs at bus 6 at 5 s. Nine cycles after the fault, i.e., at 5.15 s, the circuit breaker between buses 4 and 5 opens, clearing the fault and disconnecting the load at bus 7. The generator at bus 3, which has an AVR to keep its terminal voltage at 1.0 p.u., recovers successfully after clearing the fault, as it can be seen on the corresponding waveforms on Fig. 6.

B. UPFC in Automatic Power Flow Control Mode

A ± 380 MVA UPFC is placed at the beginning of the lower parallel line to redistribute the power flow, so that the active power on the lower line is 70 MW per phase while the upper line carries only 20 MW per phase. Approximately 25 MW per phase goes into the shunt branch of the UPFC to supply the power required by the series branch, and also to cover the losses in the inverter circuits.

The UPFC equipment consists of two identical six-pulse inverters, each rated at 190 MVA; the shunt and series transformers are also rated at 190 MVA each. After some EMTP simulations and careful assessment of the UPFC role in the sample system, it was determined that, in steady state, each inverter and transformer carry approximately 150 MVA for the given operating conditions. The shunt part of the UPFC generates 22 Mvar per phase to supply the required power while keeping the bus voltage at bus 4 at 1 p.u., while the series part of the UPFC supplies 30 Mvar per phase to the line to maintain the required power order. For these operating conditions, the dc voltage is kept constant at 15 kV, as shown in Fig. 7.

The maximum series inserted voltage magnitude is designed to be 40% of the power system voltage rating, i.e., the maximum magnitude of the series inverter voltage is 53.1 kV (phase-to-neutral). For the given operating conditions, this voltage is measured to be 0.36 p.u., while the line current is measured to be 2.4 p.u. (p.u. values are calculated on a 230 kV and 100 MVA base). This current together with the specified maximum series voltage define the rating of the series inverter and transformer [8]. The shunt transformer rating is also calculated as a product of the peak maximum rated voltage and shunt current. If the bus voltage is kept at its maximum value of 1 p.u., the shunt current is measured to be 0.9 p.u. The steady state values of these currents are depicted in Fig. 7,

The same 3-phase fault as in the previous case is applied to the system, and the results are also shown in Fig. 7. Nine cycles after the fault, the circuit breaker opens, resulting in the line conditions quickly returning to normal. Observe that the UPFC continues to control the active

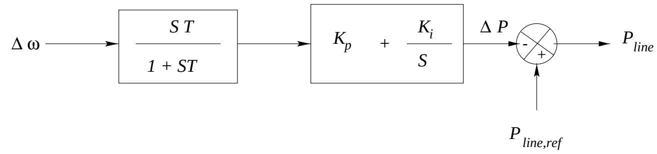

Fig. 4. Power modulation control.

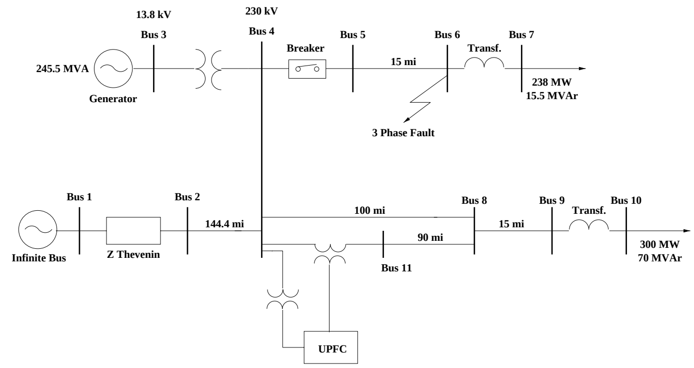

Fig. 5. Test system.

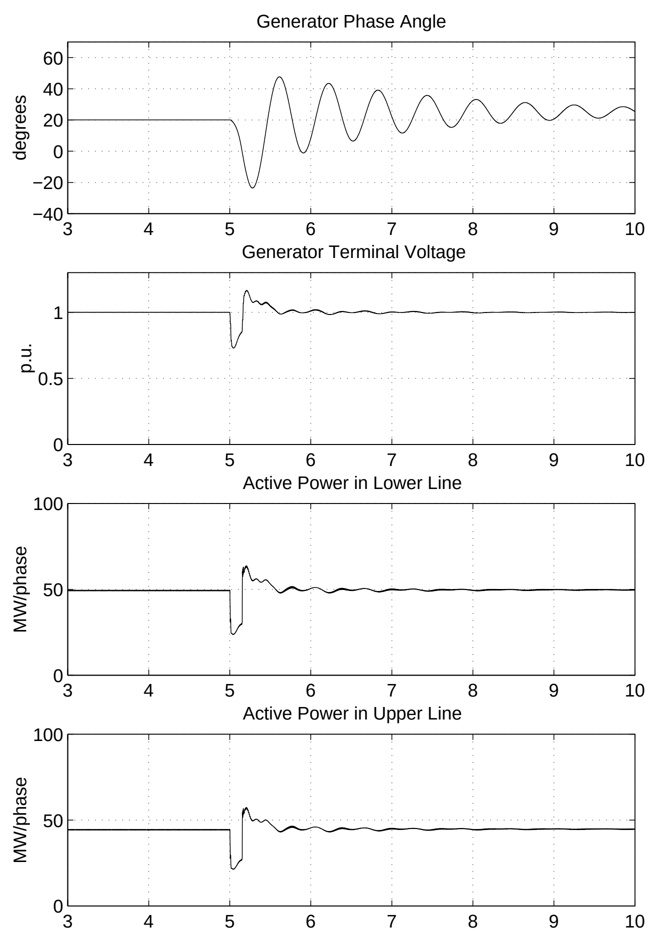

Fig. 6. Fault results for the test system without UPFC.

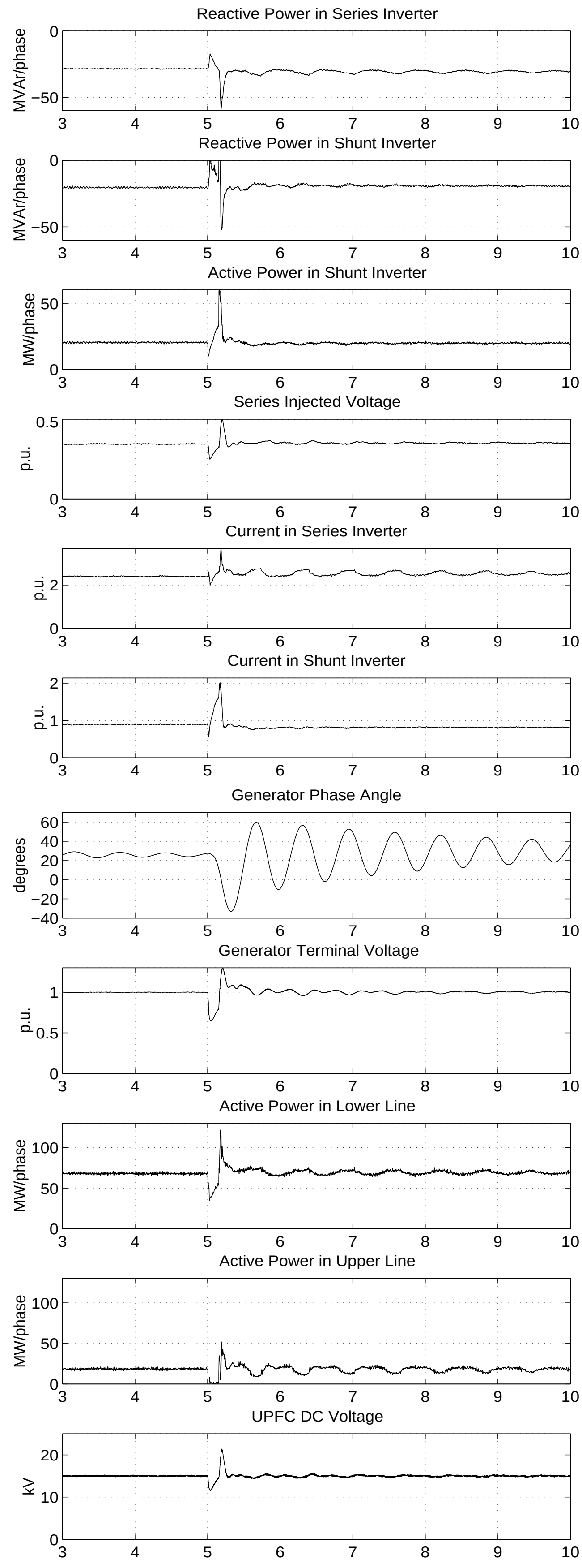

Fig. 7. Fault results for the UPFC in Automatic Power Flow Control Mode.

and reactive powers in the line at the prescribed levels. The generator experiences larger oscillations in the power angle than in the case without the UPFC; this is due to the unbalanced power flow conditions imposed on the parallel lines by the UPFC controller. Nevertheless, the oscillations are also damped in this case.

Notice that the plots clearly show that the UPFC is capable of forcing a given power flow through the line in the steady state as well as under dynamic conditions, as the series part of the UPFC controller is in Automatic Power Flow Control Mode, i.e., maintaining the given P_{line} and Q_{line} reference values. The power oscillations caused by the power angle swings are carried almost entirely by the upper parallel line.

C. UPFC in Power Oscillation Damping Control Mode

The Automatic Power Flow Control Mode is changed to a Power Oscillation Damping Control Mode by simply allowing the active power reference to change according to the changes in generator speed, as previously explained in Section III.

The results depicted in Fig. 8 show that by allowing the UPFC to counteract the changes in the generator output power, the disturbance caused by the 3-phase fault at bus 6 is quickly controlled. The generator phase angle oscillations are damped faster and, hence, the system appears to be more stable.

It is important to highlight the fact that this kind of control mode is somewhat unrealistic, since it would be very difficult in practice to obtain inputs for this control; other controls depending on local signals would be more appropriate. This study only demonstrates the UPFC capabilities to damp power flow oscillations.

V. Conclusions

This paper discusses in detail the modeling and simulation of a UPFC controller, proposing a simple control scheme for the shunt branch to control active and reactive power on transmission systems. EMTP studies are carried out in a realistic 11-bus system, demonstrating various advantages of having a UPFC controller in the system, especially when used for power damping oscillation. The problem with the proposed power damping control is that it requires certain signals that are not readily available in practice; hence, we are working on developing adequate damping controls based on local signals.

Based on the control and simulations techniques results presented here, we are also currently working on validating reduced stability and steady state UPFC models previously proposed in [18].

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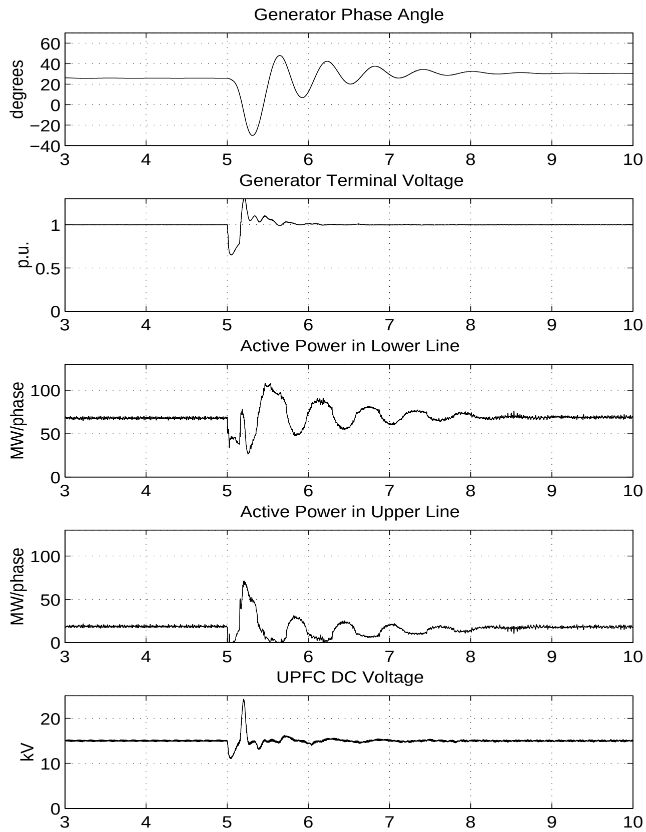

Fig. 8. Fault results for the UPFC in Power Damping Oscillation Control Mode.

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