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Modelling and design of unified power flow controller (UPFC) for power system network using PSCAD/EMTDC and MATLAB

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ABSTRACT:

Unified Power Flow Controller (UPFC) is the most widely used Flexible ac Transmission system (FACTS) device to control the power flow and to optimize the system stability in the transmission line**.** It should be installed to control the voltage, as well as to control the active and reactive power flow through the transmission line. This project is using PSCAD/EMTDC and MATLAB software to model and to verify the UPFC system in order to improve its performance in power system. MATPOWER in MATLAB software used to run the power flow of IEEE 9 bus power system network. Then, by using PSCAD/EMTDC software, IEEE 9 bus system was designed and the result of power flow 9 bus system using PSCAD/EMTDC was compared with the power flow in MATPOWER. The result of active power, P (MW), reactive power,Q (MVar) and power loss were compared to make sure that both software have the similar answer with only 1% difference. The power flow in both the software must be similar before injecting the UPFC system. Then, the active power and reactive power performance will be improved due to injecting the UPFC device. Stability and transient performance of active and reactive power was analyzed.

Keywords:

Nomenclature:

AC	- Alternating Current
EMTDC	- Electromagnetic Transient Direct Current
GTO	- Gate Turn Off
IEEE	- The Institute of Electrical and Electronics Engineers
IGBT	- Insulated Gate Bipolar Transistor
MATLAB	- Matrix Laboratory
P	-Active power
PLL	- Phase Locked Loop
PSCAD	- Power System Computer Aided Design
p.u.	- Per-unit
SPWM	- Sinusoidal Pulse Width Modulation
Q	- Reactive power
SSSC	- Series Synchronous Compensator
STATCOM	- Static Synchronous Compensator
VSC	- Voltage-sourced Converter

1. Introduction

Unified Power Flow Controller (UPFC) is the universal and most flexible FACTS (Flexible ac Transmission System). It is used to control the power flow in the transmission systems by controlling the impedance, voltage magnitude and phase angle. This device can allow the path of power as we desire. UPFC consist of two Voltage Supply Inverters, one series converter and one shunt converter. This device is actually a combination of two FACTs device which are STATCOM (Static Synchronous Compensator) and SSSC (Static Series Synchronous Compensator). SSSC is used to add controlled voltage magnitude and phase angle in series with the line, while shunt converter STATCOM is used to provide reactive power to the ac system, beside that, it will provide the dc power required for both inverter [1]. The reactive power can be compensated either by improving the receiving voltage or by reducing the line reactance

[2].UPFC should be installed to control the voltage, as well as to control the active and reactive power flow through the transmission line. However, the right transmission line to be injected by UPFC and the effect of injection will only know by doing the analysis using MATLAB and PSCAD software. Thus, this project presents the active and reactive power control through a transmission line by placing the UPFC using computer simulation. PSCAD and MATLAB program are used to model and to verify the performance of UPFC in order to increase the ability of the system.

2. Problem statement

Unified Power Flow Controller (UPFC) is the most widely used Flexible ac Transmission system (FACTS) device to control the power flow and to optimize the system stability in the transmission line**.** It should be installed to control the voltage, as well as to control the active and reactive power flow through the transmission line.

Objectives:

- The objectives of this project are to:
- Simulate power system network with MATLAB software.
- Model UPFC in power system network sample and determine the most efficient transmission line to be injected.
- Analyze the steady-state analysis of the power system network before and after UPFC applied.

3. UPFC Basic Operation and Characteristics

This chapter will explain basic operation and characteristics of the UPFC. Since UPFC consists of two voltage-sourced converters (VSCs), basics of VSCs will be briefly discussed at the beginning of the chapter.

Basics of Voltage Source Converters and Pulse Width Modulation Technique

Typical three-phase VSC is shown in Fig. 1 [3].

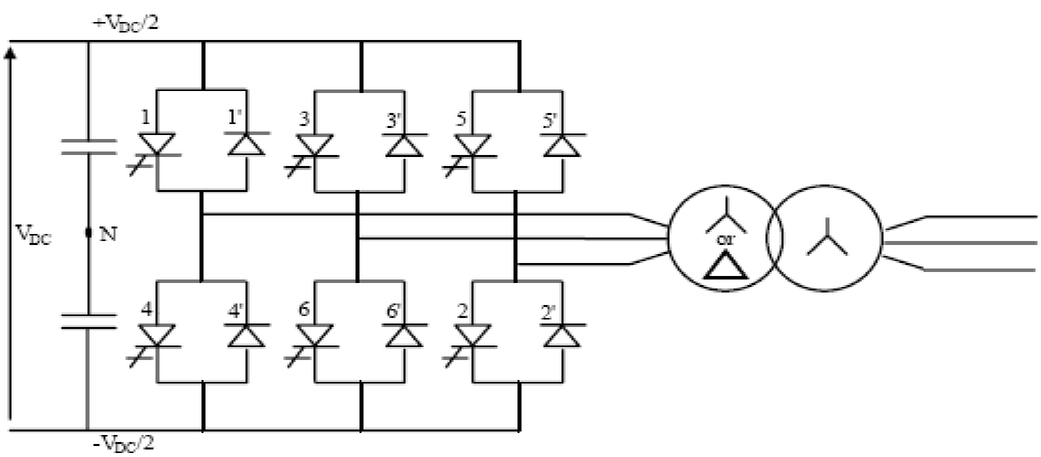

Fig. 1 Three-phase voltage sourced-converter

It is made of six valves each consisting of a gate turn off device (GTO) paralleled with a reverse diode, and a DC capacitor. An AC voltage is generated from a DC voltage through sequential switching of the GTOs. The DC voltage is unipolar and the DC current can flow in either direction. Controlling the angle of the converter output voltage with respect to the AC system voltage controls the real power exchange between the converter and the AC system. The real power flows from the DC side to AC side (inverter operation) if the converter output voltage is controlled to lead the AC system voltage. If the converter output voltage is made to lag the AC system voltage the real power will flow from the AC side to DC side (rectifier operation). Inverter action is carried out by the GTOs while the rectifier action is carried out by the diodes. Two switches on the same leg cannot be on at the same time. Controlling the magnitude of the converter output voltage controls the reactive power exchange between the converter and the AC system. The converter generates reactive power for the AC system if the magnitude of the converter output voltage is greater than the magnitude of the AC system voltage. If the magnitude of the converter output voltage is less than that of the AC system the converter will absorb reactive power. The converter output voltage can be controlled using various control techniques. Pulse Width Modulation (PWM) techniques can be designed for the lowest harmonic content. It should be mentioned that these techniques require large number of switching per cycle leading to higher converter losses. Therefore, PWM techniques are currently considered unpractical for high voltage applications. However, it is expected that recent developments on power electronic switches will allow practical use of PWM controls on such applications in the near future. Due to their simplicity many authors, i.e. [10], [19], [20], [22], have used PWM control techniques in their UPFC studies. Hence, the same approach will be used in this thesis. When sinusoidal PWM technique is applied turn on and turn off signals for GTOs are generated comparing a sinusoidal reference signal vr of amplitude Ar with a sawtooth carrier waveform vc of amplitude Ac as shown in Fig. 2 (b) [33]. The frequency of the sawtooth waveform establishes the frequency at which GTOs are switched. Consider a phase-leg as shown in Fig. 2 (a). In this case vr>vc results in a turn on signal for the device one and gate turn off signal for the device four and vr<vc results in a turn off signal for the device one and gate turn on signal for the device four.

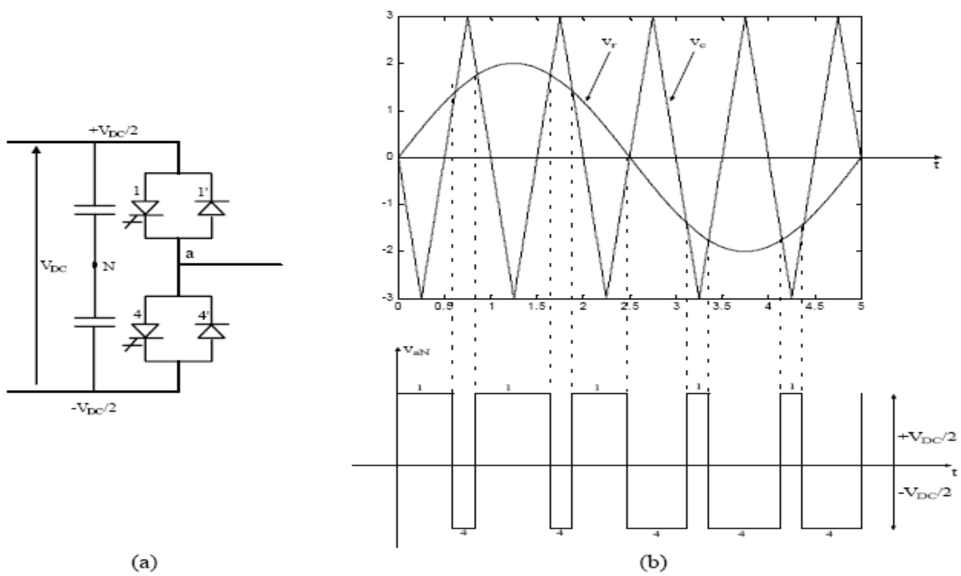

Fig. 2 PWM converter (a) A phase-leg (b) PWM waveforms

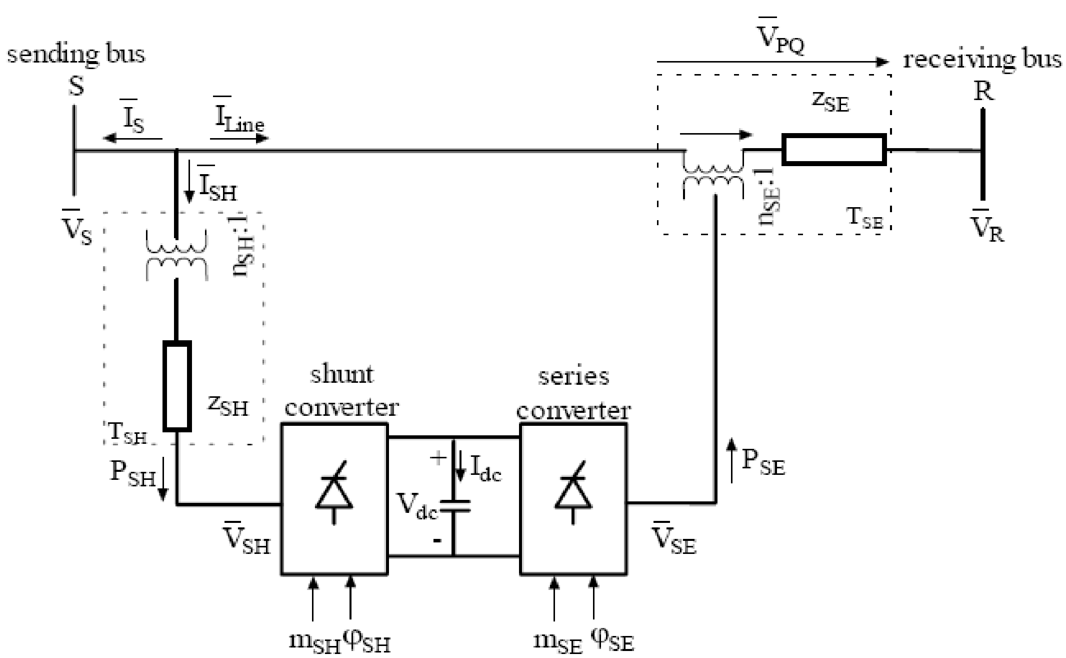

Fig. 3. Fundamental frequency model of UPFC

The fundamental frequency of the converter output voltage is determined by the frequency of the reference signal. Controlling the amplitude of the reference signal controls the width of the pulses.

4. UPFC Description and Operation

The UPFC is a device placed between two busses referred to as the UPFC sending bus and the UPFC receiving bus. It consists of two Voltage-Sourced Converters (VSCs) with a common DC link.

Applying the Pulse Width Modulation (PWM) technique to the two VSCs the following equations for magnitudes of shunt and series injected voltages are obtained.

$$V_{SH} = m_{SH} \frac{V_{DC}}{2\sqrt{2} n_{SH} V_B}$$

$$V_{SE} = m_{SE} \frac{V_{DC}}{2\sqrt{2} n_{SE} V_B}$$

where:

- mSH – amplitude modulation index of the shunt VSC control signal
- mSE – amplitude modulation index of the series VSC control signal
- nSH – shunt transformer turn ratio
- nSE – series transformer turn ratio
- VB – the system side base voltage in kV
- VDC – DC link voltage in kV

The phase angles of δ SH and δ SE are given by the following relation

$$\delta_{SH} = \angle(\delta_S - \varphi_{SH})$$

$$\delta_{SE} = \angle(\delta_S - \varphi_{SE})$$

where:

- φ_{SH} – firing angle of the shunt VSC with respect to the phase angle of the sending bus voltage
- □φ_{SE} – firing angle of the series VSC with respect to the phase angle of the sending bus Voltage respect to the phase angle of the sending bus voltage
- □φ_{SE} – firing angle of the series VSC with respect to the phase angle of the sending bus

The fundamental frequency models, the VSCs are replaced by two controlled voltage sources as shown in Fig. 3 [22]. The voltage source at the sending bus is connected in shunt and will therefore be called the shunt voltage source. The second source, the series voltage source, is placed between the sending and the receiving busses. The UPFC is placed on high-voltage transmission lines. This arrangement requires step-down transformers in order to allow the use of power electronics devices for the UPFC.

The series converter injects an AC voltage in series with the transmission line. Series voltage magnitude VSE and its phase angle ϕSE with respect to the sending bus are controllable in the range of 0≤VSE≤VSemax and 0≤ϕSE≤3600. The shunt converter injects controllable shunt voltage such that the real component of the current in the shunt branch balance the real power demanded by the series converter. The real power can flow freely in either direction between the AC terminals. On the other hand the reactive power cannot flow through the DC link. It is absorbed or generated locally by each converter. The shunt converter operated to exchange the reactive power with the AC system provides the possibility of independent shunt compensation for the line. If the shunt injected voltage is regulated to produce a shunt reactive current component that will keep the sending bus voltage at its pre-specified value, then the shunt converter is operated in *the Automatic Voltage Control Mode***.** Shunt converter can also be operated in *the Var Control Mode***.** In this case shunt reactive current is produced to meet the desired inductive or capacitive Var request.

4. UPFC MODELING AND INTERFACING

In order to simulate a power system that contains a UPFC, the UPFC needs to be modeled for steady-state and dynamic operations. The UPFC model needs to be interfaced with the power system model. Hence, in this chapter modeling and interfacing of the UPFC with the power network are described. Linearized model of the power network with UPFC, useful for small signal analysis and damping controller design, will also be derived.

4.1 UPFC Load Flow (LF) Model

For steady-state operation, the DC link voltage remains constant at its pre-specified value. The LF model discussed here assumes that the UPFC is operated to keep (i) real and reactive power flows at the receiving bus and (ii) sending bus voltage magnitude at their prespecified values [10]. In this case UPFC can be replaced by an "equivalent generator" at the sending bus (PV-type bus using load flow terminology) and a "load" at the receiving bus (PQ-type bus) as shown in Fig. 4.1. To obtain the LF solution for the power network with the UPFC an iterative procedure is needed. Power demanded at the receiving bus is set to the desired real and reactive powers at that bus. The real power injected into a PV bus for conventional LF algorithm is kept constant and the reactive power is adjusted in order to achieve the pre-specified voltage magnitude. With UPFC, the real power injected into the sending bus is not known

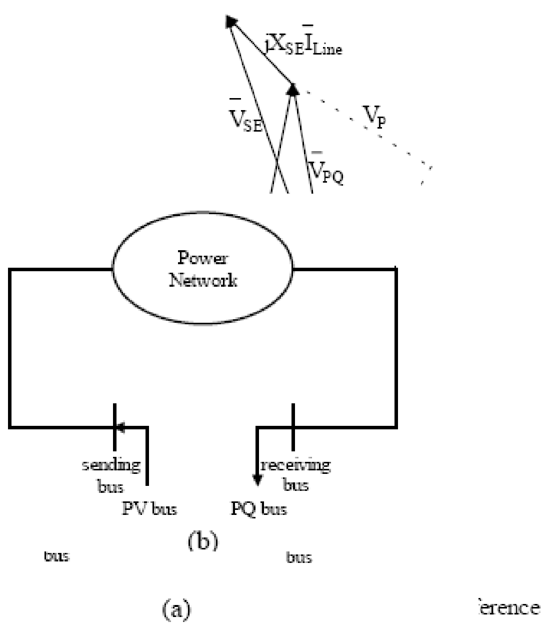

Fig. 4. Power network with a UPFC included (a) schematic (b) Load Flow Model

exactly. This real power injection is initialized to the value that equals the pre-specified real power flow at the receiving bus. During the iterative procedure the real power adjustment is done in order to cover the losses of the shunt and series impedances and to force the sum of converters' interaction to become zero.

The algorithm in its graphical form is given in Fig. 5..

Fig. 5. Load flow algorithm

Using the voltages and currents as assigned in Fig. .3

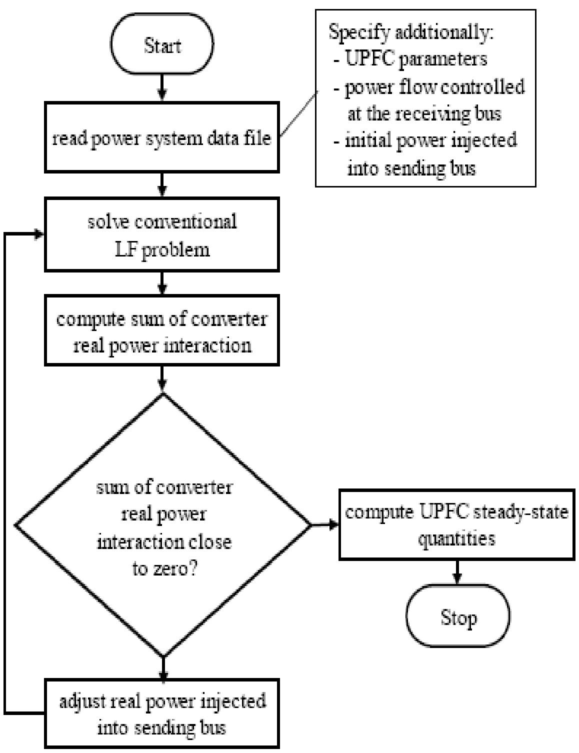

Fig. 6. Phasor diagram

Using the voltages and currents as assigned in Fig.3 Computing the line current by using the bus voltages and the power flow at the receiving
bus as given by the load flow solution

$$\bar{I}_{Line} = -\frac{S_R^*}{\bar{V}_R^*}$$

Taking the real part of (4.4) and using (4.1), the new injected real power at the sending bus becomes

$$P_S = -P_{SE} + \mathrm{Re}(-Z_{SH} I_{SH}^2 - \bar{V}_{SH} \bar{I}_{Line}^* - Z_{SH} \bar{I}_{SH} \bar{I}_{Line}^*)$$

It can be seen from Fig. 4.2 that UPFC control parameters are computed directly after a conventional LF solution satisfying (4.1) is found. Neglecting transformer losses and initializing the real power injected into sending bus to the real power flow controlled on the line the convergence of the proposed LF algorithm is obtained within one step.

5. CONTROLLER DESIGN

To operate the UPFC in the automatic control mode discussed in the third chapter, and also to use the UPFC to enhance power system stability and damp low frequency oscillations, two control designs need to be performed. A primary control design, referred to as the *UPFC basic control design,* involves simultaneous control of (i) real and reactive power flow on the transmission line, (ii) sending bus voltage magnitude, and (iii) DC voltage magnitude. A secondary control design, referred to as the *damping controller design,* is a supplementary control loop that is designed to improve transient stability of the entire electric power system. The two control designs are described in this chapter.

5.1 Basic control

The UPFC basic control design consists of four separate control loops grouped into a *series control scheme,* whose objective is to control real and reactive power flow on the line, and a *shunt control scheme,* whose objective is the control of the sending bus voltage magnitude and the DC voltage magnitude.

5.2 Series control scheme

This scheme has two control loops, one for the tracking of the real power flow at the receiving bus of the line, and the second performs the same task for the reactive power flow. Specifically, the objective is to track these real and reactive power flows following step changes and eliminate steady-state tracking errors. This is obtained by the appropriate selection of the voltage drop between the sending and the receiving buses, which is denoted PQ V (see Fig 3.3). This voltage can be decomposed into the following two quantities which affect the tracked powers, namely: 39 VP = voltage component orthogonal to the sending bus voltage (it affects primarily the real power flow on the transmission line) VQ = component in phase with the sending bus voltage (it affects mainly the reactive power flow on the transmission line). These quantities are in phasor diagram Fig. 6 [22].

Both voltages, VP and VQ, are obtained by designing classic PI (proportional-integral) controllers as illustrated in Fig. 7. The integral controller will guarantee error free steady state control of the real and reactive line power flows. After the VP and VQ components have been found the injected series voltage can be
computed as

$$V_{PQ} = \sqrt{V_P^2 + V_Q^2}$$

$$\varphi_{PQ} = tg^{-1}\frac{V_P}{V_Q}$$

$$\bar{V}_{PQ} = V_{PQ}\angle(\delta_S + \varphi_{PQ})$$

$$\bar{V}_{SE} = \bar{V}_{PQ} + jX_{SE}\bar{I}_{Line}$$

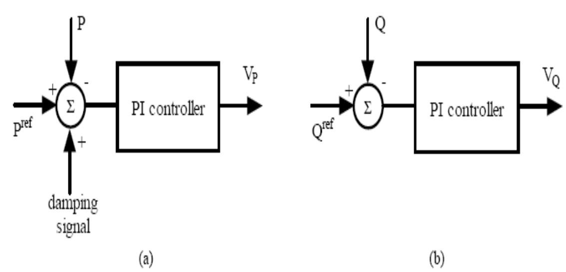

Fig. 7 Series control scheme-automatic power flow mode

From series converter amplitude modulation index and the firing angle can be computed as

$$m_{SE} = \frac{2\sqrt{2}n_{SE}V_{SE}V_B}{V_{DC}}$$
$$\varphi_{SE} = \delta_S - \delta_{SE}$$

5.3 Shunt control scheme

This control scheme also has two loops that are designed to maintain the magnitude of the sending bus voltage and the DC link voltage at their pre-specified values. The magnitude of the injected shunt voltage (equation (3.3)) affects the reactive power flow in the shunt branch, which in turn affects the sending bus voltage magnitude. The angle between the sending bus voltage and the injected shunt voltage, ϕSH (equation (3.4)), affects the real power flow in the shunt brunch. It can be used to control the power flow to the DC link and therefore the DC link voltage. This is achieved by using two separate PI controllers as shown in Fig. 8. [21], [22].

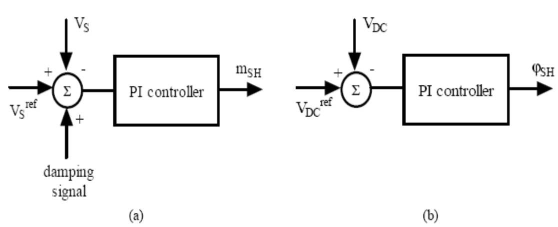

Fig. 8 Shunt control scheme

6. CONCLUSION

This thesis deals with the FACTS device known as the Unified Power Flow Controller that is used to maintain and improve power system operation and stability. It presents UPFC steady-state, dynamic and linearized models, algorithm for interfacing the UPFC with the power network and UPFC basic and damping controller design. To demonstrate various advantages of having the UPFC in the power system two-area four- generator test system was simulated using the Power System Toolbox (PST). Since PST does not come with the UPFC included the software was modified in order to incorporate the proposed tools. The main advantage of the PST over other simulation packages is that its open frame allows new device models to be included simply by inserting a few new functions within the existing steady-state, transient stability and small signal analysis programs. Further on, conventional as well as intelligent control schemes can be applied easily. The trade off is the simulation time. The simulation time is function of the number of the time steps. Adding the new devices and increasing the system size increases the simulation time leading to the quite time consuming simulations. To start the simulation MATLAB script file s_simu is called. It allows user to select the data file and the load flow (LF) analysis is performed. The convergence of the proposed LF algorithm depends on the convergence of the existing conventional LF algorithm and the initial guess for the real power injected into the sending bus. During the iterative procedure the real power injected into sending bus is adjusted in each step in order to cover the losses of the shunt and series impedances and to force the sum of converters' interaction to become zero. When transformer’s losses are included convergence is usually obtained with the third LF solution. Neglecting the transformer’s losses convergence is found within the first step. Once the LF solution is found the non-linear simulation is performed. The simulation results demonstrate the validity of the proposed fundamental frequency model and the UPFC network-interfacing algorithm. In order to operate the UPFC in the automatic control mode and to use the UPFC to damp low frequency oscillations two control designs: the UPFC basic control design and the damping controller design were performed. It has been shown that the UPFC with its basic controllers is capable of controlling independently real and reactive power flow through the transmission line both in steady state and dynamic conditions. This feature cannot be accomplished with the mechanical and other FACTS devices. It has also been shown that UPFC can be used for voltage support and for improvement of transient stability of the entire electric power through a supplementary control loop. The proposed supplementary control based on the fuzzy logic is effective in damping power oscillations. The controller is decentralized since it requires only local measurement – the tie-line power flow at the UPFC location. Simulation results have shown that controller exhibits good damping characteristics for different operating conditions and compared to the conventional controller shows superior performance.

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