

01 Jan 2002

A New Control Strategy for the Unified Power Flow Controller

Lin Zhang

Liangying Dong

Mariesa Crow

Missouri University of Science and Technology, crow@mst.edu

Follow this and additional works at: https://scholarsmine.mst.edu/ele_comeng_facwork



Part of the [Electrical and Computer Engineering Commons](#)

Recommended Citation

L. Zhang et al., "A New Control Strategy for the Unified Power Flow Controller," *Proceedings of the IEEE Power Engineering Society Winter Meeting, 2002 (2002, New York, NY)*, vol. 1, pp. 562-566, Institute of Electrical and Electronics Engineers (IEEE), Jan 2002.

The definitive version is available at <https://doi.org/10.1109/PESW.2002.985065>

This Article - Conference proceedings is brought to you for free and open access by Scholars' Mine. It has been accepted for inclusion in Electrical and Computer Engineering Faculty Research & Creative Works by an authorized administrator of Scholars' Mine. This work is protected by U. S. Copyright Law. Unauthorized use including reproduction for redistribution requires the permission of the copyright holder. For more information, please contact scholarsmine@mst.edu.

A New Control Strategy for the Unified Power Flow Controller

L. Y. Dong L. Zhang M. L. Crow
 Department of Electrical and Computer Engineering
 University of Missouri-Rolla
 Rolla, MO 65409-0040

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.

Keywords: FACTS, UPFC, Power flow control, System Oscillation Damping.

1 Introduction

The promising concept of the Flexible AC Transmission System (FACTS) makes it possible to achieve fast and reliable power system control by means of power electronic devices. The Unified Power Flow Controller (UPFC), which is the most versatile FACS device, has the capabilities of controlling power flow in the transmission line, improving the transient stability, mitigating system oscillations and providing voltage support [1][2][5]. It can control all three basic power transfer parameters (line impedance, voltage magnitude and phase angle) independently or simultaneously in any appropriate combinations. Previous efforts have focused mainly on controlling system steady state power flows and improving system stability. This paper will present the dynamic control of the UPFC.

Firstly, a dynamic model of the UPFC is derived based on the synchronous dq-frame in this article. Secondly, the PI based control strategy for the shunt part and the series part of UPFC are described respectively in the same synchronous frame and used to provide real and reactive power flow control along the transmission line at its series output end, while regulating the magnitude of the voltage at its shunt input end and maintaining the DC-link capacitor voltage constant. Finally digital simulation results obtained from two power systems are presented to illustrate the contributions of the new control approach.

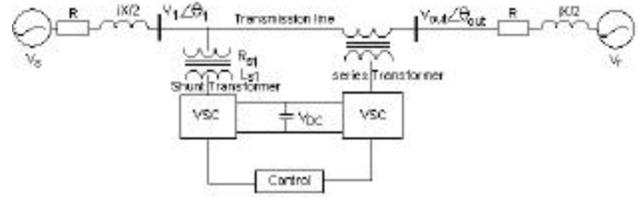


Fig. 1 Connection of a UPFC to a simplified two-bus system

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:

$$\frac{d}{dt} \begin{bmatrix} i_{pd} \\ i_{pq} \end{bmatrix} = \begin{bmatrix} -\frac{R_{s1}w_s}{L_{s1}} & w \\ -w & -\frac{R_{s1}w_s}{L_{s1}} \end{bmatrix} \begin{bmatrix} i_{pd} \\ i_{pq} \end{bmatrix} + \frac{w_s}{L_{s1}} \begin{bmatrix} E_{pd} - |V_1| \\ E_{pq} \end{bmatrix} \quad (1)$$

$$\frac{d}{dt} \begin{bmatrix} i_{ld} \\ i_{lq} \end{bmatrix} = \begin{bmatrix} -\frac{R_{s2}w_s}{L_{s2}} & w \\ -w & -\frac{R_{s2}w_s}{L_{s2}} \end{bmatrix} \begin{bmatrix} i_{ld} \\ i_{lq} \end{bmatrix} + \frac{w_s}{L_{s2}} \begin{bmatrix} E_d + |V_1| - V_{rd} \\ E_q - V_{rq} \end{bmatrix} \quad (2)$$

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 inverter and 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 and the power on the DC side of the inverters should be the same. The DC-link circuit can be derived as:

$$C \frac{dV_{dc}}{dt} = -\frac{1}{V_{dc}} (E_{pd}i_{pd} + E_{pq}i_{pq} + E_d i_{ld} + E_q i_{lq}) - \frac{V_{dc}}{R_{dc}} \quad (3)$$

where R_{dc} represents the inverter harmonics losses.

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

$E_{pd} = K_p * V_{dc} \cos \alpha_p$ and $E_{pq} = K_p * V_{dc} \sin \alpha_p$. Similarly the series injected voltage component E_d and E_q can be described as:

$$E_d = K_2 * V_{dc} \cos \alpha_2, \quad E_q = K_2 * V_{dc} \sin \alpha_2.$$

where K_1 and K_2 are the modulation index of the inverter, and α_1 and α_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:

$$i_{pq} = -\frac{w_s}{wL_{s1}} (E_{pd} - |V_1|)$$

$$i_{pd} = \frac{w_s E_{pq}}{wL_{s1}}$$

Thus reactive power supply and shunt input voltage can be regulated by active voltage component E_{pd} and the reactive voltage component E_{pq} can be regulated to achieve the DC-link capacitor voltage support. Fig 2. shows a block diagram of the shunt inverter and DC voltage control system. The output of the PI controllers are phase shift α_1 and modulation index K_1 .

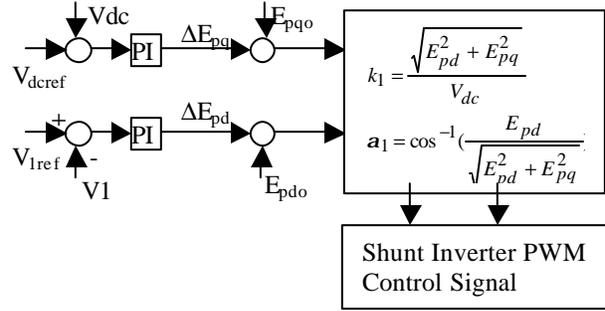


Fig. 2 Shunt inverter and DC voltage control

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:

$$P_{inj} = \frac{V(E_q - E_d \cos \mathbf{d} + E_d \sin \mathbf{d})}{X} \quad (4)$$

$$Q_{inj} = \frac{VE_d \cos \mathbf{d} + VE_q \sin \mathbf{d} - VE_d + E_d^2 + E_q^2}{X}$$

$$P_{out} = \frac{V^2 \sin \mathbf{d} + VE_q}{X}$$

$$Q_{out} = \frac{2VE_d \cos \mathbf{d} + 2VE_q \sin \mathbf{d} + E_d^2 + E_q^2}{2X} \quad (5)$$

where

$$V_{inj} = \sqrt{E_d^2 + E_q^2} \quad E_q = V_{inj} \sin(\mathbf{q}_{inj}) \quad E_d = V_{inj} \cos(\mathbf{q}_{inj})$$

Equation (5) shows that P_{out} is mainly affected by E_q , whereas Q_{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 ΔE_q and ΔE_d :

$$\begin{aligned}\Delta P_{out} &= \frac{V}{X} \Delta E_q \\ \Delta Q_{out} &= \frac{1}{X} (V \cos d \Delta E_d + V \sin d \Delta E_q + E_{d0} \Delta E_d + E_{q0} \Delta E_q)\end{aligned}\quad (6)$$

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

$$\Delta Q_{out} \approx \frac{1}{X} (V \Delta E_d + E_{d0} \Delta E_d + E_{q0} \Delta E_q) \quad (7)$$

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

$$\Delta Q_{out}' = \Delta Q_{out} - \frac{E_{q0}}{X} \Delta E_q = \Delta Q_{out} - \frac{E_{q0}}{V} \Delta P_{out} \quad (8)$$

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:

$$\begin{aligned}\Delta E_q &= K_{1P} \Delta P_{out} + K_{2P} \int_0^t \Delta P_{out}(i) di \\ \Delta E_d &= K_{2Q} \Delta Q_{out}' + K_{2P} \int_0^t \Delta Q_{out}'(i) di\end{aligned}$$

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

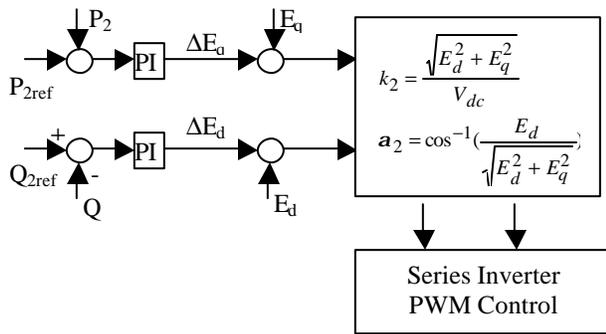


Fig. 3 PQ decoupled series inverter controller

3.2.2 Series Current Controller

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

$$P_{out} = V_{outa} \cdot i_{la} + V_{outb} \cdot i_{lb} + V_{outc} \cdot i_{lc}$$

Using the Park's transformation, P_{out} can be rewritten in terms of ds and qs quantities as follows:

$$P_{out} = \frac{3}{2} (V_{outd} \cdot i_{ld} + V_{outq} \cdot i_{lq}) \quad (9)$$

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

$$Q_{out} = \frac{3}{2} (V_{outq} \cdot i_{ld} - V_{outd} \cdot i_{lq}) \quad (10)$$

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.

$$i_{ld} = \frac{2}{3} \frac{P_{out} V_{outd} + Q_{out} V_{outq}}{V_{outd}^2 + V_{outq}^2}; \quad i_{lq} = \frac{2}{3} \frac{P_{out} V_{outq} - Q_{out} V_{outd}}{V_{outd}^2 + V_{outq}^2}$$

where $V_{outd} = |V_1| + E_d$, $V_{outq} = E_q$.

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 $R_{s2} \ll L_{s2}$, we can rewrite the eqn. (2) in the steady state:

$$\begin{aligned}i_{ld} &= w_s (E_q - V_{rq}) / (w L_{s2}) \\ i_{lq} &= -w_s (|V_1| + E_d - V_{rd}) / (w L_{s2})\end{aligned}$$

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.

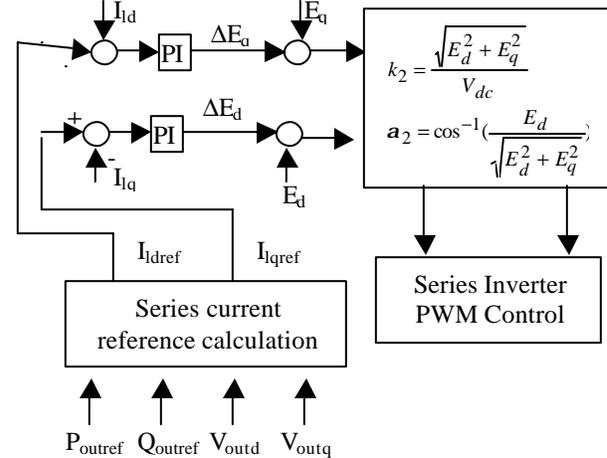


Fig. 4 Series Current control of UPFC

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: $L = 0.016H$, $R = 0.25 \Omega$, $C = 940\mu F$, $R_{s1} = 0.6267$, $L_{s1} = 0.00147H$. 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.

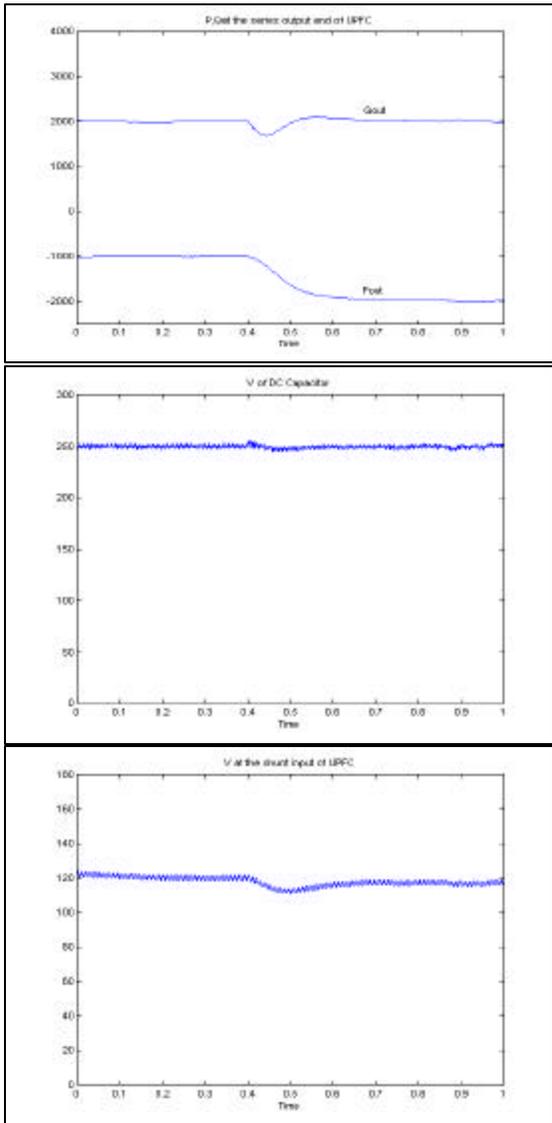


Fig. 5 UPFC response to a step change in active power

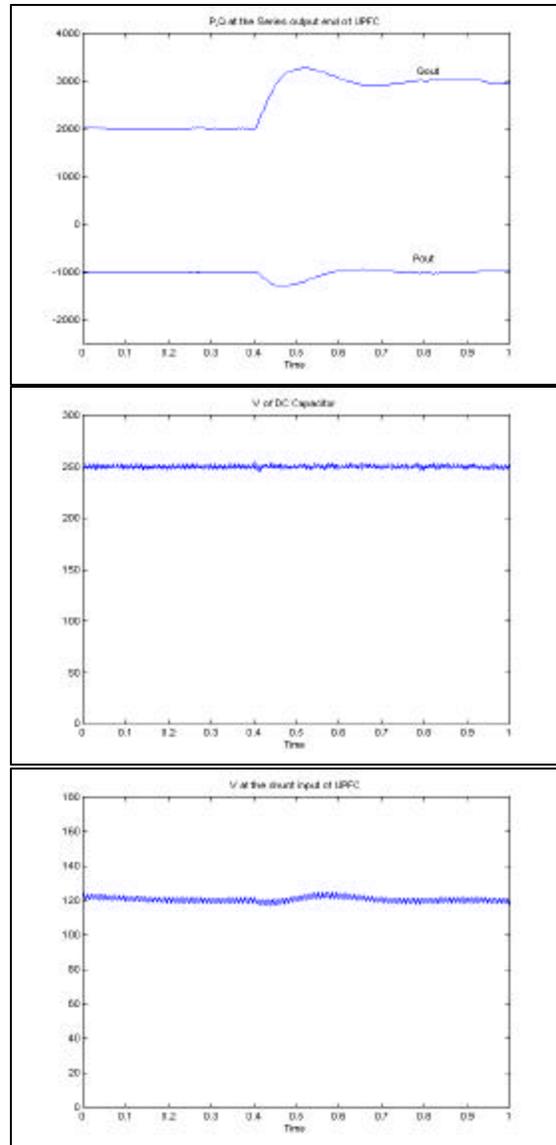


Fig. 6 UPFC response to a step change in reactive power

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 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.

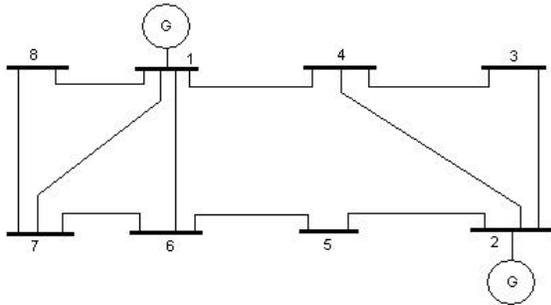


Fig. 7 2-Generator 11-bus System

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.

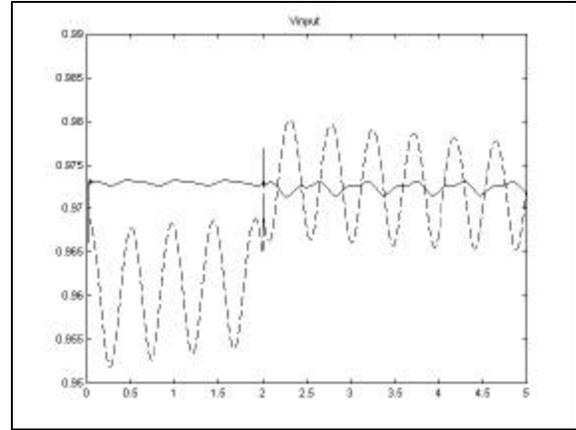
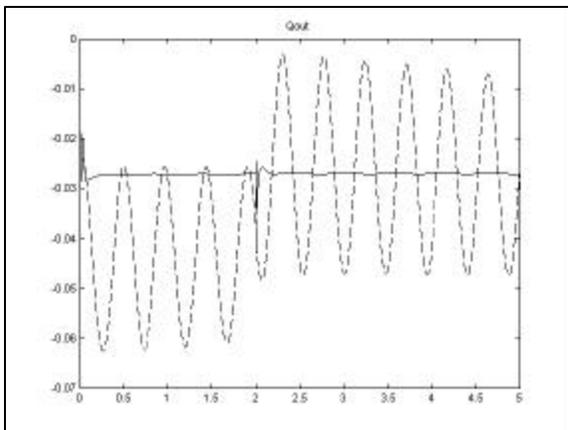
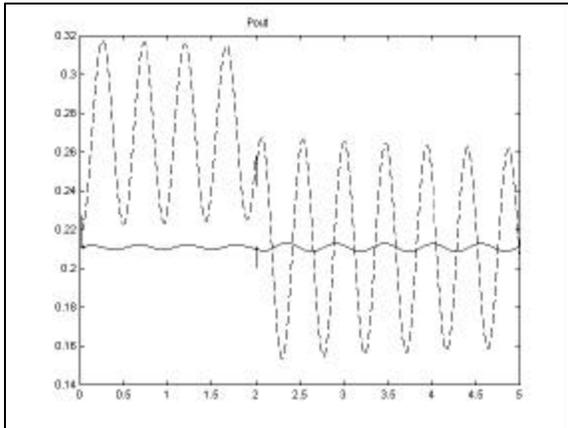


Fig. 8 Oscillation damping control result Without Control-Dash Line, With Control-Solid Line

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

- [1] Gyugyi L., Schauder C. D., Williams S. L., Rietman T. R., Torgerson D. R., Edris A, "The Unified Power Flow Controller: A new approach to power transmission control", IEEE Trans. Power Delivery, Vol. 10, No.2, April 1995, pp. 1085-1093.
- [2] Gyugyi L. "Unified Power Flow concept for Flexible AC Transmission Systems" IEE Proc-C, Vol. 139, No.4, July 1992, pp. 323-333.
- [3] Schauder, C., and Mehta, H., "Vector analysis and control of advanced static Var compensators", IEE Proc-C, 1993, pp299-306.
- [4] Lombard, X., and Therond, P. G., " Control of Unified Power Flow Controller: comparison of methods on the basis of a detailed numerical model", IEEE/PES Summer Meeting, Denver, Colorado, July 28-August 1,1996.
- [5] Sedraui K., Olivier G., AL-Haddad K., Chandra A., "Versatile Control Strategy of the Unified Power Flow Controller" IEEE CCECE 2000, vol. 1, May 2000, pp142-147.
- [6] T. Makombe and N. Jenkins, "Investigation of a unified power flow controller", IEE Proc.-Gener. Transm. Distrib., Vol. 146, No. 4, July 1999, pp 400-408.