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THE IMPACT OF UNIFIED POWER FLOW CONTROLLER IN POWER FLOW REGULATION

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Abstract—*The application of a global control based on the combination of the voltage, active and reactive power to investigate and fully understand the control capabilities and the impact of the UPFC in power flow regulation is presented. The models are presented and analysed in details in this paper. The effectiveness and convergence of the method proposed is tested on the 30 bus IEEE system. The results prove that the application of UPFC in electric power system is intended for the control of power flow, improvement of stability, voltage profile management, power factor correction, and loss minimisation.*

Key Words**:** *Power Flow, FACTS, SVC, TCSC, UPFC, Newton-Raphson, Reactive Power Compensation*

1. INTRODUCTION

Better, faster, cheaper and more reliable utilization of electrical energy is an important subject that electric power companies are concerned about. Harmonics and reactive power flowing to the supply system, transients caused by switching or faults, and other problems cause less reliable electrical supply systems. In order to cope with these kind of problems and increase usable power transmission capacity, FACTS (Flexible AC transmission systems) where developed and introduced to the market. FACTS philosophy was first introduced by N.G.Hingorani [1] from the Electric power research institute (EPRI) in the USA in 1988, although the power electronic controlled devices had been used in the transmission network for many years before that. The objective of FACTS devices is to bring a system under control and to transmit power as ordered by the control centers, it also allows increasing the usable transmission capacity to its thermal limits. With FACTS devices we can control the phase angle, the voltage magnitude at chosen buses and/or line impedances. Among a variety of FACTS controllers, UPFC is one of the more interesting and potentially the most versatile. It can provide simultaneous and independent control of important power system parameters: line active power flow, line reactive power flow, impedance and voltage [4]. The UPFC operation mode (terminal voltage Regulation, series compensation, phase shift, or any combinaison of them) can be changed from one state into another without hardware alterations to adapt to particular changing systems conditions. This feature makes it competent device. UPFC consists of two switching power converters connected to each other through a dc link capacitor as shown in Fig.1. The shunt inverter operates as a Static Synchronous Compensator (STATCOM) [5]. It compensates reactive power flow in the transmission line and keeps constant the dc voltage across the dc link capacitor. The series converter performs the function of the Static Synchronous Series Compensator (SSSC) by inserting a series voltage with variable magnitude and phase angle. By this inserted voltage, the active and reactive power flow in the transmission line can be regulated [7].

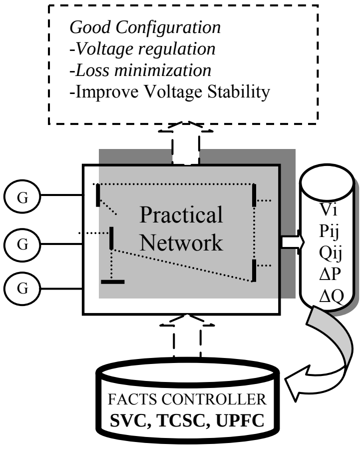

Fig. 1 FACTS implementation in a practical network

2. MODELING APPROACH OF UPFC

In this paper the configuration shown in Fig.2, is used to model the UPFC. This model has a wide range of applications for investigating the effect of UPFC on the system.

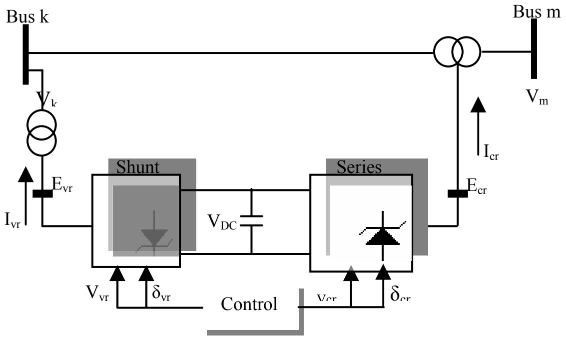

Fig. 2 Unified power flow controller (UPFC).

The UPFC may be seen to consist of two VSC sharing a common capacitor on their DC side and a unified control system. A simplified schematic representation of the UPFC is given in fig.2.The UPFC allows simultaneous control of active power flow, reactive power flow, and voltage magnitude at the UPFC terminals. Alternatively, the controller may be set to control one or of these parameters in any combination [2]. The active power demanded by the series converter is drawn by the shunt converter from the AC Network and supplied to bus m through the DC link. The output voltage of the series converter is added to the nodal voltage, at say bus k, to boost the nodal voltage at bus m. The voltage magnitude of the output voltage V_{cr} provides voltage regulation, and the phase angle δ_{cr} determines the mode of power flow control [2]. The UPFC voltage sources are:

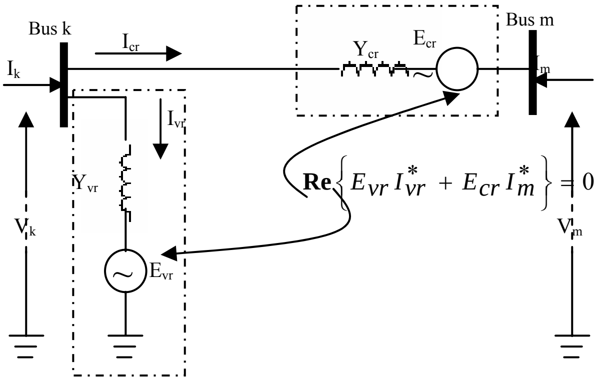

Fig. 3 Equivalent circuit based on solid-state voltages sources.

$$E_{vr} = V_{vr}\left(\cos(\delta_{vr}) + j\sin(\delta_{vr})\right) \tag{1}$$

$$E_{cr} = V_{cr}\left(\cos(\delta_{cr}) + j\sin(\delta_{cr})\right) \tag{2}$$

Where V_{vr} and V_{cr} are the controllable magnitude $V_{vr\min} \le V_{vr} \le V_{vr\max}$, and phase angle $0 \le \delta_{vr} \le 2\pi$ of the voltage source representing the shunt converter. The magnitude V_{cr} and phase angle δ_{cr} of the voltage source representing the series converter are controlled between limits: $V_{cr\min} \le V_{cr} \le V_{cr\max}$, and $0 \le \delta_{cr} \le 2\pi$.

3. BASIC RELATIONSHIP FOR POWER FLOW CONTROL

Fig.4 Shows single line diagram of a simple transmission line, modelized by inductive reactance X, connecting a sending-end voltage V_A to a receiving-end voltage V_B.

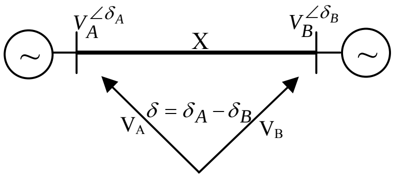

Fig. 4 Line diagram

Assuming the voltage magnitude of V_A and V_B are equal to V, the active and reactive power flow between two nodes A and B are given by the following expressions.

$$P_{AB} = \frac{V^2}{X}\sin\delta \tag{3}$$

And

$$Q_{AB} = \frac{V^2}{X}(1-\cos\delta) \tag{4}$$

The control of power flow can be performed by the following methods:

A- Line voltage control

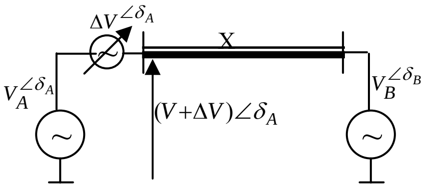

Fig. 5 Line Voltage control diagram

Fig.5 shows a single line diagram of a simple transmission line in which a voltage source is inserted. This source injects a voltage in phase with the sending voltage so as to regulate only the amplitude of the line voltage, $V_{ser} = \Delta V_A$. Active and reactive power transit becomes:

$$P_{AB} = (1+K_{sh})\frac{V^2}{X}\sin\delta \tag{5}$$

and

$$Q_{AB} = \frac{V^2}{X}(1+K_{sh})(1+K_{sh}-\cos\delta) \tag{6}$$

with $K_{sh} = \frac{\Delta V}{V}$

This approach has for main drawback to be limited by the injected voltage in series with the line.

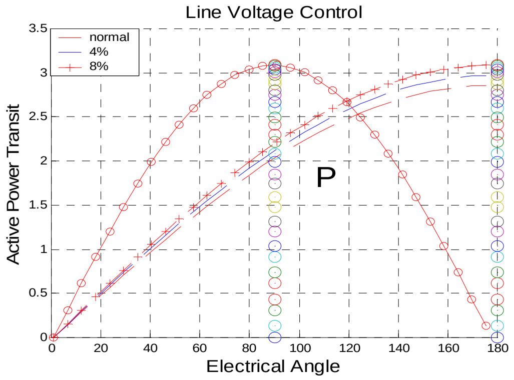

Fig. 6 Active Power with line voltage control

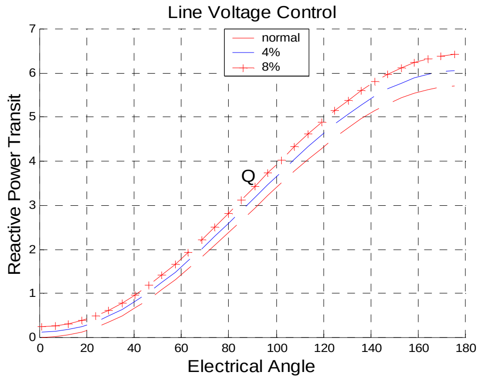

Fig. 7 Reactive power with line voltage control

B. Line impedance control:

This method has for basic principle to insert a series voltage on the line. Fig.8

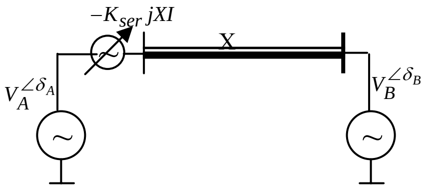

Fig. 8 Line impedance control

The total reactance of the line becomes, and the line power transit can be controlled as given bellow.

$$X_{line} = X - Xc = X(1 - K_{ser}) \qquad (7)$$

$$P_{AB} = \frac{V^2}{X(1-K_{ser})}\sin\delta \qquad (8)$$

$$Q_{AB} = \frac{V^2}{X}(1-\cos\delta)\frac{(1+K_{ser})}{(1-K_{ser})^2} \qquad (9)$$

with $-1 < K_{ser} < 1$

The variation of the line power transit as a function of the coefficient K_{ser} is presented in fig.9.

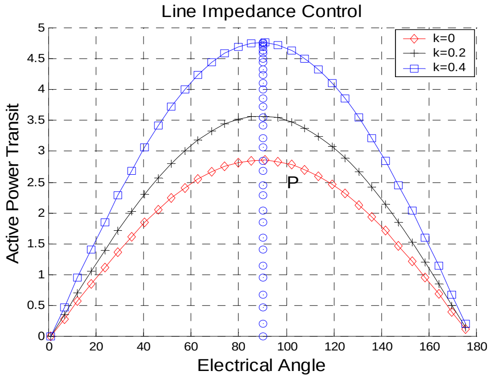

Fig. 9 Active power with line impedance control

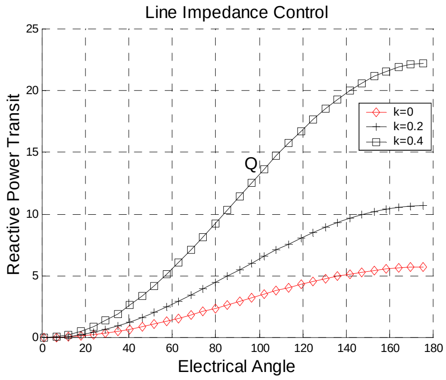

Fig. 10 Reactive power with line impedance control

C. Line impedance control:

This third method consists in the control of the electrical angle by inserting a voltage in series with the line.

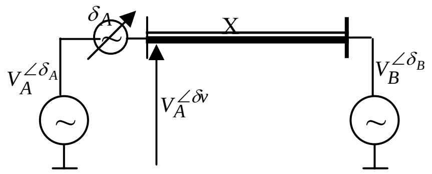

Fig. 11 Electrical angle control

In this case, the active and reactive power transferred between A and B becomes:

$$P_{AB} = \frac{V^2}{X}\sin(\delta+\alpha) \qquad (10)$$

$$Q_{AB} = \frac{V^2}{X}(1-\cos(\delta+\alpha)) \qquad (11)$$

Fig.12 shows the effect of two inserted angles α (α =15° and 30°).

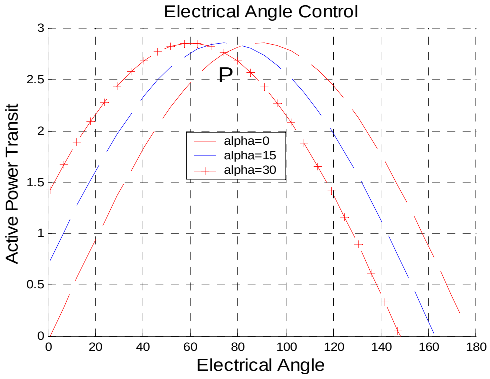

Fig. 12 Active power with line electrical angle Control

4. IMPLEMENTING UPFC IN THE POWER FLOW PROBLEM

The purpose of a power system is to deliver the required power to the customers, within acceptable voltage and frequency limits and in a reliable and economic manner. Power flow is an important issue in system planning and operation, and it is the most common of power system computer calculations. In this analysis, the transmission system is modelled by a set of buses or nodes interconnected by transmission links. Generators and loads connected to various nodes of the system inject and absorb power from the transmission system. The model considered in power flow studies is appropriate for finding the steady-state powers and voltages of the transmission system [5]. A unified approach combines the state variables describing controllable equipment (FACTS) with those describing the network in a single frame of reference for unified, iterative solutions using the Newton-Raphson algorithm.

$$\begin{aligned} f(X_{nAC}, R_{nF}) &= 0 \\ g(X_{nAC}, R_{nF}) &= 0 \end{aligned} \tag{12}$$

Where X_{nAC} stands for the AC network state variables, namely, nodal voltage magnitude and phase angles, and RnF stands for the power system controller state variables. The structure of the modified Jacobian is shown in Fig. 13.

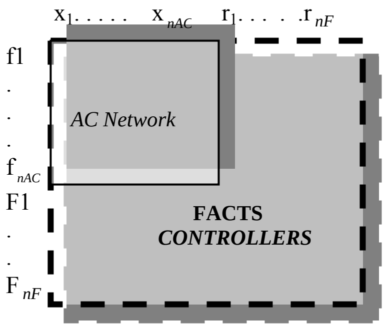

Fig. 13 : Modified Jacobian

General nodal power flow equations and the linearized power system model can be expressed in rectangular form by the following equations:

$$\begin{aligned} P &= f_1(V, \theta, G, B) \\ Q &= f_2(V, \theta, G, B) \end{aligned} \tag{13}$$

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix}^i = \begin{bmatrix} H & N \\ J & K \end{bmatrix}^i \begin{bmatrix} \Delta\theta \\ \Delta V/V \end{bmatrix}^i \tag{14}$$

Where P and Q are vectors of real and reactive nodal power injections, which are function of nodal voltages,

($V\angle\theta$), and network conductances and susceptances, (G and B), respectively. ($\Delta P = P_{spe} - P_{cal}$) is the real power mismatch vector and ($\Delta Q = Q_{spe} - Q_{cal}$) is the reactive power mismatch vector. (ΔV and $\Delta\theta$) are vectors of incremental changes in nodal voltages. H, N, J and L denote the basic elements in the Jacobian matrix.

A. Power Flow Model

Based on the equivalent circuit shown in fig.3, the active and reactive power equations are:

At bus k:

$$\begin{aligned} P_k &= V_k^2 G_{kk} + V_k V_m\left[G_{km}\cos(\theta_k - \theta_m) + B_{km}\sin(\theta_k - \theta_m)\right] \\ &+ V_k V_{cr}\left[G_{km}\cos(\theta_k - \delta_{cr}) + B_{km}\sin(\theta_k - \delta_{cr})\right] \\ &+ V_k V_{vr}\left[G_{vr}\cos(\theta_k - \delta_{vr}) + B_{vr}\sin(\theta_k - \delta_{vr})\right] \end{aligned} \tag{15}$$

$$\begin{aligned} Q_k &= -V_k^2 B_{kk} + V_k V_m\left[G_{km}\sin(\theta_k - \theta_m) - B_{km}\cos(\theta_k - \theta_m)\right] \\ &+ V_k V_{cr}\left[G_{km}\sin(\theta_k - \delta_{cr}) - B_{km}\cos(\theta_k - \delta_{cr})\right] \\ &+ V_k V_{vr}\left[G_{vr}\sin(\theta_k - \delta_{vr}) - B_{vr}\sin(\theta_k - \delta_{vr})\right] \end{aligned} \tag{16}$$

At bus m:

$$\begin{aligned} P_m &= V_m^2 G_{mm} + V_m V_k\left[G_{mk}\cos(\theta_m - \theta_k) + B_{mk}\sin(\theta_m - \theta_k)\right] \\ &+ V_m V_{cr}\left[G_{mm}\cos(\theta_m - \delta_{cr}) + B_{mm}\sin(\theta_m - \delta_{cr})\right] \end{aligned} \tag{17}$$

$$\begin{aligned} Q_m &= -V_m^2 B_{mm} + V_m V_k\left[G_{mk}\sin(\theta_m - \theta_k) - B_{mk}\cos(\theta_m - \theta_k)\right] \\ &+ V_m V_{cr}\left[G_{mm}\sin(\theta_m - \delta_{cr}) - B_{mm}\cos(\theta_m - \delta_{cr})\right] \end{aligned} \tag{18}$$

-Series converter:

$$\begin{aligned} P_{cr} &= V_{cr}^2 g_{mm} + V_{cr} V_k\left[g_{km}\cos(\delta_{cr} - \theta_k) + B_{km}\sin(\delta_{cr} - \theta_k)\right] \\ &+ V_{cr} V_m\left[g_{mm}\cos(\delta_{cr} - \theta_m) + B_{mm}\sin(\delta_{cr} - \theta_m)\right] \end{aligned} \tag{19}$$

$$\begin{aligned} Q_{cr} &= -V_{cr}^2 B_{mm} + V_{cr} V_k\left[g_{km}\sin(\delta_{cr} - \theta_k) - B_{km}\cos(\delta_{cr} - \theta_k)\right] \\ &+ V_{cr} V_m\left[g_{mm}\sin(\delta_{cr} - \theta_m) - B_{mm}\cos(\delta_{cr} - \theta_m)\right] \end{aligned} \tag{20}$$

-Shunt converter:

$$P_{vr} = -V_{vr}^2 g_{vr} + V_{vr} V_k\left[g_{vr}\cos(\delta_{vr} - \theta_k) + B_{vr}\sin(\delta_{vr} - \theta_k)\right] \tag{21}$$

$$Q_{vr} = V_{vr}^2 B_{vr} + V_{vr} V_k\left[g_{vr}\sin(\delta_{vr} - \theta_k) - B_{vr}\cos(\delta_{vr} - \theta_k)\right] \tag{22}$$

And assuming loss-less converter: $P_{vr} + P_{cr} = 0$

B. CONTROL STRATEGY FOR THE UPFC

Consider again the generalized power flow controller shown in Fig.14, Assume that the voltage source (V_{pq}) in series with the line can be controlled without restrictions. That is, the phase angle of phasor V_{pq} can be chosen independently of the line current between 0 and 2π, and its magnitude is variable between zero at a defined maximum value, $V_{pq\max}$. This implies that voltage source V_{pq} must be able to generate and absorb both real and reactive power. The reactive current source I_q is assumed to be either capacitive or inductive with a variable magnitude that is dependent of the terminal voltage.

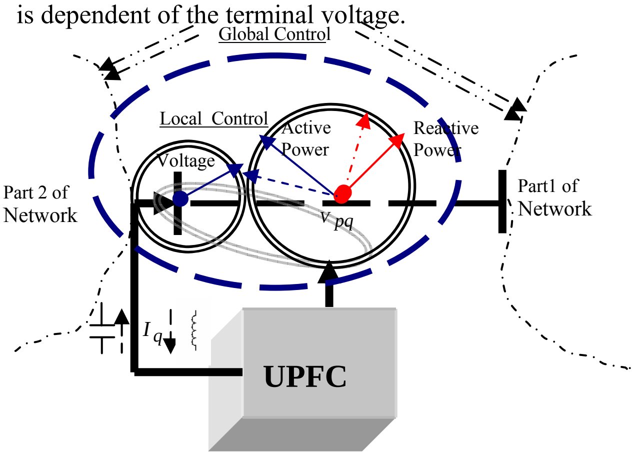

Fig. 14 Control strategy for the UPFC

In order to show the capabilities of the UPFC model and the performance of the proposed algorithm, two test cases have been investigated.

-Case A: Voltage and Active power Control

The UPFC device is positioned on line L34, between bus.3 and bus.4, Line L34 is the controlled line. Effects of UPFC parameters such as; real and reactive power flows on line L34, overall total real and reactive transmission losses of the system are investigated. When a UPFC parameter is controlled, another is kept constant (Local Control), but when all parameters of UPFC are controlled together, voltage, active power and reactive power, this control strategy called a global control.

Table.1 Voltage and active power control

UPFC in Line 3-4	UPFC Parameters with $Q_{ij}reg = 0.02$ p.u			V_{reg} =1 p.u at bus 3		
$P_{ij}reg$ p.u	V_{se} p.u	V_{sh} p.u	δ_{se} p.u	ΔP_t p.u	$V_{\min}$ p.u	It
0.5	0.0672	1.0061	-4.9107	0.1965	0.9471	13
0.6	0.0317	1.005	-6.0093	0.1885	0.9476	13
0.7	0.0444	1.0031	-7.1195	0.1829	0.9479	13
0.8	0.0862	1.0005	-8.2442	0.1796	0.9483	13
0.9	0.1319	0.9972	-9.3862	**0.1786**	**0.9486**	13
1	-0.1786	0.9932	-10.5485	0.1800	0.9489	13
UPFC in Line 4-6	UPFC Parameters with $Q_{ij}reg = 0.02$ p.u			V_{reg} =1 p.u at bus 6		
$P_{ij}reg$ p.u	V_{se} p.u	V_{sh} p.u	δ_{se} p.u	ΔP_t p.u	$V_{\min}$ p.u	It
0.15	0.0157	1.0020	-11.2543	**0.1831**	**0.9394**	13
0.20	0.0576	1.0013	-11.2656	0.1833	0.9386	13
0.25	0.1013	1.0001	-11.2765	0.1837	0.9376	13
0.30	0.1458	0.9985	-11.2869	0.1842	0.9365	13

Table.1 shows the effect of this type of control. Voltage magnitude at bus 3 is set to 1p.u, with $Q_{ij}reg$ =0.02 p.u and by controlling power flow $P_{ij}reg$ at a value 0.9 p.u, the power loss is reduced to 0.1786 p.u and the voltage magnitude incremented to 0.9486. With the same control, but if we choose another location to UPFC at line 4-6, by controlling power flow $P_{ij}reg$ at a value 0.15 p.u , V_{reg} =1 p.u at bus.6, the power loss become 0.1831 p.u witch is greater than the first case and the voltage magnitude is reduced to 0.9394 p.u.

Table.2 Voltage and reactive power control

UPFC in Line 3-4	UPFC Parameters with $P_{ij}reg = 0.7$ p.u			V_{reg} =1 p.u at bus 3		
$Q_{ij}reg$ p.u	V_{se} p.u	V_{sh} p.u	δ_{se} p.u	ΔP_t p.u	$V_{\min}$ p.u	It
0.02	0.0444	1.0031	-7.119	0.1829	0.9479	10
0.04	0.0463	1.0051	-7.129	0.1828	0.9482	10
0.1	0.0532	1.0110	-7.159	0.1828	0.9490	10
0.2	0.0666	1.0207	-7.209	0.1831	0.9504	10
0.6	0.1286	1.0581	-7.416	0.1891	0.9556	10
0.8	-0.1602	1.0761	-7.525	0.1947	0.9581	10
UPFC in Line 4-6	UPFC Parameters with $P_{ij}reg = 0.15$ p.u			V_{reg} =1 p.u at bus 6		
$Q_{ij}reg$ p.u	V_{se} p.u	V_{sh} p.u	δ_{se} p.u	ΔP_t p.u	$V_{\min}$ p.u	It
0.04	0.0136	1.004	-11.266	0.1828	0.9402	13
0.06	0.0244	1.006	-11.278	0.1826	0.9410	13
0.08	0.0381	1.0079	-11.290	0.1824	0.9418	13
0.1	0.0521	1.0097	-11.301	**0.1822**	**0.9425**	13

-Case B: Voltage and Reactive Power Control

The UPFC device is positioned on line L34, between bus.3 and bus.4, Line L34 is the controlled line. Table.2 shows the effect of this type of control. One of the UPFC parameter is kept constant $P_{ij}reg$ = 0.7 p.u and the two others parameters are controlled, V_{reg} =1, and $Q_{ij\,reg}$.

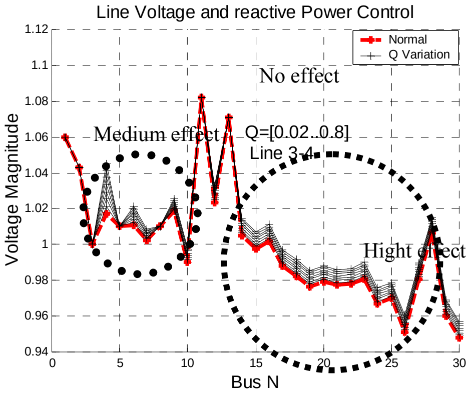

Fig. 15 Line Voltage and Reactive Power Control
At a fixed Active Power –Normal Condition-Line 3-4

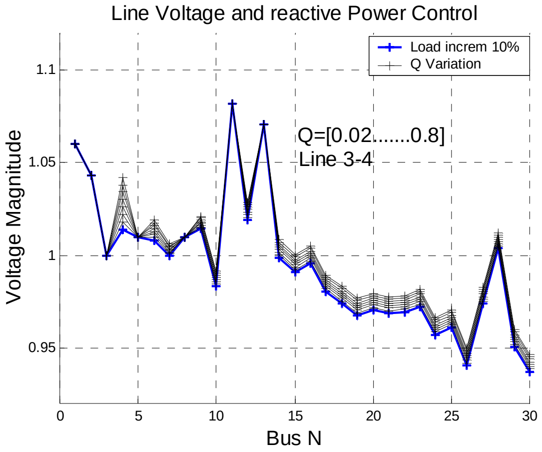

Fig. 16 Line Voltage and Reactive Power Control
At a fixed Active Power–load increment 10% -Line 3-4

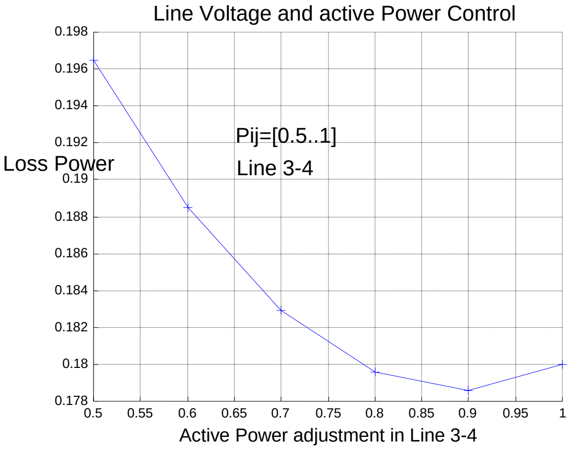

Fig. 17 Total Power losses With Line Voltage and active Power Control

With $Q_{ij}reg$ =0.1 p.u the power become 0.1828 p.u witch is greater than the first case (Case A) and the voltage magnitude become 0.9494 p.u. With the same control, but if we choose another location to UPFC at line 4-6, by fixing power flow $P_{ij}reg$ at a value 0.15 p.u ,V_{reg} =1 p.u at bus 6, the power loss reduced to 0.1822 p.u , and the voltage magnitude become 0.9425 p.u.

4. GENERAL INTERPRETATION OF NUMERICAL RESULTS

Numerical results are given for tests carried out on the IEEE 30-bus system. In the tests a convergence tolerance of 10^{-12} p.u for maximal absolute bus power mismatches is utilized.

-Impact in voltage regulation

One of the UPFC parameter is kept constant $P_{ij}reg$ = 0.10 p.u and the two others parameters are controlled, V_{reg} =1 and $Q_{ij}reg$ is adjusted from 0.02 to 0.4p.u.

Fig.(15-16-19-20) give results of line voltage and reactive power control at a fixed active power in normal and abnormal condition (Load increase 10%), to improve the effect of a global control, UPFC is installed in different lines, Line 3-4, Line 6-10 and Line 9-10. The voltage magnitude is highly affected by this type of control.

-Impact in total loss minimization

Fig. (17-18-21) give results of total power losses with line voltage active and reactive power Control in normal condition when UPFC installed in line 3-4

And line 9-10.

-We can conclude that the high performance of the index power quality require an optimal placement of UPFC in a network.

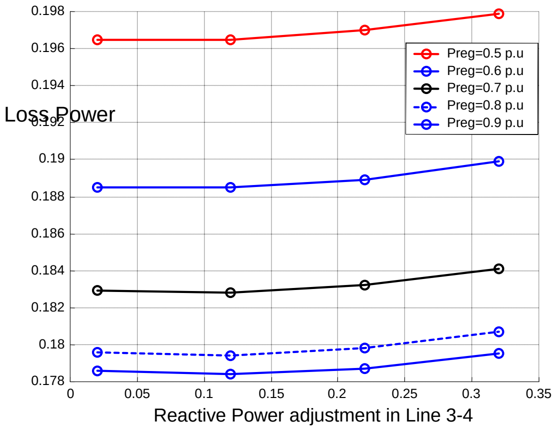

Fig. 18 Total Power losses With Line Voltage and reactive Power Control

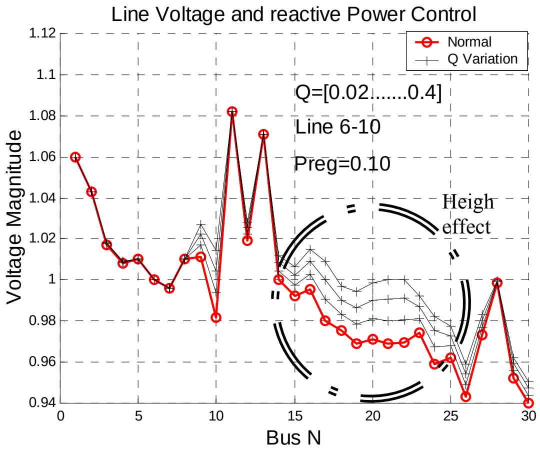

Fig. 19 Line Voltage and Reactive Power Control
at a fixed Active Power –Normal Condition-Line 6-10

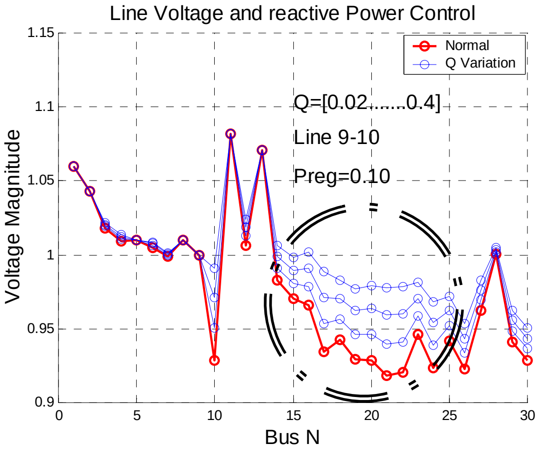

Fig. 20 Line Voltage and Reactive Power Control at a fixed Active Power–Normal Condition-Line 9-10

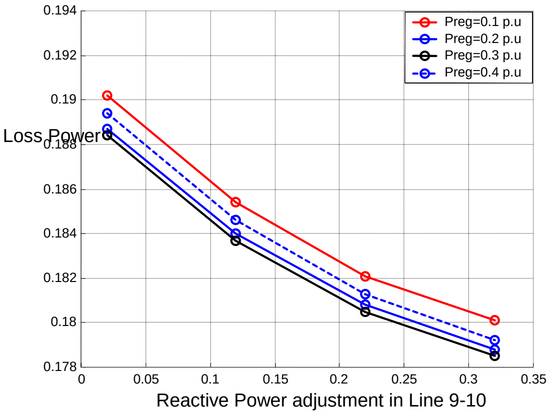

Fig. 21 Total Power loss With Line Voltage, active and reactive power control

5. CONCLUSION

Among the FACTS components, Unified Power flow controller (UPFC) is one of the most efficient. It possesses a great aptitude to achieve an independent and simultaneous control of both, voltage active and reactive power flow. A global control based on the combination of the voltage, active and reactive power are proposed to improve the effectiveness of the method proposed and the impact of the UPFC in power flow regulation and loss minimization. Numerical results on the IEEE 30-bus system with single UPFC have demonstrated the feasibility and effectiveness of the established control functional model of the UPFC and the proposed Newton power flow algorithm. We can conclude that the high performance of the index power quality require an optimal placement of UPFC in a network.

6. REFERENCES

[1] N.G. Hingorani, “High Power Electronics and Flexible AC Transmission System,” *IEEE Power Engineering review,* july 1988.

[2] Fuerte CR, Acha E, Tan SG , Rico JJ, “Efficient object oriented power systems software for the analysis of large-scale networks containing FACTS controlled branches,” *IEEE Trans. Power Systems,* vol. 13, no. 2, pp. 464-472, May 1998.

[3] A. J. F. Keri, X. Lombard, A. A. Edris, “ Unified power flow controller (UPFC): modeling and analysis,” *IEEE Trans. Power Delivery,* vol. 14, no. 2, pp. 648-654, April 1999.

[4] M. Noroozian, L. Ängquist, M. Ghandhari, G. Andersson, “ Use of UPFC for optimal power flow control,” *IEEE Trans. Power Delivery,* vol. 12, no. 4, pp. 1629-1634, October 1997.

[5] Kalyan K. Sen, Eric J.Stacey, “UPFC-Unified power flow controller: theory, modeling, and applications,” *IEEE Trans. Power Delivery,* vol. 13, no.4, pp. 1453-1460, October 1998.

[6] Xiao-Ping Zhang and Keith R Godfrey, “Advanced unified power flow controller model for power system steady state ontrol,” *IEEE International Conference on DRPT*, April 2004 Hong Kong.

[7] K. Belacheheb, S.Saadate, “Compensation of the electrical means of unified power flow controller (UPFC)-comparison of three control method,” *2000 IEEE*.

[8] L. Gyugyi, “Unified power-flow control concept for flexible AC transmission systems,” *IEE Proceedings-C*, vol. 139, no. 4, pp.323-331, July 1992.

[9] C. D. Schauder, L. Gyugyi, M.R. Lund, D. M. Hanni, T.R. Rietman, D.R. Torgerson, A. Edris, “ Operation of unified power flow controller (UPFC) under practical constraints,” *IEEE Trans. Power Delivery,* vol. 13, no. 2, pp. 630-637, April 1998.

[10] C.R.Feurt-Esquivel, E.Acha, “Unified power flow controller:A critical comparison of Newton-Raphson UPFC algorithms in power flow studies,” *IEE Proc-Gener. Transm. Distrib*, vol. 144, no. 5, pp. 437-444, september 1997.