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Application of Unified Power Flow Controller to Improve Steady State Voltage Limit

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ABSTRACT

This paper utilizes the voltage source model of Unified Power Flow Controller (UPFC) and examines its abilities in mitigating the steady state stability margins of electric power system. It analyzes its behavior for different controls strategies and proposes the most efficient mode of controlling the controller for voltage stability enhancement. A systematic analytical methodology based on the concept of modal analysis of the modified load flow equations is employed to identify the area in a power system which is most prone voltage instability. Also to identify the most effective point of placement for the UPFC, a computer program has been developed using MATLAB. The results of analysis on 14 bus system is presented here as a case study.

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1. INTRODUCTION

The problems related to voltage instability in power system are one of the major concerns in power system planning and operation. One of the causes of this increased concern is the load growth without corresponding increase in transmission capacity, due to which many power systems are brought closer to their voltage stability boundaries. Conventionally, the reactive power control was used to have control on steady state voltage and to minimize transmission loss thereby enhancing power system stability. But these conventional reactive power controllers were based on electro-mechanical mechanism, with inherent inertia thus preventing high speed control. These controllers therefore cannot provide operational flexibility and adaptability to the power system. The recently developed FACTS technology provides a way to relieve the stability problem imposed by increasing load demand. The application of FACTS devices to improve voltage stability margins in highly developed networks is well documented in [1]. The shunt as well as the series connected FACTS devices has been effectively used to provide voltage stabilization. The static voltage compensators have been used to provide voltage stabilization at critical system location [1], [2]. The FACTS devices like STATCOM, TCSC and SSSC can provide significant benefits, in terms of extended voltage stability and operational flexibility [3], [4].

Many analysis tools and techniques have been proposed in the literature for predicting voltage instability and collapse [5]-[9]. Among these techniques are conventional methods in which stability is determined by computing the V-P and Q-V curves at selected load buses. Generally such curves are generated by executing a large number of power flows using conventional models. These are time consuming and do not readily provide information useful in gaining insight into causes of stability problem [10]. N.Flatobo, R.Ognedal and T.Carlsen [5] describes the practical applications of an approach based on V-Q sensitivity. The problem with Q-V curve method is that it is generally not known a priori at which bus the curve is generated. Also in producing a Q-V curve the system in the neighborhood of the bus is unduly stressed and the result may be misleading. Minimum Singular value of the power flow Jacobian is a relative measure of the proximity of the system to the stability limit. But the method still does not indicate specific causes of voltage instability such as highly loaded transmission lines and generators reaching reactive limits [11].

A Modal analysis approach has the advantage that it provides the information regarding the mechanism of instability [12]. Among the shunt connected devices, analysis of SVC for voltage stability using modal analysis was done by Y.Mansour, Wilsun Xu, F.Alvarado and C.Rinzin [14]. Voltage stability margin enhancement by SVC and STATCOM was compared in [15] using Continuation power flow method. Study of STATCOM and UPFC Controllers for Voltage Stability is carried out using Continuation power flow based on Saddle-Node Bifurcation Analysis [3], [16] and [18]. Arthit sode-Yome [3] and R. Natesan, G. Radman [16] utilized the UWPFlow, a research tool, to calculate the loadable margins using PWM based steady state EMTP models. M.A. Perez et al [18] utilized UPFC model which is a modification of voltage source model and didn’t consider the operating limits of the UPFC.

The present work uses voltage source model of UPFC, [19] to examine the ability of UPFC in enhancing voltage stability, at its various operating modes. Modal analysis of the modified Jacobian matrix is used to identify critical bus prone to voltage instability. The advantage of this Model technique over other static analysis methods for voltage stability is that it provides both a relative proximity of the system to voltage instability, as well as the mechanism or key contributing factors to instability.

2. MODAL ANALYSIS

The Modal Analysis Technique [12] computes the eigen values and the associated eigen vectors of the reduced power system steady state Jacobian matrix which retains the Q-V relationship in the network. The participation factor for the minimum eigen value identifies the weakest buses. By using the reduced Jacobian matrix, the relationship between the incremental changes in bus reactive power can be examined.

The linearized steady state, power voltage equations are expressed as shown in equation (1):

$$\left[\frac{\Delta P}{\Delta Q}\right] = \begin{bmatrix} J_{p\theta} & J_{pv} \\ J_{q\theta} & J_{qv} \end{bmatrix} \left[\frac{\Delta \theta}{\Delta V}\right] \tag{1}$$

Where: ΔP=incremental change in bus real power
ΔQ=incremental change in bus reactive power
Δθ=incremental change in bus voltage angle
ΔV= incremental change in bus voltage magnitude

To express the relation between ΔQ and ΔV for a small change in real power, ΔP = 0 can be assumed, this yields as shown in equation (2).

$$\Delta Q = \left[J_{qV} - J_{q\theta} J_{P\theta}^{-1} J_{pV}\right]\Delta V \tag{2}$$

Rearrangement of equation (2) gives equation (3)

$$\Delta Q = J_R^{-1} \Delta Q \tag{3}$$

Where equation (4)

$$J_R = \left[J_{qV} - J_{q\theta} J_{P\theta}^{-1} J_{pV}\right] \tag{4}$$

J_R is the reduced Jacobian matrix of the system, relating the reactive power injections and the bus voltage magnitude. It can be represented as shown in equation (5).

$$J_R = \xi \lambda \eta \tag{5}$$

Where: η =left eigenvector of matrix of
ξ= right eigenvector of matrix of
λ = diagonal eigen value matrix of

Equation (5) and (3) yields in equations (6-7)

$$\Delta V = \xi\lambda^{-1}\eta\Delta Q \tag{6}$$

And

$$v = \Lambda^{-1}q \tag{7}$$

Where: $v = \eta\Delta V$, is the vector of modal voltage variations.
$q = \eta\Delta Q$, is the vector of modal reactive power variations

and $\xi = \eta$

The difference between equations (3) and (7) is that Λ^{-1} is a diagonal matrix whereas $J_R^{-1}$is non-diagonal. Equation (3) represents uncoupled first order equations [12]. Thus for the i[th] mode like as shown in equation (8).

$$v_i = \frac{1}{\lambda_i}\, q_i \tag{8}$$

The eigen values of the reduced Jacobian matrix identify different modes through which the system could become voltage unstable. The magnitudes of the eigen values provide a relative measure of the proximity to instability. The eigenvectors on the other hand, provide information related to the mechanism of loss of voltage stability. If $\lambda_i > 0$, the i[th] modal voltage and the ith modal reactive power variation are along the same direction, indicating that the system is voltage stable. If $\lambda_i < 0$, the i[th] modal voltage and the ith modal reactive power variation are along the opposite directions, indicating that the system is voltage unstable. In this sense, the magnitude of λ_i, determines the degree of stability of the ith modal voltage. The smaller the magnitude of positive λ_i, the closer the i[th] modal voltage is to being unstable. From equation (6), the stability of a mode i with respect to reactive power change is defined by the modal eigenvalue λ_i.

Large values of $\lambda_i$suggest small changes in the modal voltage for reactive power changes. As the system is stressed, the value of λ_i becomes smaller and the modal voltage becomes weaker. If the magnitude of λ_i is equal to zero, the corresponding modal voltage collapses since it undergoes infinite changes for reactive power changes. A system is therefore defined as voltage stable if all the eigenvalues of J_R are positive. The bifurcation or voltage stable limit is reached when at least one eigenvalue reaches zero; that is, one or more modal voltage collapses. If any of the eigenvalues are negative, the system is unstable. The magnitude of the eigenvalues provides a relative measure of the proximity of the system to instability. The critical modes (associated with minimum eigenvalues) are of major importance in the voltage stability analysis. The left and right eigenvectors corresponding to the critical modes in the system can provide information concerning the mechanism of voltage instability, by identifying the elements participating in these modes. The bus participation factor measuring the participation of the k[t]h and the i[th] mode can be given as shown in equation (9).

$$P_{ki} = \xi_{ki}\eta_{ki} \tag{9}$$

Bus participation factors corresponding to the critical modes can predict areas or nodes in the power system susceptible to voltage instability. Buses with large participation factors to the critical mode correspond to the most critical system buses[12].

3. OPERATING PRINCIPLE OF UPFC

Unified power flow controller is a combination of a Shunt and a series connected FACTS device capable of providing simultaneous control of series active and reactive power, between the two nodes. It can also provide reactive power compensation simultaneously to the sending end node to which it is attached. It has numerous operating constraints as well as modes of operation. Figure 1 shows the schematic diagram of UPFC connected between two nodes.

The shunt connected converter supplies real power to the dc link capacitor (to meet the demand of series connected converter) and provides shunt reactive compensation for the transmission line. The flow of real power in or out of the dc link capacitor is controlled by the real power exchange between the shunt converter and the ac power system. This real power exchange is governed by the phase angle between the inverter and the ac system voltages. By contrast, the reactive power exchange, resulting from the line compensation, is determined by the amplitude difference between the inverter and ac system voltages, If this difference is zero (the converter voltage has the same amplitude as the system voltage), then the reactive power exchange is also zero, if it is positive, then the converter generates reactive power for the ac system, and if it is negative, the converter absorbs reactive power from the ac system.

Series converter injects the desired ac voltage in series with the line for power flow control. In general, the phase angle of the injected voltage determines the mode of power flow control (transmission line voltage, impedance, or angle), and the amplitude defines to what extent it is applied. Thus, the amplitude of the output voltage generated by series converter must be controllable from zero to a maximum determined by the rating of the power flow controller. The real and reactive powers exchanged at the ac output of series converter are consequences of the voltage injection and are not directly controllable; the ratio between real and reactive power is determined strictly by the relative phase angle between the injected voltage and the line current. [20]

The UPFC can be represented as two ideal voltage sources in series to the transmission line and in shunt as shown in Figure 1 [3]. The losses of the coupling transformers are modeled as impedances in series with the voltage sources. The ideal voltage sources are put mathematically as shown in equation (10).

$$\begin{Bmatrix} V_{se} = V_{se}(cos\theta_{se} + jsin\theta_{se}) \\ V_{sh} = V_{sh}(cos\theta_{sh} + jsin\theta_{sh}) \end{Bmatrix} \tag{10}$$

Where V_{sh} and θ_{sh} are the controllable magnitude and angle of the ideal voltage source representing the shunt converter between the limits and $V_{shmin} \leq V_{sh} \leq V_{shmax}\ and\ 0 \leq \theta_{sh} \leq 2\pi$ respectively. Similarly V_{se} and θ_{se} are controllable magnitude and angle of the ideal voltage source representing the series converter between the limits and $V_{semin} \leq V_{se} \leq V_{semax}\ and\ 0 \leq \theta_{se} \leq 2\pi$ respectively.

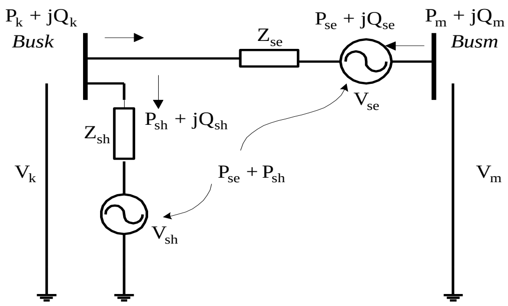

Figure 1. UPFC Equivalent Circuit

The UPFC converters are assumed lossless in this voltage sources model. This implies that there is no absorption or generation of active power by the two converters for its losses and the active power demanded by the series converter at its output is supplied from the AC power system by the shunt converters via the common D.C link. The DC link capacitor voltage Vdc remains constant. Hence the active power supplied to the shunt converter Psh must be equal to the active power demanded by the series converter Pse at the DC link. Then the following equality constraint has to be guaranteed as shown in equation (11).

$$P_{se} + P_{sh} = P_{\infty} = 0 \tag{11}$$

The active and reactive power of the shunt and series converters of the unified power flow controller placed between two buses (nodes) are represented by [12], [13] as shown in equations (12-13).

$$P_{se} = V_{se}^2 G_{mm} + V_{se}V_k(G_{km}\cos(\theta_{se} - \theta_k) + B_{km}\sin(\theta_{se} - \theta_k)) + V_{se}V_m(G_{mm}\cos(\theta_{se} - \theta_k) + B_{mm}\sin(\theta_{se} - \theta_m)) \tag{12}$$

$$P_{sh} = -V_{sh}^2 G_{sh} + V_{sh}V_k(G_{sh}\cos(\theta_{sh} - \theta_k) + B_{sh}\sin(\theta_{sh} - \theta_k)) \tag{13}$$

Where equations (14-16)

$$G_{mm} + jB_{mm} = \frac{1}{Z_{se}} \tag{14}$$

$$G_{sh} + jB_{sh} = -\frac{1}{Z_{sh}} \tag{15}$$

$$G_{se} + jB_{se} = -\frac{1}{Z_{se}} = G_{mk} + jB_{mk} \tag{16}$$

4. DEVICE MODELING IN THE NETWORK

The UPFC power equations are combined with the network equations of the buses k and m between which the UPFC is employed and are represented as equation (17-20).

$$P_k = P_{km} + |V_k| \sum_{j=1}^{n} |V_j| \{G_{kj} \cos(\theta_k - \theta_j) + B_{kj} V_j \sin(\theta_k - \theta_j)\} \quad (17)$$

$$Q_k = Q_{km} + |V_k| \sum_{j=1}^{n} |V_j| \{G_{kj} \sin(\theta_k - \theta_j) + B_{kj} V_j \cos(\theta_k - \theta_j)\} \quad (18)$$

$$P_m = P_{mk} + |V_m| \sum_{j=1}^{n} |V_j| \{G_{mj} \cos(\theta_m - \theta_j) + B_{mj} V_j \cos(\theta_m - \theta_j)\} \quad (19)$$

$$Q_m = Q_{mk} + |V_m| \sum_{j=1}^{n} |V_j| \{G_{mj} \sin(\theta_m - \theta_j) + B_{mj} V_j \cos(\theta_m - \theta_j)\} \quad (20)$$

In the above equations the summation terms represent the same equations for the system without the UPFC. The equations, $P_{km}\ Q_{km}\ or\ P_{mk} Q_{mk}$ are the power flow in or out of the series converter flowing from k to m or from m to k respectively. These can be represented by the equations (21-22).

$$P_{mk} = V_m^2 G_{mm} + V_m V_k (G_{mk} \cos(\theta_m - \theta_k) + B_{mk} \sin(\theta_m - \theta_k)) + V_m V_{se} (G_{mm} \cos(\theta_m - \theta_{se}) + B_{mm} \sin(\theta_m - \theta_{se})) \quad (21)$$

$$Q_{mk} = -V_m^2 B_{mm} + V_m V_k (G_{mk} \sin(\theta_m - \theta_k) + B_{mk} \cos(\theta_m - \theta_k)) + V_m V_{se} (G_{mm} \sin(\theta_m - \theta_{se}) + B_{mm} \cos(\theta_m - \theta_{se})) \quad (22)$$

The power flow equations for the other buses of the network remain the same as of the system without UPFC. These equations are linearized with respect to the state variable of the network and the UPFC. The linearized power flow equations can be represented as [F(X)] = [J] [ΔX] where [F(X)] is power flow mismatch vector, equation (23), [J] is the Jacobian matrix, equation (24), [ΔX] is the state variable correction vector, equation (25) [1].

$$[J] = \begin{bmatrix}
\frac{\partial P_k}{\partial \theta_k} & \frac{\partial P_k}{\partial \theta_m} & \frac{\partial P_k}{\partial V_k} V_k & \frac{\partial P_k}{\partial V_m} V_m & \frac{\partial P_k}{\partial \theta_{se}} & \frac{\partial P_k}{\partial V_{se}} V_{se} & \frac{\partial P_k}{\partial \theta_{sh}} \\
\frac{\partial P_m}{\partial \theta_k} & \frac{\partial P_m}{\partial \theta_m} & \frac{\partial P_m}{\partial V_k} V_k & \frac{\partial P_m}{\partial V_m} V_m & \frac{\partial P_m}{\partial \theta_{se}} & \frac{\partial P_m}{\partial V_{se}} V_{se} & 0 \\
\frac{\partial Q_k}{\partial \theta_k} & \frac{\partial Q_k}{\partial \theta_m} & \frac{\partial Q_k}{\partial V_k} V_k & \frac{\partial Q_k}{\partial V_m} V_m & \frac{\partial Q_k}{\partial \theta_{se}} & \frac{\partial Q_k}{\partial V_{se}} V_{se} & \frac{\partial Q_k}{\partial V_{sh}} \\
\frac{\partial Q_m}{\partial \theta_k} & \frac{\partial Q_m}{\partial \theta_m} & \frac{\partial Q_k}{\partial V_k} V_k & \frac{\partial Q_m}{\partial V_m} V_m & \frac{\partial Q_m}{\partial \theta_{se}} & \frac{\partial Q_m}{\partial V_{se}} V_{se} & 0 \\
\frac{\partial P_{mk}}{\partial \theta_k} & \frac{\partial P_{mk}}{\partial \theta_m} & \frac{\partial P_{mk}}{\partial V_k} V_k & \frac{\partial P_{mk}}{\partial V_m} V_m & \frac{\partial P_{mk}}{\partial \theta_{se}} & \frac{\partial P_{mk}}{\partial V_{se}} V_{se} & 0 \\
\frac{\partial Q_{mk}}{\partial \theta_k} & \frac{\partial Q_{mk}}{\partial \theta_m} & \frac{\partial Q_{mk}}{\partial V_k} V_k & \frac{\partial Q_{mk}}{\partial V_m} V_m & \frac{\partial Q_{mk}}{\partial \theta_{se}} & \frac{\partial Q_{mk}}{\partial V_{se}} V_{se} & 0 \\
\frac{\partial P_{oo}}{\partial \theta_k} & \frac{\partial P_{oo}}{\partial \theta_m} & \frac{\partial P_{oo}}{\partial V_k} V_k & \frac{\partial P_{oo}}{\partial V_m} V_m & \frac{\partial P_{oo}}{\partial V_{se}} & \frac{\partial P_{oo}}{\partial V_{se}} V_{se} & \frac{\partial P_{oo}}{\partial V_{sh}}
\end{bmatrix} \quad (23)$$

$$[F(X)] = [\Delta P_k\ \Delta Q_K\ \Delta P_m\ \Delta Q_m\ \Delta P_{mk}\ \Delta Q_{mk}\ \Delta(P_{se} + P_{sh})]^T \quad (24)$$

$$\Delta X = [\Delta\theta_k\ \Delta\theta_m\ \frac{\Delta V_k}{V_K}\ \frac{\Delta V_m}{V_m}\ \Delta\theta_{se}\ \frac{\Delta V_{se}}{V_{se}}\ \Delta\theta_{sh}]^T \quad (25)$$

The introduction of UPFC in Newton Raphson algorithm causes some adjustment to the Jacobian as per the nodal power equations of node k and m. The last three column and three rows of the Jacobian represents the appropriate sensitivity relations [18]. The operating limits of the UPFC are considered in this paper. This model allows the following modes of operation of the UPFC in enhancing the voltage stability limit.

a. Series Active Power Flow Control: In this control mode the series voltage V_{se} is injected at quadrature with respect bus voltage i.e. is θ_{se} at right angles to θ_k. In this mode there is no reactive power control.
b. Series Reactive Power Flow Control: In this control mode the series voltage is injected at quadrature with respect line current, i.e. θ_{se} is at right angles to θ_m. In this mode there is no reactive power control.

c. Voltage Magnitude Regulation: In this control mode the series voltage injected in phase or antiphase with respect line voltage This injected voltage adds to the nodal voltage at bus k to boost the voltage at bus m.
d. UPFC can operate as a combination of above three modes, two or one at a time for any other appropriate value of angle θ_{se} at which it injects the voltage in line.
e. Independent Voltage Control Mode: In this control mode the shunt voltage V_{sh} is injected to the node to support its voltage.

5. TEST CASE AND SIMULATION

The IEEE 14 bus as shown in Figure 2 is used for voltage stability studies. This system has 5 generating units which are 282odelled as standard PV buses. The load buses are represented as constant PQ loads which are not voltage dependent. The behaviour of the system is investigated with and without UPFC.

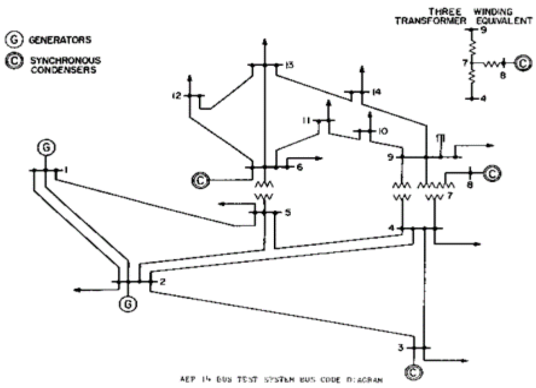

Figure 2. IEEE 14 Bus Systems.

Voltage stability studies are performed by starting from an initial base load and increasing the loads gradually by a factor. The loads can then be defined as shown in equations (26-27).

$$P_L = P_0(1+\alpha) \tag{26}$$

$$Q_L = Q_0(1+\alpha) \tag{27}$$

where P_0 and Q_0 are the active and the reactive base loads, whereas P_L and Q_L are the active and the reactive loads at a bus L for the current operating point as defined by α .

At each step the new equilibrium point is determined by the corresponding load flow solution the procedure is repeated up to the point where the power flow solution diverges. Maximum loading point or bifurcation point where the Jacobian matrix become singular occurs at α = 3.93. Then Modal Analysis described in section 2, is applied to system for last converged load flow solution condition and the eigen values are computed. Table 1 shows the eigen values for the critical operating condition for an IEEE 14 bus system.

Table 1.Relevent Eigen values for IEEE 14 bus network

Eigen values	At critical loading
1	30.716
2	18.93
3	15.073
4	11.708
5	**0.15395**
6	7.5853
7	5.7245
8	3.2145
9	2.4062

The minimum eigen values is 0.15395 at critical mode. The participating factor for this mode is calculated and the result is shown in Figure 3.

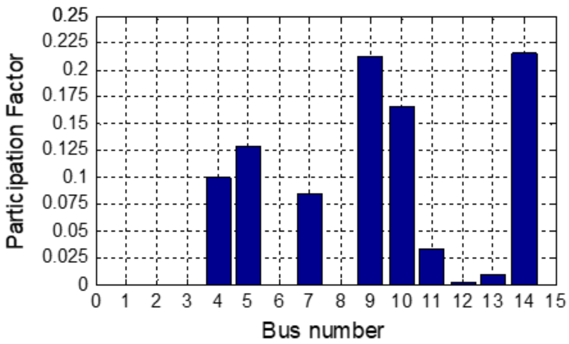

Figure 3.The participating factors for most critical mode for 14 Bus System.

For the 5th mode as shown in Table 1 the Jacobian matrix has the lowest eign value. Hence for this mode the participation factor for the 14 buses are calculated and shown in Figure 3. 14th bus has the highest participation and the next highest participating bus is 9th bus. The voltage level of these buses at the critical loading condition are 0.73042 p.u and 0.76595 p.u respectively as shown in Table 2.

Table 2. Voltage at Buses at Critical Loading.

Bus No. ↓	Voltage at buses without UPFC at critical loading
1	1.06
2	1.045
3	1.01
4	0.79885
5	0.79263
6	1.07
7	**0.85365**
8	1.09
9	**0.76595**
10	**0.78096**
11	0.90718
12	0.98274
13	0.93939
14	**0.73042**

At this critical loading UPFC is placed between bus 9 and 14. The UPFC model can be set to control the active, reactive power and the voltage magnitude simultaneously or one or two at a time.The different modes of operation of UPFC for enhancing the voltage stability margin of networks are.

(a) Simultaneous Control of the Active Power,

Reactive Power and the Voltage Magnitude: UPFC model is incorporated between the bus 14 and 9. Figure 4 shows the impact of UPFC on the voltage levels of bus 14. The basic observation based on these result are;

(i) UPFC can significantly increase the voltage magnitude at the critical mode for both the base case and the maximum loading case. Without UPFC the system experiences a voltage collapse at a load of less than 600MW where as it can sustain more than 600MW loading demand with a voltage level of 0.899 p.u, when UPFC is inserted in the line.

(ii) It is clearly seen that with UPFC, voltage is better regulated at heavier loading conditions than at light loads.

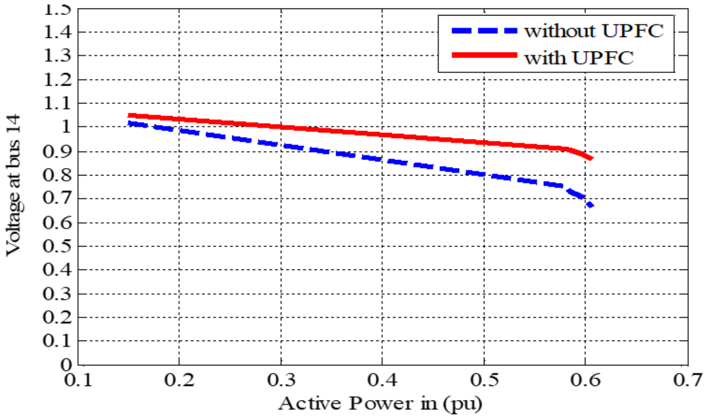

Figure 4. Effect of UPFC on voltage stability at critical case

(b) Control of Active and Reactive Power

The shunt converter of the UPFC is operated to control the voltage at bus 15 to 1 per unit while series converter is operated to inject reactive power at bus 14 to support the voltage. The point of collapse is near a power increase of 75% of the base load. The increase of voltage margin for the14th bus is form 0.73042 p.u to 0.9315 p.u as shown in Table 3.

(c) Independent Control of Voltage Magnitude:

Shunt compensation is provided to fictitious bus 15 to a level of 1 put. This is similar to the function of a STATCOM where the shunt converter is independently controlling the voltage at the node from 0.73042 p.u to 0.94028 p.u.

(d) Control of only Reactive Power:

In this control mode, series converter is employed to inject only reactive power to the AC system which in turn alleviates the voltage at bus 14 from 0.73042 p.u to 0.9162 p.u.

(e) The other control modes provide less voltage support, or in some cases the solution diverges.

Table 3. Voltage at different mode of operation of UPFC

Case No.	Modes Of Operation Of UPFC	Voltage At Bus 14
(a)	Active and reactive power control	0.93149 per unit
(b)	Only voltage magnitude Control	0.94028 per unit
(c)	Only reactive power control	0.91621 per unit

6. CONCLUSION

Series and shunt compensation devices based on power electronics, supports the power system to improve their voltage stability. UPFC which is a combination of both the series as well as shunt device is evaluated here. Modal analysis technique has been employed to ascertain the appropriate location of the FACTS device. The results obtained shows that UPFC can significantly increase the voltage magnitude at the critical mode for both, the base case and the maximum loading case. The UPFC also has the multi control ability and can be worked upon different mode of operations providing different level of support to enhance the voltage profile.

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