Power Flow Regulation by UPFC in Networks with Voltage Dependent Loads

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Abstract*—*In this paper calculations are made to find out the power flow regulation capabilities of Unified Power Flow Controller (UPFC) in load flow analysis with loads which are voltage dependent. New equations for load flow analysis are developed that includes the models of voltage sensitive loads and voltage sources model of UPFC. Newton Raphson algorithm is used to solve the power flow equations of the network. UPFC voltage source model when included in the power equations has unique advantages over other modeling approaches. Analysis is done for two types of Loads. In the first analysis Constant current, Constant Power and Constant Impedance type of loads are examined. In the second analysis Composite loads are analyzed. The results of analysis on standard 5 bus system is presented here as a case study.

Index Terms*—*Constant Current loads, Constant Impedance loads, Constant power loads, Unified Power flow Controller, Newton Raphson Load-flow analysis, Voltage sensitive loads.

I. NOMENCLATURE

P_i^{sp} = Specified real power at i^th^ bus.

Q_i^{sp} = Specified reactive power at i^th^ bus.

ΔP_i =Incremental change real power at i^th^ bus.

ΔQ_i =Incremental change reactive power at i^th^ bus. $\Delta\theta_i$ =Incremental change in voltage angle at i^th^ bus.

ΔV_i = Change in bus voltage at i^th^ bus.

J = Jacobian matrix

V_{se} =Magnitude of series voltage of UPFC

θ_{se} = Phase angle of series voltage of UPFC

V_{sh} = Magnitude of Shunt voltage of UPFC

θ_{sh} = Phase angle of Shunt voltage of UPFC

P_{se} =Active Power injected by UPFC series converter

P_{sh} =Active Power injected by UPFC shunt converter

Z_{se} = Impedance of series transformer

Z_{sh} = Impedance of shunt transformer

II. INTRODUCTION

Full utilization of the transmission lines has become the issue of utmost importance because of the several reasons including environmental concerns, economical constraints and deregulation policies. With the advancement in FACTS technology, transmission lines are drawn to function much closure to their operating limits with higher efficiency. Among the various Shunt and Series FACTS devices the Unified Power Flow Controller (UPFC) is the most advanced device incorporating the features of both the Shunt and the Series controllers and thus mitigating numerous power system static and dynamic issues, such as power flow regulation, power system stability etc. It has been widely utilized for load flow analysis in Newton Raphson, fast decoupled or Gauss Seidal algorithms. Conventionally the load representation at the buses in these methods is constant specified active and reactive powers that are independent of the voltage and frequency at the bus. The assumption underlying this representation is that a constant frequency is always maintained at the system, and the voltage level is maintained at 1 per unit at each bus, all the time. But as discussed by El-Hawary et al [1, 2] the loads which actually comprise of industrial, commercial and residential loads, are dependent on voltage variations and have significant effect on load flow results. El-Hawary et al also studied the sensitivity of bus bars to variations in load model parameters [1]. P.S.R.Murthy discussed the modeling of voltage dependent loads in Newton Raphson load flow algorithm [3]. L.G.Dias et al analyzed the behavior of voltage dependent loads in optimal load flow studies [4]. El-Hawary also discussed that obtaining detailed load models for the loads is justifiable at bus bars sensitive to load modeling [5]. However the effects of incorporating load models in networks with controlling device such as FACTS have not been treated so far, to the author's knowledge. Hence in this paper Load Flow calculation is carried out for system with variable voltage loads and simultaneously the capabilities of UPFC has been analyzed. The paper is further organized as follows. Static load models are presented in section II. A modified Newton Raphson algorithm is formulated with voltage dependent loads in section III. Then Unified Power flow controller is modeled in the above mentioned algorithm in section IV. Voltage source model of UPFC is utilized for the study which offers the control of voltage, active and reactive power simultaneously as well as one or two variables at a time independently. The advantage of using this model of UPFC over other models used in power flow analysis algorithms is that, when it is incorporated in the Newton Raphson algorithm it allows for the automatic adjustment of its variable along with the network variable, hence provides complete controllability of its functioning.

III. STATIC LOAD MODELS

The load models used are the constant impedance type, constant current type and constant power type of models and different combination of them. For an electric power network the exponential model for representing the Dependence of active power (P) and reactive power (Q), on

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the voltage magnitude at a bus has been expressed in the following form [4].

$$P_i^* = P_{i(n)}\left(\frac{V_i}{V_{i(n)}}\right)^a \qquad (1)$$

$$Q_i^* = Q_{i(n)}\left(\frac{V_i}{V_{i(n)}}\right)^b \qquad (2)$$

The coefficients $P_{i(n)}$ and $Q_{i(n)}$ represents the active and reactive powers at nominal voltage $V_{i(n)}$. Alternate form of equations (1) and (2) can be written as

$$P_i^* = P_i\,(V_i)^a \qquad (3)$$

$$Q_i^* = Q_i\,(V_i)^b \qquad (4)$$

Where V_i is per unit voltage with base voltage as $V_{i(n)}$. This model is commonly used in power systems load modeling [1-3]. The value of exponential parameters *a* and *b* for the active and reactive powers , representing the constant current, constant power loads, constant impedance loads, residential, and commercial loads are mentioned in table I [7].

TABLE I. LOAD TYPES AND EXPONENT VALUES

S. No	Type of Load	Range of Exponent	
		Active Power *a*	Reactive Power *b*
1.	Constant Power	0	0
2.	Constant Current	1	1
3.	Constant Impedance	2	2
4.	Commercial	1.51	3.40
5.	Residential	0.92	4.04

IV. NEWTON RAPHSON LOAD FLOW FORMULATION WITH VOLTAGE SENSITIVE LOADS

In conventional load flow studies, for a network with n buses the 2n-1 equations for the active and reactive powers at buses normally solved are:

$$\Delta P_i = P_i - P_i^{sp} = 0 \quad for\ i = 2,...,n \qquad (5)$$

$$\Delta Q_i = Q_i - P_i^{sp} = 0 \quad for\ i = m+1,......,n \qquad (6)$$

where

$$P_i = V_i \sum_{i=1}^{n} V_j Y_{ij} \cos(\theta_i - \theta_j) \qquad (7)$$

$$Q_i = V_i \sum_{i=1}^{n} V_j Y_{ij} \sin(\theta_i - \theta_j) \qquad (8)$$

m= total number of generator buses including the swing bus
n= total number of buses in a network

The load flow equations (7) and (8) are non linear in nature and are solved using Newton Raphson iterative method. This requires finding a Jacobian matrix to update the current estimates of improved solutions. Since instead of constant specified powers, model of the form as in equations (3) and (4) are used, then equations (5) and (6) change to

$$\Delta P_i = (P_i - P_i^{sp})(V_i)^a = 0 \quad for\ i = 2,...,n \qquad (9)$$

$$\Delta Q_i = (Q_i - Q_i^{sp})(V_i)^b = 0 \quad for\ i = m+1,......,n \qquad (10)$$

Let (9) and (10) be denoted as ΔP_i^* and ΔQ_i^*. In conventional Newton Raphson algorithm the matrix vector relationship between the changes in bus voltages and angle and real and reactive powers are represented as

$$[\Delta P_i] = [\partial P_i/\partial\theta_i].[\Delta\theta_i] + [\partial P_i/\partial V_i].[\Delta V_i]$$

$$[\Delta Q_i] = [\partial Q_i/\partial\theta_i].[\Delta\theta_i] + [\partial Q_i/\partial V_i].[\Delta V_i]$$

where

$$[\Delta P_i] = [\Delta P_2 ... \Delta P_n]^T, [\Delta Q_i] = [\Delta Q_2 ... \Delta Q_n]^T$$

$$[\Delta\theta_i] = [\Delta\theta_2 ... \Delta\theta_n]^T, [\Delta V_i] = [\Delta V_2 ... \Delta V_n]^T$$

$$[\partial P_i/\partial\theta_i] = [\partial P_2/\partial\theta_2 ... \partial P_n/\partial\theta_n]^T$$

$$[\partial P_i/\partial V_i] = [\partial P_2/\partial V_2 ... \partial P_n/\partial V_n]^T$$

$$[\partial Q_i/\partial\theta_i] = [\partial Q_2/\partial\theta_2 ... \partial Q_n/\partial\theta_n]^T$$

$$[\partial Q_i/\partial V_i] = [\partial Q_2/\partial V_2 ... \partial Q_n/\partial V_n]^T$$

Where slack bus is taken as bus 1.The Jacobian sub matrices are:

$$J_1 = [\partial P_i/\partial\theta_i],\ \ J_2 = [\partial P_i/\partial V_i],$$

$$J_3 = [\partial Q_i/\partial\theta_i],\ \ J_4 = [\partial Q_i/\partial V_i].$$

When variable voltage loads are considered the powers P_i and Q_i will change to P_i^* and Q_i^* as in equations (3) and (4). This changes the Jacobian elements also. Hence equations for determining the elements of the Jacobian matrix with variable voltage loads are derived from the bus power equations (3) and (4). Differentiating equation (3) the diagonal elements of J_2 are

$$\frac{\partial P_i^*}{\partial V_i} = P_{i(n)}.a.V_i^{a-1} + \frac{\partial P_{i(n)}}{\partial V_i}V_i^a \quad \text{but}$$

$$\frac{\partial P_{i(n)}}{\partial V_i} = 2V_iY_{ii}cos\theta_{ii} - \sum_{\substack{k=1\\k\neq i}}^{n} V_iY_{ik}cos(\theta_i - \theta_k) \quad \text{hence}$$

$$\frac{\partial P_i^*}{\partial V_i} = a.P_{i(n)}.V_i^{a-1} + \{2V_iY_{ii}\cos\theta_{ii} - \sum_{\substack{k=1\\k\neq i}}^{n} V_iY_{ik}\cos(\theta_i - \theta_k)\}V_i^a \qquad (11)$$

The off-diagonal elements of J_2 will be

$\frac{\partial P_i^*}{\partial V_j} = \frac{\partial P_{i(n)}}{\partial V_j}V_i^a$ Similarly differentiating equation (4) the diagonal elements of J_4 is $\frac{\partial Q_i^*}{\partial V_i} = Q_{i(n)}.b.V_i^{b-1} + \frac{\partial Q_{i(n)}}{\partial V_i}V_i^b$

but

$$\frac{\partial Q_{i(n)}}{\partial V_i} = -2V_iY_{ii}\sin\theta_{ii} + \sum_{\substack{k=1\\k\neq i}}^{n} V_iY_{ik}\sin(\theta_i - \theta_k) \quad \text{so}$$

$$\frac{\partial Q_i^*}{\partial V_i} = b.\frac{Q_{i(n)}}{V_{i(n)}}V_i^{b-1} - \{2V_iY_{ii}sin\theta_{ii} + \sum_{\substack{k=1\\k\neq i}}^{n} V_iY_{ik}sin(\theta_i - \theta_k)\}V_i^b \qquad (12)$$

and the off-diagonal elements of J_4 are $\frac{\partial Q_i^*}{\partial V_j} = \frac{\partial Q_{i(n)}}{\partial V_j}V_i^b$

The diagonal and off diagonal terms of J_1 are

$\frac{\partial P_i^*}{\partial \theta_i} = \frac{\partial P_{i(n)}}{\partial \theta_i} V_i^a$ and $\frac{\partial P_i^*}{\partial \theta_j} = \frac{\partial P_{i(n)}}{\partial \theta_j} V_i^a$ respectively.

Similarly the diagonal and off diagonal terms of J_3 are

$\frac{\partial Q_i^*}{\partial \theta_i} = \frac{\partial Q_{i(n)}}{\partial \theta_i} V_i^b$ and $\frac{\partial Q_i^*}{\partial \theta_j} = \frac{\partial Q_{i(n)}}{\partial \theta_j} V_i^b$ respectively.

To evaluate the elements of Jacobian matrix, the estimated bus voltages and powers are used. Then the new estimates for each bus voltage magnitude and angle are

$$\theta_i^{k+1} = \theta_i^k + \Delta\theta_i^k$$
$$V_i^{k+1} = V_i^k + \Delta V_i^k$$

The process is repeated until ΔP_i^* and ΔQ_i^* for all buses are within the given tolerance. The power flow on the lines can be calculated with the values of line admittances, line charging and the final bus voltages.

V. OPERATING PRINCIPLE OF UPFC

The Voltage Source model of UPFC is represented by two ideal voltage sources, V_{sh} in shunt to the node k and V_{se} in series to the transmission line between two nodes k and m as shown in Fig.1 [6]. The impedances in series with the voltage sources are used to represent losses of the coupling transformers. The ideal voltage sources are represented mathematically as

$$\mathbf{V_{se}} = V_{se}(cos\theta_{se} + jsin\theta_{se})$$
$$\mathbf{V_{sh}} = V_{sh}(cos\theta_{sh} + jsin\theta_{sh}) \quad (13)$$

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

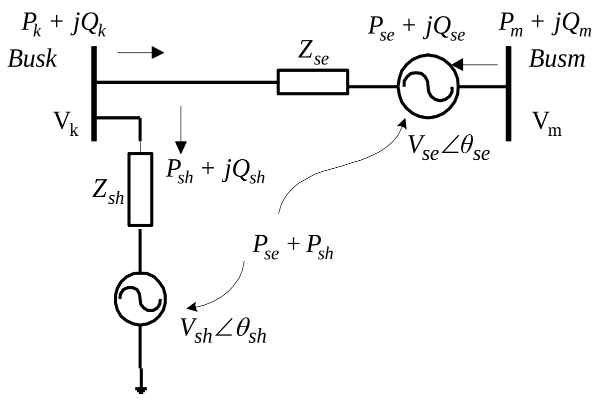

Fig. 1 UPFC equivalent circuit

The output voltage (angle and magnitude) of series converter is used to control the mode of power flow, while the output voltage (angle and magnitude) of shunt converter controls the voltage of connected node. The various control modes of UPFC shown in Fig. 2

(i) If a voltage V_{se} is injected at an angle θ_{se} in phase or antiphase with the node voltage angle θ_k the UPFC regulates the terminal voltage.

(ii) If a voltage V_{se}' is injected in quadrature (lead or lag) to the line current $(\theta_{se}' = \gamma_m \pm 90^o)$, it controls the active power flow acting as series reactive compensation.

(iii) If a voltage V_{se}'' of magnitude 1 is injected in quadrature to the node voltage at m i.e. $\theta_{se}'' = \theta_m \pm 90^o$,it act as phase shifter.

(iv) If V_{se} is injected at any other value of θ_{se}, simultaneous operation of all three functions can be obtained.

(v) The amplitude difference between shunt voltage V_{sh} and node k voltage V_k results in exchange of reactive power between the converter and the node supporting the node voltage directly to the specified value.

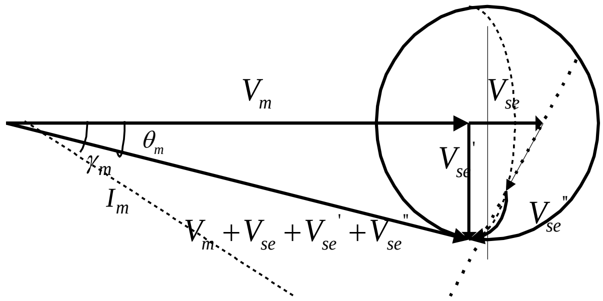

Fig.2 UPFC control of voltage, impedance & angle simultaneously

In this voltage sources model the losses in UPFC converters are assumed negligible. This implies that there is no generation or absorption of active power by the two converters for its losses. The active power demanded by the series converter at its output is supplied from the AC power system by regulating the shunt converter angle θ_{sh} via the common D.C link. The DC link capacitor voltage V_{dc} remains constant. Hence the active power supplied to the shunt converter P_{sh} must be equal to the active power demanded by the series converter P_{se} at the DC link. Then the following equality constraint has to be guaranteed.

$$P_{se} + P_{sh} = P_{oo} = 0 \quad (14)$$

The active and reactive power of the series and shunt converters of the UPFC placed between two buses k and m are represented by (15-18)

$$P_{se} = V_{se}^2 G_{mm} + V_{se}V_k(G_{km}cos(\theta_{se} - \theta_k) + B_{km}\, sin(\theta_{se} - \theta_k))$$
$$+ V_{se}V_m(G_{mm}cos(\theta_{se} - \theta_m) + B_{mm}\, sin(\theta_{se} - \theta_m)) \quad (15)$$

$$Q_{se} = -V_{se}^2 B_{mm} + V_{se}V_k(G_{km}\, sin(\theta_{se} - \theta_k) - B_{km}\, cos(\theta_{se} - \theta_k))$$
$$+ V_{se}V_m(G_{mm}\, sin(\theta_{se} - \theta_m) - B_{mm}\, cos(\theta_{se} - \theta_m)) \quad (16)$$

$$P_{sh} = -V_{sh}^2 G_{sh} + V_{sh}V_k(G_{sh}cos(\theta_{sh} - \theta_k)$$
$$+ B_{sh}sin(\theta_{sh} - \theta_k)) \quad (17)$$

$$Q_{sh} = V_{sh}^2 G_{sh} + V_{sh}V_k(G_{sh}sin(\theta_{sh} - \theta_k)$$
$$+ B_{sh}cos(\theta_{sh} - \theta_k)) \quad (18)$$

Where G is conductance and B is susceptance. These are related to the impedance as below

$$G_{mm} + jB_{mm} = 1 / Z_{se}$$
$$G_{sh} + jB_{sh} = -1 / Z_{sh}$$
$$G_{se} + jB_{se} = -1 / Z_{se} = G_{mk} + jB_{mk}$$

The power flow in or out of the series converter flowing from k to m (P_{km}, Q_{km}) or from m to k (P_{mk}, Q_{mk}) are represented by the equations (19-20) and (21-22) respectively.

$$\begin{aligned} P_{km} = {} & V_k^2 G_{kk} + V_k V_m G_{km} \cos(\theta_k - \theta_m) \\ & + V_k V_{se} G_{km} \cos(\theta_k - \theta_{se}) + V_k V_{sh} G_{sh} \cos(\theta_k - \theta_{sh}) \\ & + V_k V_m B_{km} \sin(\theta_k - \theta_m) + V_k V_{se} B_{km} \sin(\theta_k - \theta_{se}) \\ & + V_k V_{sh} B_{sh} \sin(\theta_k - \theta_{sh}) \end{aligned} \quad (19)$$

$$\begin{aligned} Q_{km} = {} & -V_k^2 B_{kk} + V_k V_m B_{km} \cos(\theta_k - \theta_m) \\ & + V_k V_{se} B_{km} \cos(\theta_k - \theta_{se}) + V_k V_{sh} B_{sh} \cos(\theta_k - \theta_{sh}) \\ & + V_k V_m G_{km} \sin(\theta_k - \theta_m) + V_k V_{se} G_{km} \sin(\theta_k - \theta_{se}) \\ & + V_k V_{sh} G_{sh} \sin(\theta_k - \theta_{sh}) \end{aligned} \quad (20)$$

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

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

VI. DEVICE MODELING IN THE NETWORK WITH VOLTAGE DEPENDENT LOADS

The inclusion of UPFC voltage source model in a network which is supplying power to voltage dependent loads requires combining of the UPFC power equations between the nodes k and m and the power equations of network with variable voltage loads. Hence the equation of power for nodes k and m between which the UPFC is connected, can be written as equation (23-26).

$$P_k = P_{km} + P_k^* \quad (23)$$
$$Q_k = Q_{km} + Q_k^* \quad (24)$$
$$P_m = P_{mk} + P_m^* \quad (25)$$
$$Q_m = Q_{mk} + Q_m^* \quad (26)$$

In the above equations the terms P_k^* and Q_k^* represent the equations for the k^{th} node and P_m^* and Q_m^* for the m^{th} node of the network with voltage dependent loads (without the UPFC). The equations P_{km} and Q_{km} or P_{mk} and Q_{mk} are the power flows in or out of the series converter flowing from k to m or from m to k respectively. The power flow equations for the other buses remain same as of the network without UPFC. These equations are linearized with respect to state variable of the network and the UPFC. The linearized power flow equations can be represented as [F(X)] = [J] [ΔX] where [J] represents the Jacobian matrix, equation (27), [F(X)] is power flow mismatch vector, equation (28), [ΔX] is the state variable correction vector, equation (29) [6].

$$[J]=\begin{bmatrix} \frac{\partial P_k}{\partial \theta_k} & \frac{\partial P_k}{\partial \theta_m} & \frac{\partial P_k}{\partial V_{sh}}V_{sh} & \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_{sh}}V_{sh} & \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_{sh}}V_{sh} & \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 \theta_{sh}} \\ \frac{\partial Q_m}{\partial \theta_k} & \frac{\partial Q_m}{\partial \theta_m} & \frac{\partial Q_k}{\partial V_{sh}}V_{sh} & \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_{sh}}V_{sh} & \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_{sh}}V_{sh} & \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_{sh}}V_{sh} & \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 \theta_{sh}} \end{bmatrix} \quad (27)$$

$$[F(X)] = [\Delta P_k \; \Delta Q_k \; \Delta P_m \; \Delta Q_m \; \Delta P_{mk} \; \Delta Q_{mk} \; \Delta(P_{se} + P_{sh})]^T \quad (28)$$

$$\Delta X = \left[\Delta\theta_k \;\; \Delta\theta_m \; \frac{\Delta V_{sh}}{V_{sh}} \; \frac{\Delta V_m}{V_m} \; \Delta\theta_{se} \; \frac{\Delta V_{se}}{V_{se}} \; \Delta\theta_{sh} \right]^T \quad (29)$$

The introduction of UPFC in Newton Raphson algorithm with variable voltage loads causes some changes to the Jacobian as per the nodal power equations of node k and m as shown in equation (27). The last three column and three rows of the Jacobian matrix represents the sensitivity relations between the network variables and the UPFC [6]. Since the UPFC variables are included in the Jacobian and updated at each iteration along with the network variables, hence a better control action between UPFC and network parameters is achieved. In this case, the UPFC parameters are automatically adjusted within specified limits along with the network variables. Hence the UPFC operates in a closed loop form. The corresponding power flow is a controlled power flow.

VII. TEST CASE AND SIMULATION

In order to find the power flow regulation, Standard 5 bus test network [8] is tested with and without UPFC. To include the UPFC in the system an additional bus (bus No. 6) is introduced in the test network as shown in Fig. 3. Generators are at buses 1and 2 and bus 1 is taken as the slack bus. Bus 3, 4, 5 are the load buses.

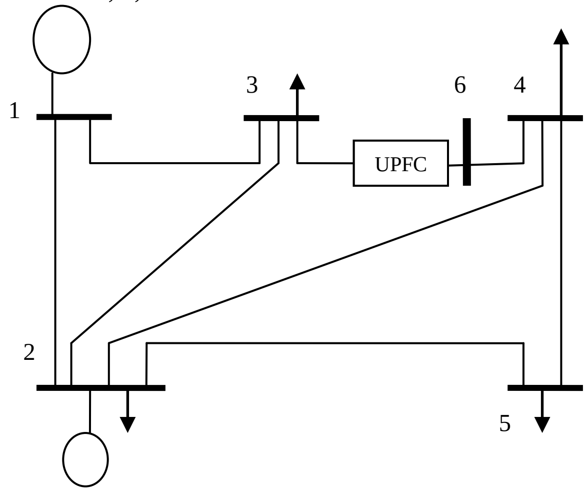

Fig. 3 Single line diagram of 5-Bus System.

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In this iterative algorithm good starting conditions are necessary to arrive at a solution. A voltage magnitude of 1.p.u is taken for all the PQ buses and voltage angle of 0^o for all the buses. Similarly the starting voltage and angle for the two converters are calculated by using the formulas in [6]. In this paper the UPFC is operated for controlling the voltage, active power and reactive power simultaneously in power flow algorithm.

Test data of 5 bus system, is given in table II and III.

TABLE II. Bus Data

Bus No.	Voltage		Load		Generator	
	|v|	θ	MW	Mvar	(MW, Mvar)	Qmin, Qmax
1	1.06	0.0	0	0	0, 0	50, 50
2	1.0	0.0	20	10	40, 0	10, 50
3	1.0	0.0	45	15	0, 0	0, 0
4	1.00	0.0	40	5	0, 0	0, 0
5	1.00	0.0	60	10	0, 0	0, 0

TABLE. III. Line Data

Transmission Line	Sending Bus	Receiving Bus	Line resistance (pu)	Line reactance (pu)	Line suseptance (pu)
1	1	2	0.02	0.06	0.06
2	1	3	0.08	0.24	0.05
3	2	3	0.06	0.18	0.040
4	2	4	0.06	0.18	0.040
5	2	5	0.04	0.12	0.030
6	3(6)	4	0.010	0.03	0.020
7	4	5	0.08	0.24	0.050

VIII. RESULT OF SIMULATION

The test network with models of voltage dependent loads was tested without UPFC and with UPFC. The convergence for both the cases i.e. with UPFC and without UPFC for all the type of loads is within 6 to 12 iterations satisfying a power mismatch tolerance of 10^{-12}. At all the iteration, UPFC variables were within limits. The simulation gives the power flow in the transmission line for constant power, constant current, constant impedance, commercial and residential loads as shown in Fig. 4 to 8 respectively. The power flows in the UPFC included network differ from the original case. The most significant changes are as follows. The increase in power flow through transmission line 2 is from 41.790 MW to 50.3410 MW denoted by 'x' in Fig.4, and through transmission line 3 is from 24.4730 MW to 37.4840 MW as denoted by 'y' in Fig.4. Hence the total increase in active power flow towards bus 3 is 32.64%. Similarly for constant current, constant impedance, commercial and residential type of load, the total increase in active power flow towards bus 3 is 31.42%, 30.21%, 45.49%and 30.12% respectively as shown in Fig 5 to 8. The increase is in response to the large amount of active power demanded by the UPFC series converter.

Since the UPFC generates its own reactive power the generator at node 1 decreases its reactive power generation by 5.6%, 5.4%, 5.1% 5.49% and 5.73% and the generator connected at node 2 increases its absorption of reactive power by 22.6%, 24.77%, 27.49%, 27.7% and 26.9% for constant power, constant current, constant impedance, commercial and residential type of load respectively as shown in Fig 9 -13 respectively.

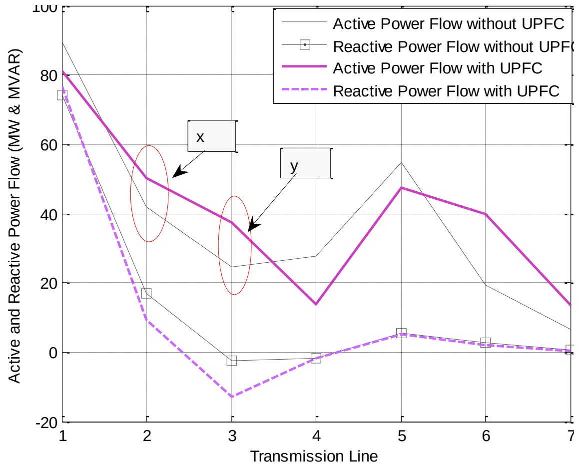

Fig. 4 Power Flows with constant Power Loads

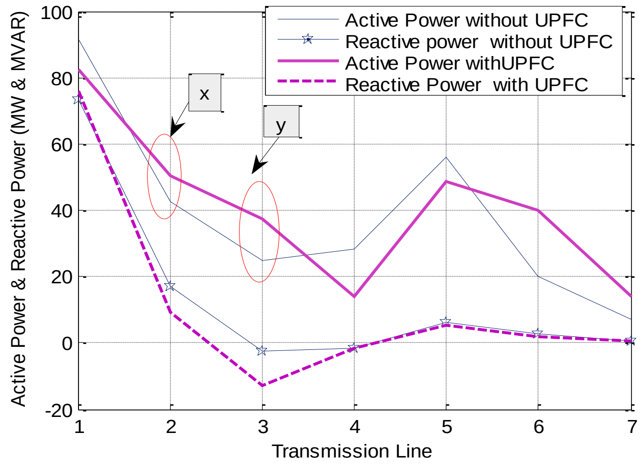

Fig. 5 Power Flow with Constant Current Loads

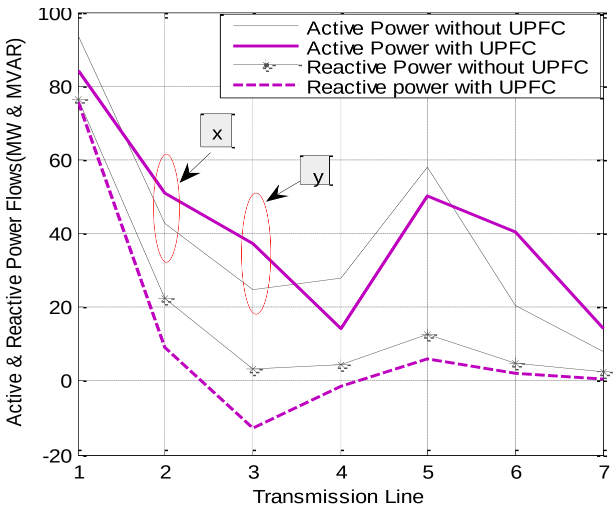

Fig. 6 Power Flow with Constant Impedance Loads

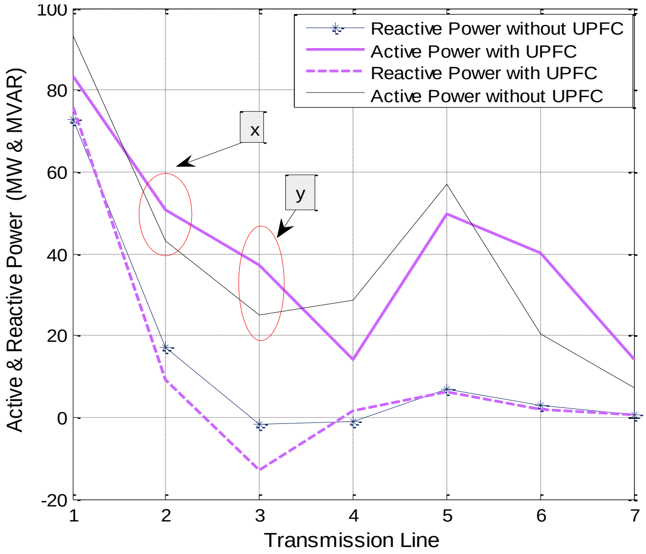

Fig. 7 Powers Flows with Commercial Loads

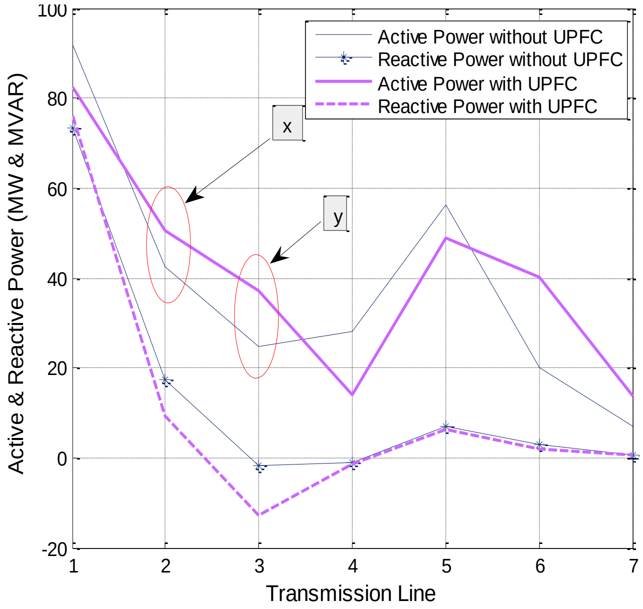

Fig. 8 Powers Flows with Residential Loads

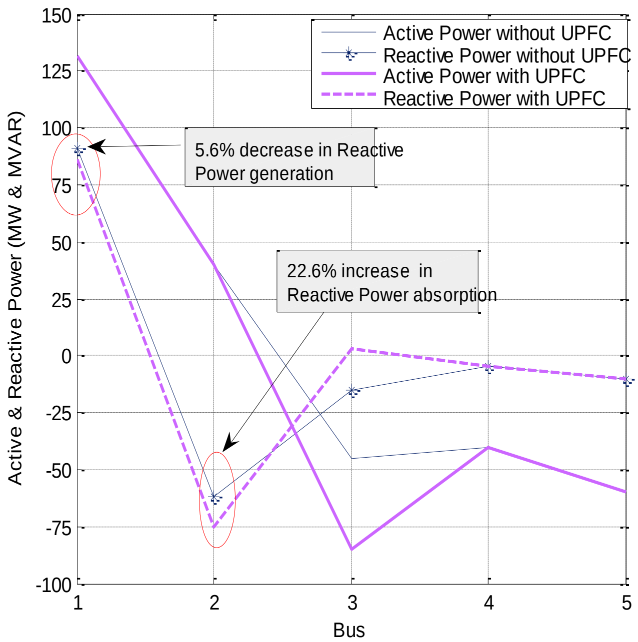

Fig. 9 Bus Powers with Constant Power Loads

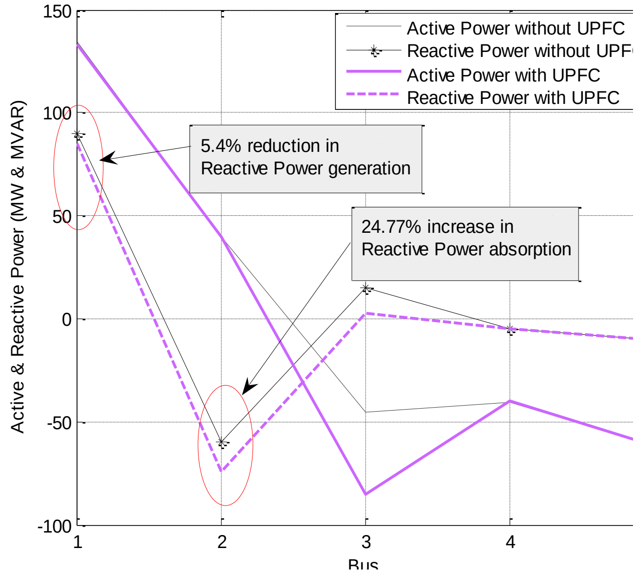

Fig. 10 Bus Powers with Constant Current Loads

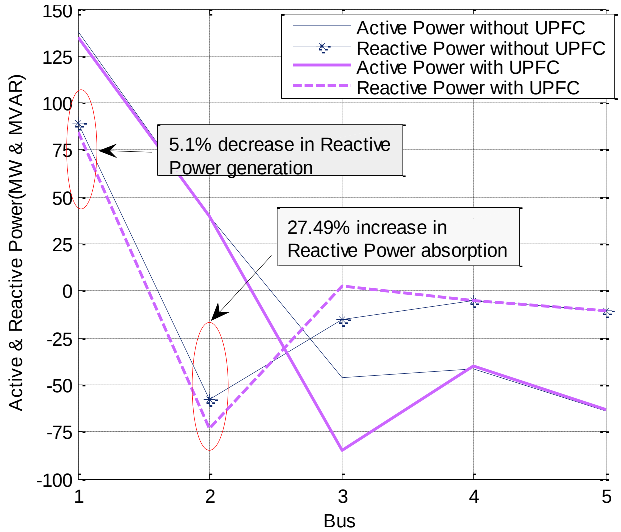

Fig. 11 Bus Powers with Constant Impedance Loads

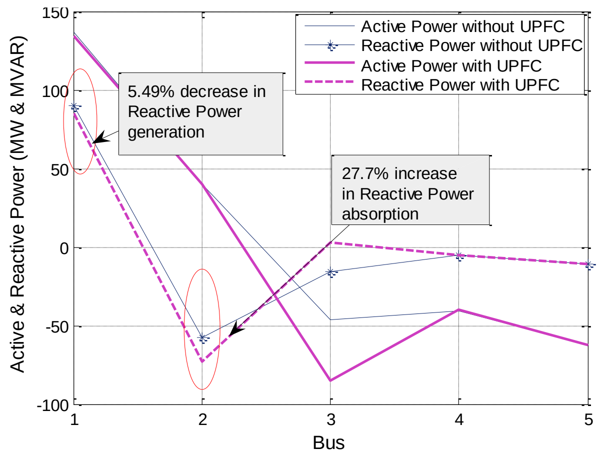

Fig. 12 Bus Powers with Commercial Loads

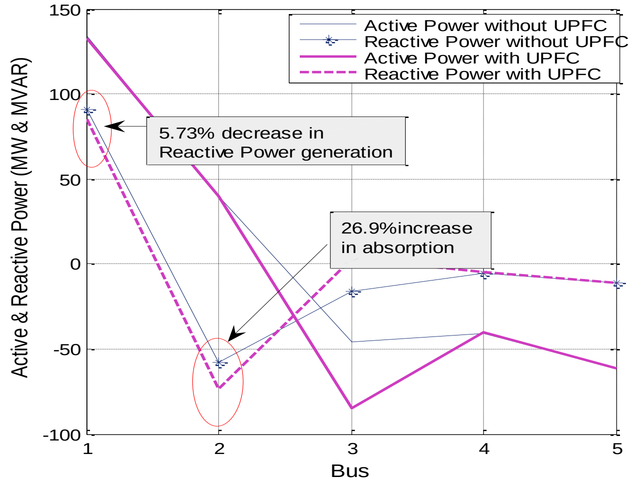

Fig. 13 Bus Powers with Residential Loads

Variations of the voltage magnitude and angle at the buses with different types of loads are given in table IV, V, VI, VII and VIII. It is clearly seen that with UPFC there is enhancement in the voltage level of each bus as compared to the respective base case. The voltage of UPFC Voltage Sources for different types of loads is as shown in table IX. The values of the voltage magnitude and angles of the Voltage Sources at the converged iteration suggest that the UPFC is effective in controlling the active and reactive powers well within the prescribed limits of its variables. Also the series voltage magnitude is least for the constant impedance case while it is highest for constant power case.

TABLE. IV. Bus Voltages with constant Power Loads

Bus No	Without UPFC		With UPFC	
	Voltage Magnitude (p u)	Phase angle (deg)	Voltage Magnitude (p u)	Phase angle(deg)
1	1.06	0	1.06	0
2	*1*	*-2.0612*	*1*	*-1.7693*
3	0.98725	-4.6367	1	-6.0161
4	0.98413	-4.957	0.99167	-3.1906
5	0.9717	-5.7649	0.97451	-4.9741

TABLE.V. Bus Voltage with Constant Current Loads

Bus No	Without UPFC		With UPFC	
	Voltage Magnitude (p u)	Phase angle (deg)	Voltage Magnitude (p u)	Phase Angle (deg)
1	1.06	0	1.06	0
2	1	-2.2447	1	-1.8721
3	0.98581	-4.8885	1	-6.0737
4	0.98261	-5.2332	0.99095	-3.3462
5	0.96936	-6.1591	0.97267	-5.2526

TABLE.VI. Bus Voltages with Constant Impedance Loads

Bus No	Without UPFC		With UPFC	
	Voltage Magnitude (p u)	Phase Angle (deg)	Magnitude (p u)	Phase angle(deg)
1	1.06	0	1.06	0
2	1	-2.1476	1	-1.8183
3	0.98675	-4.7552	1	-6.0435
4	0.98342	-5.0871	0.99133	-3.2651
5	0.9706	-5.9506	0.97364	-5.1067

TABLE. VII. Bus Voltages with Commercial Loads

Bus No	Without UPFC		With UPFC	
	Voltage Magnitude (p u)	Phase angle (degrees)	Voltage Magnitude (p u)	Phase angle (degrees)
1	1.06	0	1.06	0
2	1	-2.1999	1	-1.8466
3	0.98569	-4.8199	1	-6.0594
4	0.98251	-5.1587	0.99091	-3.307
5	0.96924	-6.0518	0.97259	-5.175

TABLE. VIII. Bus Voltages with Residential Loads

Bus No	Without UPFC		With UPFC	
	Voltage Magnitude (p u)	Phase angle (degrees)	Voltage Magnitude (p u)	Phase angle (degrees)
1	1.06	0	1.06	0
2	1	-2.1447	1	-1.8158
3	0.98583	-4.7393	1	-6.0421
4	0.98267	-5.0709	0.99099	-3.2547
5	0.96951	-5.9262	0.97279	-5.0858

TABLE.IX. UPFC Voltages

Type of Load	Series Source		Shunt Source	
	|Voltage| (p u)	Phase Angle (deg)	|Voltage | (p u)	Phase Angle (deg)
Constant Power	0.10126	**-1.6185**	1.0173	-0.10482
Constant Current	0.1005	-1.6161	1.0174	-0.10528
Constant Impedance	0.09969	-1.6134	1.0174	-0.10579
Commercial Load	0.10016	**-1.6185**	1.0173	-0.10482
Residential Load	0.10068	-1.6161	1.0174	-0.10528

IX. CONCLUSION AND FUTURE SCOPE

This paper, reports on the development of steady state load flow algorithm with voltage dependent loads and implementation of UPFC voltage source model into the developed algorithm for the purpose of analyzing its behavior. The UPFC model has been vigorously tested in the developed algorithm for various voltage sensitive load models. The obtained results suggest that with UPFC, iterative algorithm successfully converged for all the types of load model, controlling the active power, reactive power and the voltage magnitude simultaneously. The modeled UPFC functioned within the limits of voltage and angle of its two voltage sources. The speed of convergence as compared with the case without UPFC was found nearly equal. The iterations converged to a high degree of accuracy of 10^{-12} in all the cases suggesting that the inclusion of UPFC along with the voltage dependent loads did not drive the system to a state of ill condition.

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