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Research Paper

OPTIMAL POWER FLOW USING UNIFIED POWER FLOW CONTROLLER (UPFC)

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A critical factor effecting power transmission system is the power flow control. To regulate the power flow control in power transmission line unified power flow controller (UPFC) is used. The UPFC is represented with two voltage sources named Voltage Source Model (VSM), which is used to study the behaviour of the UPFC in regulating the active, reactive power and voltage profile in the system. These VSM is incorporated in Newton Raphson (N-R) algorithm for load flow studies. The equations of UPFC and the power balance equations of network are combined in to one set of non-linear algebraic equations by employing Simultaneous method and is calculated according to the Newton raphson algorithm; Performed on the IEEE 30-bus system. Simulation is done in Matlab. The results are compared with and without UPFC in terms of active and reactive power flows in the line and active and reactive power flows at the bus to analyze the performance of UPFC.

Keywords: Newton-Raphson algorithm, Load flow, Unified power flow controller, Voltage source model

INTRODUCTION

Electrical power systems are a large interconnected network that requires a careful design to maintain the system with continuous power flow operation without any limitations. Flexible Alternating Current Transmission System (FACTS) is an evolving technology used to help electric utilities fully utilize their transmission assets. This concept was first introduced by N G Hingorani, in (1988). Many types of FACTS devices have been proposed, among them Unified Power Flow Controller (UPFC) is a versatile and flexible device in the FACTS family of controllers which has the ability to simultaneously control all the transmission parameters of power systems i.e., voltage, impedance and phase angle which determines the power flow of a transmission line, this device was proposed by Gyugyi in (1992); and Gyugyi *et al*. (1995).

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The UPFC seen to be consists of two Voltage Source Converters (VSCs), one VSC is connected in series to the transmission line through a series transformer, similarly the other is connected in shunt to the transmission line through a shunt transformer and both are connected back to back through a DC storage capacitor (Gyugyi *et al*., 1995). In this paper the performance of UPFC is investigated on power systems effectively, to this it is required to formulate their appropriate model. In the area of power flow analysis the UPFC models have been published (Fuerete-Esquivel and Acha, 1998; Noroozian *et al*., 1995; and Nabavi-Niaki and Iravani, 1996a and b) and consider the UPFC as one series voltage source and one shunt current source model or both the series and shunt represented by two voltage sources.

In the area of power flow concept the UPFC is represented by two voltage sources called Voltage Source Model(VSM) (Fuerete-Esquivel and Acha, 1998) also introduced another model called the Power Injection Model (PIM).

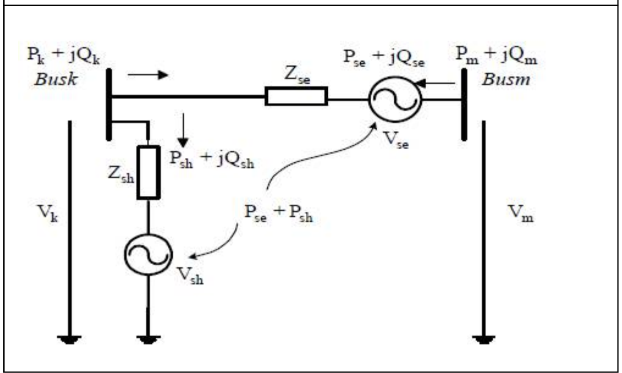
The Voltage source model of UPFC is incorporated in N-R algorithm in to estimate the performance of UPFC in power flow control. Generally there are ways of solving power flow solutions, the Sequential and the simultaneous method: In the first method, the equations of UPFC are separated from the power flow equations and both the set of equations are solved separately and sequentially.

In simultaneous method, the equations of UPFC and the power flow equations are combined in to one set of non-linear algebraic equations which find less complexity. A jacobian matrix is then formed and are in non symmetric in nature. Here in this paper the simultaneous method was used.

UPFC OPERATING PRINCIPLE

The UPFC consists of two voltage source converters, one connected in series to the transmission line through a series transformer and the other in shunt to the transmission line through a shunt transformer, both are connected back to back through a DC link and can modelled as two ideal voltage sources between the two busses (Fuerte-Esquivel and Acha, 1997; and Fuerte-Esquivel *et al*., 2000). 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 more of these parameters in any combination or to control none of them. 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 output of the series voltage source V_{se} and θ_{se} are controllable magnitude and angle between the limits $V_{se\,max} \leq V_{se} \leq V_{semin}$ and $0 \leq \theta_{se} \leq 2\pi$ respectively and of the shunt voltage source is V_{sh} and θ_{sh} controllable between the limits $V_{sh\,max} \leq V_{sh} \leq V_{shmin}$ and $0 \leq \theta_{sh} \leq 2\pi$. The voltage magnitude of the output voltage V_{se} provides voltage regulation, and the phase angle θ_{se} determines the mode of power flow control. Figure 1 shows the voltage source model of the UPFC. Z_{se} and Z_{sh} are the impedances of the two transformers between

Figure 1: Voltage Source Model of UPFC



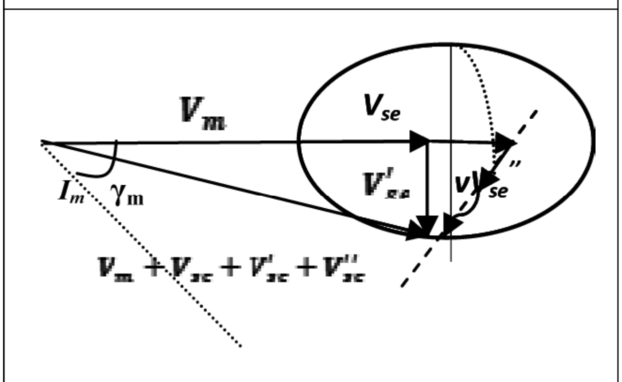
the line and UPFC.

In addition to providing a supportive role in the active power exchange that take place between a series converter and the AC system, the shunt converter may also generate or absorb reactive power in order to provide independent voltage magnitude regulation at its point of connection with the AC system.

The converter output voltage was used to control the mode of power flow and voltage regulation at the nodes as follows:

a. The bus voltage magnitude can be controlled by injecting a voltage V_{se} in phase or anti-phase has shown in Figure 2.

Figure 2: Simultaneous Control of Voltage, Impedance and Angle



b. Power flow can be controlled by injecting a voltage $V_{se}{}'$ in quadrature to the line current ($\theta_{se} = \gamma_m \pm 90$, γ_m is the angle between V_m and I_m) Figure 2.

c. Power flow can be controlled by injecting a voltage of magnitude $\left(V''_{se}\right)$ in quadrature to node voltage $\theta_{m.}$ Figure 2.

MODELLING OF UPFC

The two ideal series and shunt voltages source equations of the UPFC from Figure 1 are:

$$V_{se} = V_{se}\left(\cos\theta_{se} + j\sin\theta_{se}\right) \qquad ...(1)$$

$$V_{sh} = V_{sh}\left(\cos\theta_{sh} + j\sin\theta_{sh}\right) \qquad ...(2)$$

Based on the voltage source model of UPFC the active and reactive power equations are:

At node k:

$$\begin{aligned} P_k = {} & V^2{}_k G_{kk} + V_k V_m (G_{km}\cos(\theta_k - \theta_m) + B_{km}\sin(\theta_k - \theta_m)) \\ & + V_k Vse(G_{km}\cos(\theta_k - \theta_{se)}) + B_{km}\sin(\theta_k - \theta_{se})) \\ & + V_k V_{sh}(G_{sh}\cos(\theta_k - \theta_{sh}) + B_{sh}\sin(\theta_k - \theta_{sh})) \end{aligned} \qquad ...(3)$$

$$\begin{aligned} Q_k = {} & -V^2{}_k B_{kk} + V_k V_m (G_{km}\sin(\theta_k - \theta_m) - B_{km}\cos(\theta_k - \theta_m)) \\ & + V_k V_{se}(G_{km}\sin(\theta_k - \theta_{se}) - B_{km}\cos(\theta_k - \theta_{se})) \\ & + V_k V_{sh}(G_{sh}\sin(\theta_k - \theta_{sh}) - B_{sh}\cos(\theta_k - \theta_{sh})) \end{aligned} \qquad ...(4)$$

At node m:

$$\begin{aligned} P_m = {} & V^2{}_m G_{mm} + V_m V_k (G_{mk}\cos(\theta_m - \theta_k) + B_{mk}\sin(\theta_m - \theta_k)) \\ & + V_m V_{se}(G_{mm}\cos(\theta_m - \theta_{se}) + B_{mm}\sin(\theta_m - \theta_{se})) \end{aligned} \qquad ...(5)$$

$$\begin{aligned} Q_m = {} & -V^2{}_m B_{mm} + V_m V_k (G_{mk}\sin(\theta_m - \theta_k) \\ & - B_{mk}\cos(\theta_m - \theta_k)) + V_m V_{sh}(G_{mm}\sin(\theta_m - \theta_{se}) \\ & - B_{mm}\cos(\theta_m - \theta_{se})) \end{aligned} \qquad ...(6)$$

Series converter

$$\begin{aligned} P_{se} = {} & V^2{}_{se} G_{mm} + V_{se} V_k (G_{km}\cos(\theta_{se} - \theta_k) + B_{km}\sin(\theta_{se} - \theta_k)) \\ & + V_{se} V_m (G_{mm}\cos(\theta_{se} - \theta_k) + B_{mm}\sin(\theta_{se} - \theta_m) \end{aligned} \qquad ...(7)$$

$$Q_{se} = -V^2_{se}B_{mm} + V_{se}V_k(G_{km}\sin(\theta_{se}-\theta_k) - B_{km}\cos(\theta_{se}-\theta_k)) + V_{se}V_m(G_{mm}\sin(\theta_{se}-\theta_m) - B_{mm}\cos(\theta_{se}-\theta_m)) \quad ...(8)$$

Shunt converter:

$$P_{sh} = -V^2_{sh}G_{sh} + V_{sh}V_k(G_{sh}\cos(\theta_{sh}-\theta_k) + B_{sh}\sin(\theta_{sh}-\theta_k)) \quad ...(9)$$

$$Q_{sh} = V^2_{sh}B_{sh} + V_{sh}V_k(G_{sh}\sin(\theta_{sh}-\theta_k) - B_{sh}\cos(\theta_{sh}-\theta_k)) \quad ...(10)$$

where

$$Y_{kk} = G_{kk} + jB_{kk} = Z^{-1}{}_{se} + Z^{-1}{}_{sh} \quad ...(11)$$

$$Y_{mm} = G_{mm} + jB_{mm} = Z^{-1}{}_{se} \quad ...(12)$$

$$Y_{km} = Y_{mk} = G_{km} + jB_{km} = -Z^{-1}{}_{se} \quad ...(13)$$

$$Y_{sh} = G_{sh} + jB_{sh} = -Z^{-1}{}_{sh} \quad ...(14)$$

Assuming the UPFC converters were lossless in this voltage source model, which implies that there is no absorption or generation of active power by the two converters for its losses and hence the active power supplied to the shunt converter P_{sh} equals the active power demand by the series converter P_{se} at the DC link. Then the following equality constraint has to be guaranteed.

$$P_{se} + P_{sh} = 0 \quad ...(15)$$

Further more if the coupling transformers are assumed to contain no resistance then the active power at the bus k matches the active power at bus m, then

$$P_{sh} + P_{se} = P_k + P_m = 0 \quad ...(16)$$

NEWTON-RAPHSON ALGORITHM AND FLOWCHART WITH INCORPORATION OF THE UNIFIED POWER FLOW CONTROLLER

From the mathematical modelling point of view, the set of nonlinear, algebraic equations that describe the electrical power network under the steady state conditions were solved for the power flow solutions. Over the years, several approaches have been put forward to solve for the power flow equations. Early approaches were based on the loop equations and methods using Gauss-type solutions.

This method was laborious because the network loops has to be specified by hand by the systems engineer. The drawback of these algorithms is that they exhibit poor convergence characteristics when applied to the solution of the networks. To overcome such limitations, the Newton-Raphson method and derived formulations were developed in the early 1970s and since then it became firmly established throughout the power system industry (Gyugyi *et al*., 1995).

In this project a Newton Raphson power flow algorithm was used to solve for the power flow problem in a transmission line with UPFC as shown in the flow chart in Figure 3.

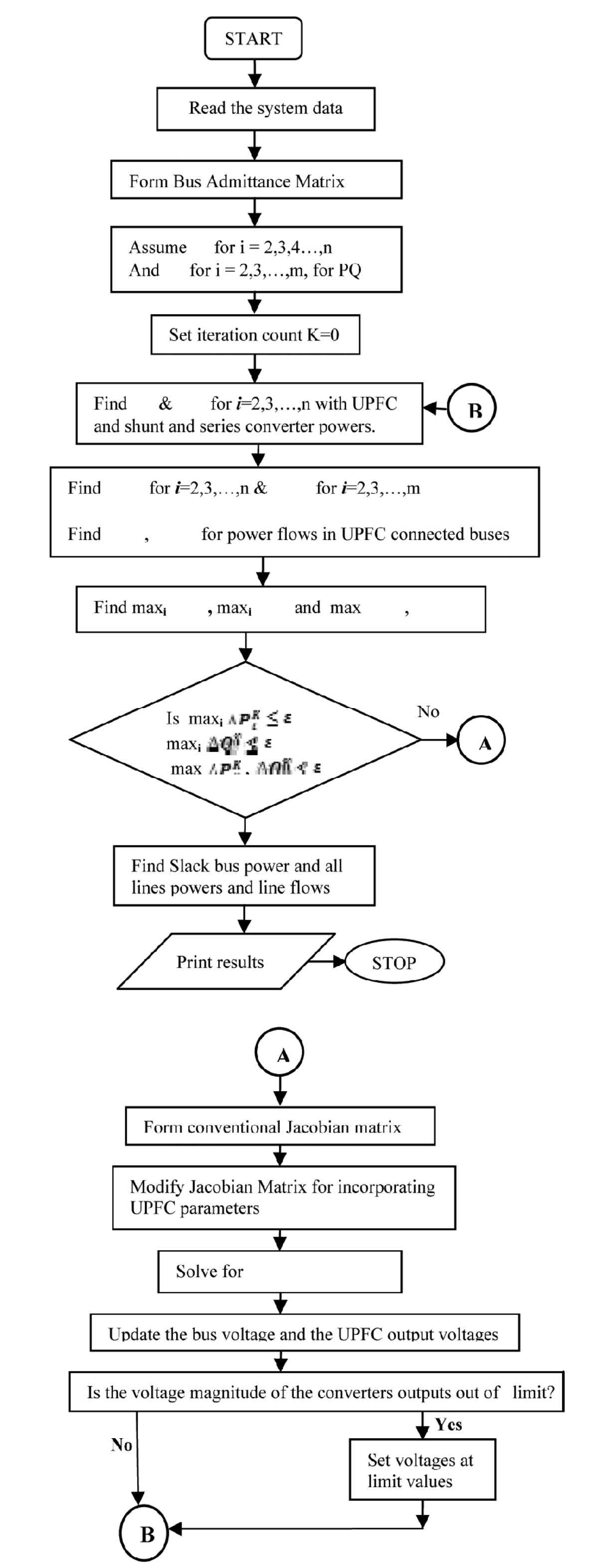
Steps to Solve the Newton-Raphson Algorithm

Step 1: Read the input of the system data that includes the data needed for conventional power flow calculation, i.e., the number and types of buses, transmission line data, generation, load data and location of UPFC and the control variables of UPFC, i.e., the magnitude and angles of output voltage series and shunt converters.

Step 2: Formation of admittance matrix Y_{bus} of the transmission line between the bus i and j.

Step 3: Combining the UPFC power equations with network equation, we get the conventional power flow equation:

Figure 3: Flowchart for Load Flow by N-R Method with UPFC



$$P_i + Q_i = \sum_{j=1}^{n} V_i V_j Y_{ij} \angle\left(\theta_{ij} - \delta_i + \delta_j\right) + P_i' + jQ_i' \quad \text{...(17)}$$

where

$P_i' + jQ_i'$ = Active and Reactive power flow due to UPFC between the two buses.

$P_i + Q$ = Active and Reactive power flow at the i[th] bus.

$V_i < \delta_i$ = Voltage and angle of i[th] bus

$V_j < \delta_j$ = Voltage and angle at j[th] bus

Y_{ij} = Admittance of the transmission line between the bus *i* and *j*

Step 4: The conventional jacobian matrix are formed (P_i^k and Q_i^k) due to the inclusion of UPFC. The inclusion of these variables increases the dimensions of the jacobian matrix.

Step 5: In this step, the jacobian matrix was modified and power equations are mis-matched ($\Delta P_i^k, \Delta Q_i^k$ for *i* = 2, 3, …, *m* and $\Delta P_{ii}^k, \Delta Q_{ii}^k$).

Step 6: The busbar voltages were updated at each iteration and convergence was checked.

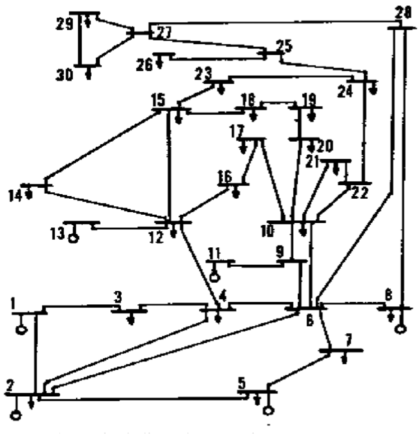
Step 7: If convergence is not achieved in the next step the algorithm goes back to the step 6 and the jacobian matrix is modified and the power equations were mismatched until convergence was attained.

Step 8: If the convergence achieved in Step 7, the output load flow was calculated for PQ bus that includes the Bus bars voltages, generation, transmission line flow and losses.

TEST CASE AND SIMULATION

Standard 30-bus network was tested with and without UPFC to investigate its performance.

Figure 4: Single Line Diagram of IEEE 30 Bus System



Flat voltage start was assumed for the two UPFC voltage sources.

RESULT OF SIMULATION

The network was tested without UPFC and with UPFC. And it was observed that the UPFC parameters were within limits. The simulations show the power flow for the line active and reactive powers which were tabulated below (Table 1). The voltages of the buses with and without UPFC were also tabulated (Table 2).

Table 1: Line Flows With and Without UPFC

Line No.	Line Flows without UPFC			Line Flows with UPFC		
	P(MW)	Q(MVAR)	Losses	P(MW)	Q(MVAR)	Losses
1-2	1.7323	-.2754	0.052311	1.4088	-0.529	0.038091
1-3	0.8774	0.0039	0.031001	0.7607	-0.095	0.023493
2-4	0.4335	0.0125	0.009839	0.4062	-0.005	0.008311
3-4	0.8224	-.0769	0.008525	0.7132	-0.148	0.006387
2-5	0.8238	0.0058	0.029284	0.5988	-0.145	0.015552
2-6	0.6055	-.0189	0.019449	0.5485	-0.054	0.015480
4-6	0.7453	-.1538	0.006609	0.6213	-0.221	0.004738
5-7	-0.147	0.1072	0.001587	0.0329	0.1695	0.001370
6-7	0.3807	-.0211	0.003740	0.1975	-0.094	0.001135
6-8	0.2963	-.0925	0.001107	0.2965	-0.095	0.001057
6-9	0.2916	-.0133	0.000000	0.2958	-0.011	0.000000
6-10	0.1650	0.0232	0.000000	0.1674	0.0242	0.000000
9-11	-0.000	-.1570	0.000000	0.0000	-0.157	0.000000
9-10	0.2916	0.1266	0.000000	0.2958	0.1288	0.000000

Table 1 (Cont.)

Line No.	Line Flows without UPFC			Line Flows with UPFC		
	P(MW)	Q(MVAR)	Losses	P(MW)	Q(MVAR)	Losses
4-12	0.4163	0.0670	0.000000	0.4075	0.0578	0.000000
12-13	-0.000	-.1044	0.000000	-0.000	-0.104	0.000000
12-14	0.0731	0.0155	0.000677	0.0719	0.0149	0.000623
12-15	0.1643	0.0315	0.001822	0.1600	0.0288	0.001639
12-16	0.0668	0.0057	0.000418	0.0635	0.0036	0.000359
14-15	-.0105	-.0018	0.000025	0.0093	-0.002	0.000020
16-17	0.0313	-0.013	0.000095	0.0281	-0.015	0.000080
15-18	0.0580	0.0050	0.000369	0.0564	0.0041	0.000331
18-19	0.0256	-.0047	0.000045	0.0240	-0.005	0.000038
19-20	-.0693	-.0388	0.000221	-0.070	-0.039	0.000219
10-20	0.0926	0.0485	0.001005	0.0941	0.0492	0.000986
10-17	0.0589	0.0721	0.000276	0.0621	0.0740	0.000282
10-21	0.1903	0.1413	0.001921	0.1925	0.1425	0.001865
10-22	0.0567	0.0323	0.000305	0.0563	0.0322	0.000286
21-23	0.0134	0.0252	0.000010	0.0158	0.0264	0.000011
15-23	0.0329	-.00390	0.000112	0.0292	-0.005	0.000086
22-24	0.0564	0.0317	0.000482	0.0560	0.0316	0.000453
23-24	0.0143	0.0050	0.000031	0.0129	0.0044	0.000024
24-25	-.0167	0.0119	0.000082	-.0184	0.0113	0.000086
25-26	0.0354	0.0237	0.000475	0.0354	0.0236	0.000449
25-27	-.0523	-.0118	0.000323	-.0539	-0.012	0.000325
28-27	0.1856	0.0607	0.000000	0.1870	0.0604	0.000000
27-29	0.0619	0.0168	0.000914	0.0619	0.0166	0.000863
27-30	0.0710	0.0168	0.001720	0.0709	0.0166	0.001623
29-30	0.0370	0.0061	0.000356	0.0370	0.0060	0.000336
8-29	-.0047	-.0140	0.000005	-.0044	-0.016	0.000004
6-28	0.1910	-.1018	0.000615	0.1921	-0.109	0.000595

Table 2: Bus Voltage with and Without UPFC

Bus No.	Voltage without UPFC		Voltage with UPFC	
	[V]	θrad	[V]	θrad
1	1.06	0	1.06	0
2	1.04659	-0.0941	1.06472	-0.08027
3	1.02738	-0.13237	1.04596	-0.11657
4	1.01997	-0.16304	1.04252	-0.14310
5	1.01585	-0.24716	1.06760	-0.19006
6	1.01783	-0.19447	1.04437	-0.16909
7	1.00932	-0.22519	1.04620	-0.18601
8	1.01805	-0.20751	1.04467	-0.18150
9	1.02230	-0.25281	1.04836	-0.22533
10	1.00916	-0.28392	1.03531	-0.25532
11	1.05426	-0.25281	1.07958	-0.22533
12	1.00857	-0.26683	1.03319	-0.24011
13	1.02307	-0.26683	1.04736	-0.24011
14	0.99583	-0.28357	1.02103	-0.25582
15	0.99388	-0.28612	1.01946	-0.25811
16	1.00126	-0.27944	1.02674	-0.25169
17	1.00123	-0.28654	1.02733	-0.25801
18	0.98659	-0.29850	1.01271	-0.26962
19	0.98555	-0.30222	1.01190	-0.27301
20	0.99063	-0.29874	1.01696	-0.26963
21	0.99215	-0.29325	1.01856	-0.26430
22	1.00028	-0.29001	1.02670	-0.26106
23	0.99139	-0.29327	1.01777	-0.26437
24	0.98813	-0.29654	1.01491	-0.26720
25	0.98737	-0.28856	1.01467	-0.25923
26	0.96914	-0.29635	0.99694	-0.26660
27	0.99573	-0.20609	1.02308	-0.24970
28	1.01676	-0.20609	1.04355	-0.18025
29	0.97528	-0.39473	1.00324	-0.27117
30	0.96345	-0.31779	0.99176	-0.28659

Figure 5: Shows the Bus Voltages without UPFC

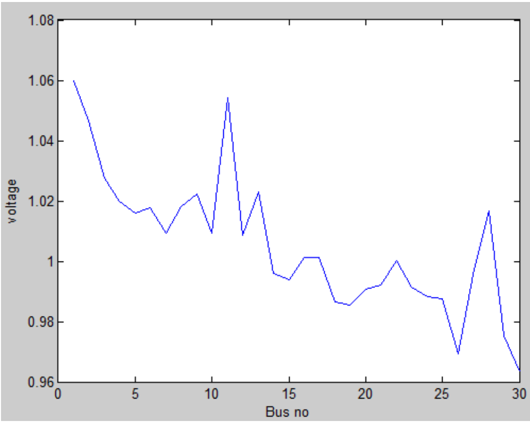


Figure 6: Shows the Phase Angle Without UPFC

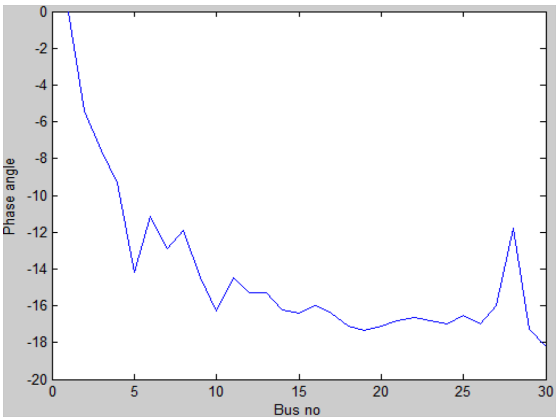


Figure 7: Shows the Active Power Flow without UPFC

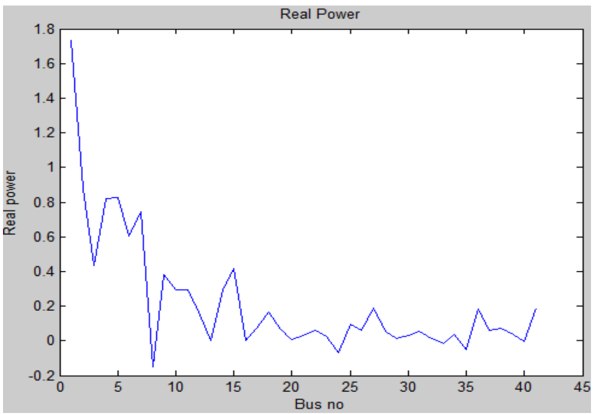


Figure 8: Shows the Reactive Power Flow without UPFC

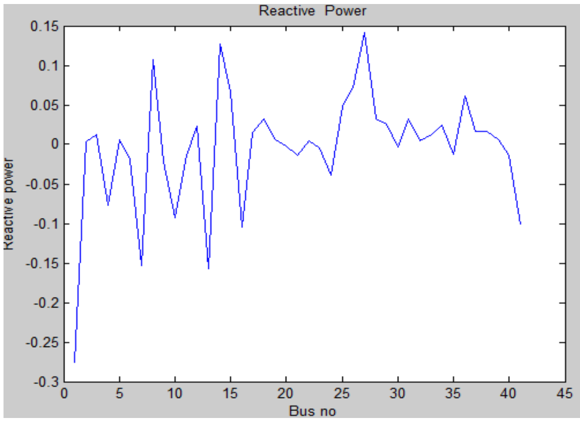


Figure 9: Shows the Total Losses without UPFC

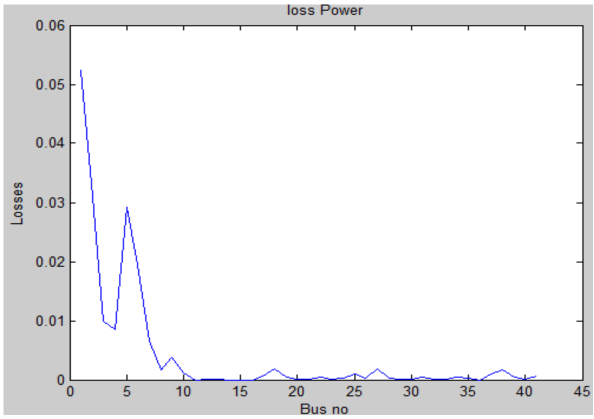


Figure 10: Shows the Bus Voltages with UPFC

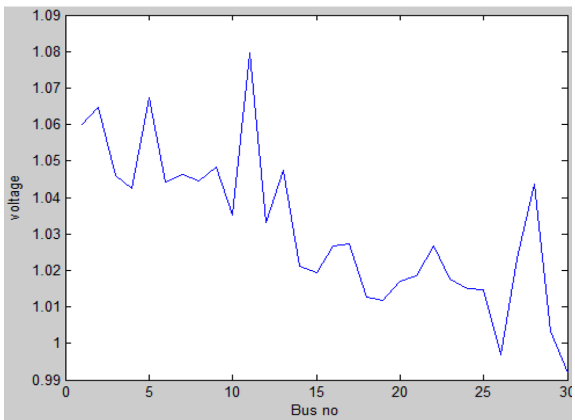


Figure 11: Shows the Phase Angle with UPFC

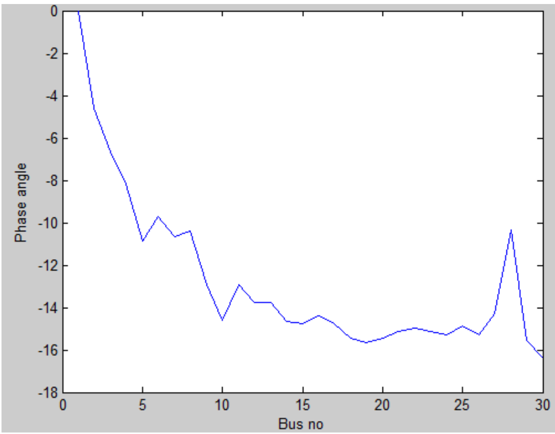


Figure 12: Shows the Active Power Flow with UPFC

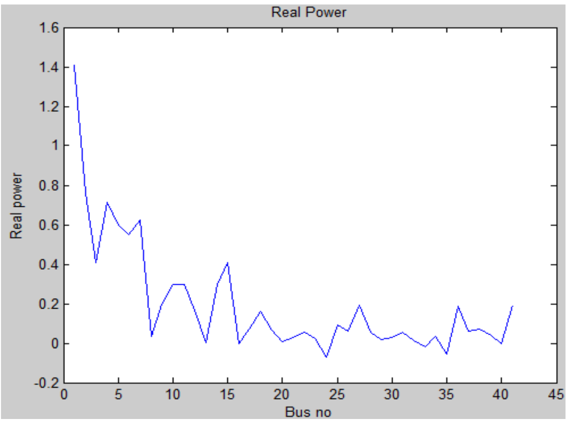


Figure 13: Shows the Reactive Power Flow with UPFC

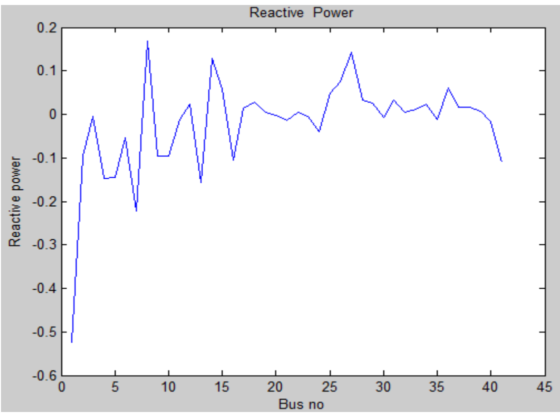
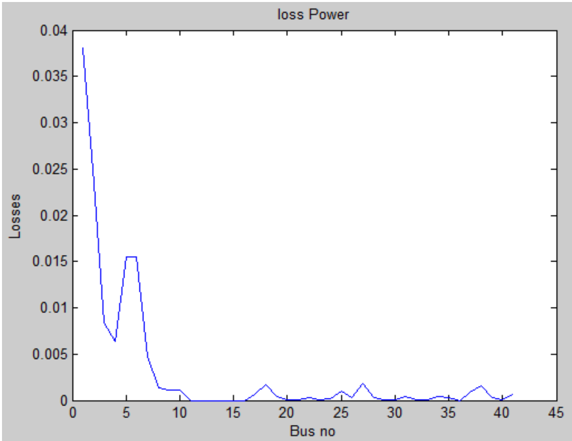


Figure 14: Shows the Total Losses with UPFC



CONCLUSION

In this paper the UPFC Voltage Source Model (VSM) was used to investigate the performance of the Unified Power Flow Controller (UPFC) and thereby the load flow studies were done by incorpating the Voltage Source Model of UPFC in the Newton Raphson (N-R) algorithm.

The N-R algorithm is able to control the flow of power and voltage individually as well as simultaneously. The result for a IEEE-30 Bus system has been presented above without and with UPFC and were compared in terms of Real and Reactive power flow and the Voltage magnitude. Hence it was observed that the UPFC regulates the real and reactive power of the buses and the lines and it also controls the voltage of the bus within specified limits, thereby reduces the total losses in the lines.

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