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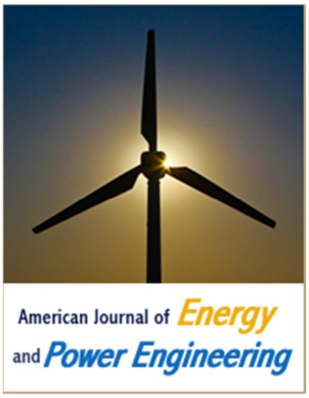

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Implementing of UPFC in the Power System Network to Control Power Flow and Minimization of Losses

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Abstract
Controlling power flow in modern power systems can be made more flexible by the use of recent developments in power electronic and computing control technology. The Unified Power Flow Controller (UPFC) is a Flexible AC transmission system (FACTS) device that can control all the three system variables namely line reactance, magnitude and phase angle difference of voltage across the line. The UPFC provides a promising means to control power flow in modern power systems. Essentially the performance depends on proper control setting achievable through a power flow analysis program. This paper presents a reliable method to meet the requirements by developing a Newton-Raphson based load flow calculation through which control settings of UPFC can be determined for the pre-specified power flow between the lines. The proposed method keeps Newton-Raphson Load Flow (NRLF) algorithm intact and needs (little modification in the Jacobian matrix). A MATLAB program has been developed to calculate the control settings of UPFC and the power flow between the lines after the load flow is converged. Case studies have been performed on IEEE 5-bus system and 14-bus system to show that the proposed method is effective. These studies indicate that the method maintains the basic NRLF properties such as fast computational speed, high degree of accuracy and good convergence rate.

1. Introduction

As the power systems are becoming more complex it requires careful design of the new devices for the operation of controlling the power flow in transmission system, which should be flexible enough to adapt to any momentary system conditions. The operation of an ac power transmission line, is generally constrained by limitations of one or more network parameters and operating variables by using FACTS technology such as STATCON (Static Condenser), Thyristor Controlled Series Capacitor(TCSC), Thyrisistor controlled Phase angle Regulator (TCPR), UPFC etc., the bus voltages, line impedances, and phase angles in the power system can be regulated rapidly and flexibly. FACTS do not indicate a particular controller but a host of controllers which the system planner can choose based on cost benefit analysis.

The UPFC is an advanced power system device capable of providing simultaneous control of voltage magnitude and active and reactive power flows in an adaptive fashion.

Owing to its instantaneous speed of response and unrivalled functionality, it is well placed to solve most issues relating to power flow control in modern power systems. The UPFC can control voltage, line impedance and phase angles in the power system[1] which will enhance the power transfer capability and also decrease generation cost and improve the security and stability(which is out of the scope of the paper) of the power system. UPFC can be used for power flow control, loop flow control, load sharing among parallel corridors. In this paper UPFC is treated to operate in closed loop form and control parameters of UPFC are derived to meet the required power flow along the line.

2. UPFC Model for Power Flow Studies

2.1. Principles of UPFC

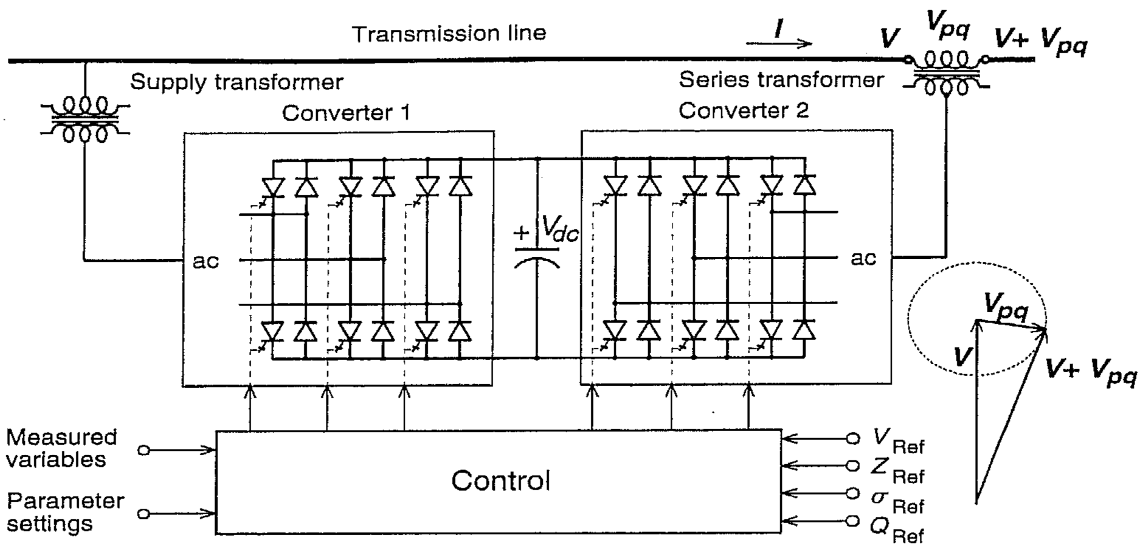

Fig. 1. *Implementation of the UPFC by back-to-back voltage source converters*

The UPFC can provide simultaneous control of transmission voltage, impedance and phase angle of transmission line. It consists of two switching converters as shown in fig1. These converters are operated from a common d.c link provided by a d.c storage capacitor. Converter 2 provides the power flow control of UPFC by injecting an ac voltage V_{pq} with controllable magnitude and phase angle in series with the transmission line via a series transformer. Converter 1 is to absorb or supply the real power demand by the converter 2 at the common d.c link. It can also absorb or generate controllable reactive power and provide shunt reactive power compensation.

The UPFC concept provides a powerful tool for cost effective utilization of individual transmission lines by facilitating the independent control of both the real and reactive power flow and thus the maximization of real power transfer at minimum losses in the line[5] This is the topic of this paper.

2.2. Power Injection Model of UPFC

The two voltage source model of UPFC is converted in to two power injections in polar form for power flow studies with approximate impedances as shown in fig 2. The advantage of power injection representation is does not destroy the symmetric characteristics of admittance matrix. When formulated in polar form, the power flow equations are quadratic. Some numerical advantages can be obtained from the form. The polar form also leads naturally to the idea of an optimal power flow, which will be discussed in next section. The voltage sources can be represented by the relation- ship between the voltages and amplitude modulation ratios and phase shift of UPFC.In this model the shunt transformer impedance and the transmission line impedance including the series transformer impedance are assumed to be constant. No power loss is considered with the UPFC. However the proposed model and algorithm will give the solution of optimal power flow in the transmission lines this will be discussed in section 3.3

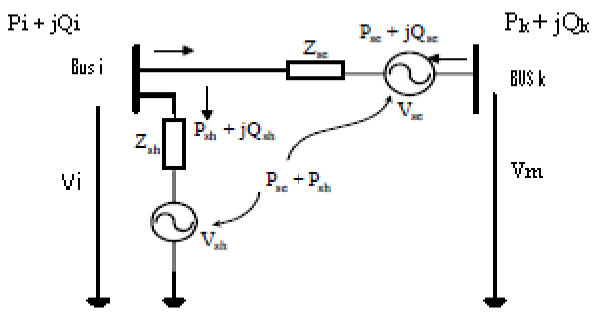

Fig. 2. *Two Voltage source model of UPFC*

2.3. Steady State UPFC Representation

There are two aspects in handling the UPFC in steady state analysis

1. When the UPFC parameters are given, a power flow program is used to evaluate the impact of the given UPFC on the system under various conditions. In this case UPFC is operated in open loop form. The corresponding power flow is treated as normal power flow(Which is the out of the scope of the paper).
2. As UPFC can be used to control the line flow and bus voltage, control techniques are needed to derive the UPFC control parameters to achieve the required objective. In this case UPFC is operated in closed loop form. The corresponding power flow is called controlled power flow. This is the topic of this paper.

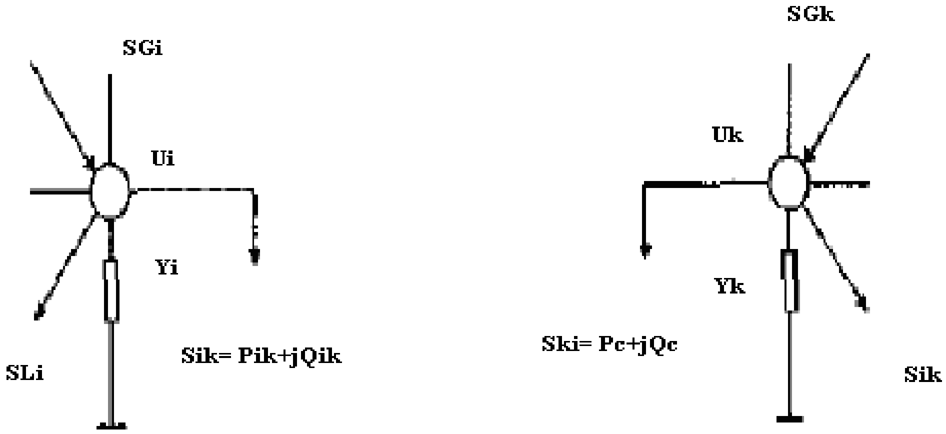

Fig. 3. *Steady state model of UPFC connected between bus l and m*

For a given control strategy, the power S_{ml} on the UPFC-controlled transmission line i-k is set to constant (P_c + jQ_c). By means of the substitution theorem, this branch i-k can be detached as shown in Fig.3. in which S_{ki}, represents power from the bus k and S_{ik}, from the bus i . For each other additional UPFC, its corresponding branch can be dealt with similarly

3. Problem Formulation of UPFC for Power Flow Studies

3.1. Load Flow Problem

In this paper the load flow problems are solved by using N-R method in polar co-ordinate form is an iterative method which approximates the set of linear simultaneous equations using Taylor's series expansion and the terms are limited to first approximation. In the power flow of the transmission line the complex power injected at the ith bus with respect to ground system is

$$S_i=P_i+ jQ_i \quad (3.1)$$

$$= V_i I_i^* \quad (3.2)$$

Where i=1, 2, 3……….n.

Where V_i is the voltage at the ith bus with respect to ground and I_i is the source current injected into the bus.

$$P_i +j\, Q_i = V_i I_i^* \quad (3.3)$$

Substituting for

$$I_i= \sum_{k=1}^{n} Y_{ik} V_k \quad (3.4)$$

Equating real and imaginary parts

$$P_i=\text{Real}V_i^* \sum_{k=1}^{n} Y_{ik} V_k \quad (3.5)$$

$$Q_i=-\text{imag}V_i^* \sum_{k=1}^{n} Y_{ik} V_k \quad (3.6)$$

$$V_i = |V_i| e^{j\delta 1} \quad (3.7)$$

$$Y_{ik} = |Y_{ik}| e^{j\delta 1} \quad (3.8)$$

Real power reactive power can now be expressed as

$$P_i \textit{ (Real power)}= |\, V_i\, || \sum_{k=1}^{n} |V_k||Y_{ik}| \cos(\theta_{ik}+\delta_k-\delta_i); \quad (3.9)$$

$$Q_i \textit{ (Reactive power)}= |\, V_i\, || \sum_{k=1}^{n} |V_k||Y_{ik}| \sin(\theta_{ik}+\delta_k-\delta_i); \quad (3.10)$$

i=1, 2, 3, 4………………..n-;i≠slack bus

The following are the formulae of the UPFC to be involved in power flow studies. The major symbols used are:

S : Complex or Apparent power

S_{ik}: Complex power flowing from bus i to bus k

ΔS: Change in complex power

P : Real power

P_c : Pre – Specified real power

P_f : Real power flowing in the line

P_e : Difference in pre-specified an line real power
P_B: Real power supplied by booster transformer
P_E : Real power supplied by excitation transformer
P_{ik}: Real power flowing from bus i to k
ΔP : Change in real power
Q: Reactive power
Q_c: Pre specified reactive power
Q_f: Reactive power in line
Q_e: Difference in pre specified and line reactive power
Q_{ik} : Reactive power flowing from bus i to k
Q_B: Reactive power supplied by booster transformer
Q_E : Reactive power supplied by excitation transformer
ΔQ : Change in reactive power
V : Voltage magnitude
U_T : Injected voltage magnitude.
$U_{T\,max}$: Limits on injected voltage magnitude
$\Delta |V|$: Change in magnitude of voltage
δ: Phase angle of voltage
δ_{lm}: Phase angle difference between bus l and bus m
$\Delta\delta$: Change in phase angle of voltage.
Φ_T : Injected voltage phase angle
ε : Tolerance
Iq : Exciting transformer reactive current
Y: Admittance
θ_{ik}: Phase angle of admittance w.r.t reference
Y_{BUS} : Bus admittance matrix
Y_{ii} : Self Admittance
Y_{ik} : Mutual admittance, $i \neq k$
G_{ik} : Real part of admittance in p.u
B_{ik} : Imaginary part of admittance in p.u
J = Jacobian matrix
j: complex power$\sqrt{-1}$
m: Amplitude modulation index
R_{ik} : Resistance between bused i and k in p.u
X_{ik}: Reactance between bused i and k in p.u
B_{ik}: Line charging susceptance between i and k in p.u
Z_{ik}: Impedance between bused i and k in p.u

3.2. UPFC Modified Jacobian Matrix Elements

In power flow the two power injections(Pi, Qi) and (Pj, Qj) as shown in fig 2 in section 2.2 of a UPFC can be treated as generators, however because they vary with the connected bus bar voltage amplitudes and phases the relevant elements of Jacobin matrix at each iteration.

The formation of Jacobian matrix

$$\begin{bmatrix}\Delta p\\ \Delta Q\end{bmatrix} = \begin{bmatrix}H & N\\ J & L\end{bmatrix}\begin{bmatrix}\Delta\delta\\ |\Delta v|\end{bmatrix}$$

Where H, N, J, L are the elements of Jacobian matrix.

$$H_{im} = \frac{\partial Pi}{\partial \delta m};\ N_{im} = \frac{\partial Pi}{\partial |Vm|};$$

$$J_{im} = \frac{\partial Qi}{\partial \delta m};\ L_{im} = \frac{\partial Pi}{\partial |Vm|};$$

The elements of Jacobian matrix can be calculated as follows

case1: $m \neq 1$

$$H_{im} = L_{im} = a_m f_i - b_m e_i\ ; N_{im} = -J_{im} = a_m e_i - b_m f_i$$

Where $Y_{im} = G_{im} + jB_{im},\ V_i = e_i - jf_i$

$$(a_m + jb_m) = (G_{im} + j\,B_{im}) * (e_i - j\,f_i)$$

Case 2: $m = i$

$$H_{ii} = -Q_i - B_{ii}|V_i|^2;$$

$$N_{ii} = P_i + G_{ii}\,|V_i|^2\ ;\ J_{ii} = P_i - G_{ii}\,|V_i|^2;\ L_{ii} = Q_i - B_{ii}\,|V_i|^2$$

3.3. Optimal Power Flow Algorithm

In this paper optimal power flow algorithm is adopted as it offers a number of advantages that is to detect the distance between the desired operating point and the closest unfeasible point. Thus it provides a measure of degree of controllability and it can provide computational efficiency with out destroying the advantages of the conventional power flow when used error feedback adjustment to implement UPFC model. The proposed model and algorithm as follows

1. Assume bus voltage$V_p$except at slack bus i.e. p=1, 2, 3………n; p≠s Where n is the number of buses.
2. Form Y-bus matrix.
3. Set iteration count k=0.
4. Set the convergence criterion,€
5. Calculate the real and reactive power P_p and Q_p at each bus where p=1, 2, 3…….n; p≠s.
6. Evaluate $\Delta P_p = P_{spe} - P_p$ and $\Delta Q_p = Q_{spe} - Q_p$at each bus where p=1, 2, 3…….n; p≠s.
7. Compare each and every residue with € and if all of them are ≤€ then go to step 13.
8. Calculate the elements of Jacobian matrix.
9. Calculate increments in phase angles and voltages.
10. Calculate new bus voltages and respective phase angles $V_p^{k+1} = V_p^k + \Delta V_p^k$ and $\theta_p^{k+1} = \theta_p^k + \Delta\theta_p^k$ where p=1, 2, 3…….n; p≠s.
11. Replace V_p^k by V_p^{k+1} and θ_p^k by θ_p^{k+1} where p=1, 2, 3…….n; p≠s.
12. Set k=k+1 and go to step 5.
13. Print the final values of voltage magnitudes and corresponding phase angles.

4. Power Flow Studies of UPFC by Using Control Strategies

The Implementation of UPFC models in power flow is essentially a controlled power flow problem. The UPFC modeling needs the change of relevant elements of Jacobian matrix however the user defined power flow software do not allow users to directly modify the Jacobian matrix and only provide the facilities for the iteration between the main program and user defined model. This iteration sometimes diverges especially when the system is heavily loaded.

In this section the UPFC represented by two voltage sources of series path and shunt path is often transformed in to a pair of power injections (Pi, Qi), (Pj, Qj) at both sides of UPFC locations in order to be incorporated into power flow algorithm. From the view point of effects of these power injections on the system Qi can be independently regulated to support bus bar voltage connected at the shunt path Pi and Pj are used to manipulate line active power with equal magnitude but at reverse direction and Qj can control both j bus bar voltage and line reactive power based on this analysis the philosophy of the UPFC local control strategy is described. After modifying all the UPFC connected branches, the load flow equations can be written as follows

$$P_i + jQ_i = V_i^* \sum_{k=1}^{n} V_k Y_{ik} \quad i \neq 1,m \tag{3.11}$$

$$P_l + jQ_l = V_i^* \sum_{k=1}^{n} V_k Y_{ik} + (P_{lm} + jQ_{lm}) i \neq 1,m \tag{3.12}$$

$$P_m + jQ_m = V_i^* \sum_{k=1}^{n} V_k Y_{ik} + (P_c + jQ_c) \tag{3.13}$$

With the above modifications the load flow studies should be done, after convergence the control settings of UPFC can be determined as follows [1].

1. Use Qi to control bus voltage Vi
2. Use Pi and Pj to control the line power.
3. Set Qj= 0 (i.e. better to use Qi to control Vi since it is closer to the bus).
4. The feedback information of power injections (Pi, Qi) (Pj, Qj) derived from the above closed-loop controllers is then converted into UPFC control parameters.

5. Case Study and Conclusion

5.1. Case Study

In order to investigate the feasibility of the proposed technique, a large number of power systems of different sizes and under different system conditions has been tested. It should be pointed out that the results are under so-called normal power flow, i.e. the control parameters of UPFC are given and UPFC is operated in an closed -loop form. All the results indicate good convergence and high accuracy achieved by the proposed method. In this section, the IEEE 5-bus system and a 14-bus practical system have been presented to numerically demonstrate its performance. It have been used to show quantitatively, how the UPFC performs. The original network is modified to include the UPFC. This compensates the line between any of the buses. The UPFC is used to regulate the active and reactive power flowing in the line at a pre- specified value. The load flow solution for the modified network is obtained by the proposed power flow algorithm and the Matlab program is used to find the control setting of UPFC for the pre-specified real and reactive power flow between any buses and the power flow between the lines are observed the effects of UPFC. The same procedure is repeated to observe the power flow between the buses. (Depending on the pre specified value of the active and reactive power the UPFC control setting is determined after the load flow is converged.)

5.2. Test Results for IEEE 5 Bus System

The performance of UPFC on the IEEE 5 bus system shown in figure4.

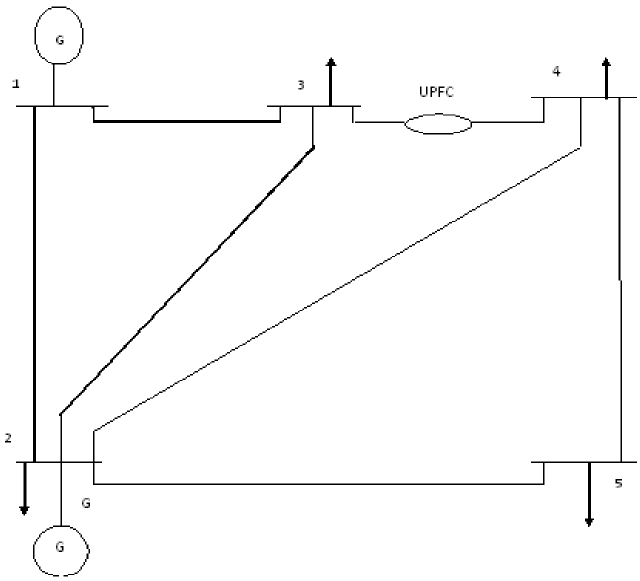

Fig. 4. *IEEE 5 bus system*

5.2.1. Test Results Without UPFC

The voltage profile of the system is tabulated below

Table 01. *Voltage profile of the IEEE 5 bus system without UPFC*

Bus code	Voltage(p.u)	Angle(rad)	Angle(deg)
1	1.060000	0.000000	0.000000
2	0.992621	-0.033974	-1.946578
3	0.981487	- 0.080021	-4.584891
4	0.977982	-0.085585	-4.903633
5	0.964484	-0.099667	-5.710501

and the Power flow profile of the system

Table 02. *Power flows in the IEEE 5 bus system without UPFC*

Bus code	Real power(p.u)	Reactive power(p.u)	Loss(p.u)
1-2	0.896246	0.868027	0.028772
1-3	0.420055	0.192529	0.016028
2-3	0.244368	-0.034026	0.003649
2-4	0.276769	-0.024054	0.004666
2-5	0.546338	0.053060	0.012304
3-4	0.194745	0.040617	0.000420
4-5	0.066428	0.009338	0.000462

5.2.2. Test Results with UPFC (Bus 3 and 4)

The voltage profile of the system with pre-specified real and reactive power flows as 0.4 and 0.02.

Table 03. *Voltage profile of the IEEE 5 bus system with UPFC (bus 3-4)*

Bus code	Voltage(p.u)	Angle(rad)	Angle(deg)
1	1.060000	0.000000	0.000000
2	0.998054	-0.018069	-1.035270
3	0.990627	-0.047300	-2.710086
4	0.988389	-0.045750	-2.621289
5	0.972024	-0.075181	-4.307549

The choice of "P_c" and "Q_c" are valid

The control settings of UPFC are:

Table 04. *Control settings of UPFC (bus3-4)*

Voltage (U_T in p.u)	Phase angle (φ_T in rad)	Phase angle (φ_T in deg)
0.013630	-1.817928	-104.159581

The Power flow profile of the system

Table 05. *Power flow of the IEEE 5 bus system with UPFC (bus3-4)*

Bus code	Real power (p.u)	Reactive power(p.u)	Loss(p.u)
1-2	0.615899	0.858253	0.020914
1-3	0.279573	0.190009	0.008952
2-3	0.157541	-0.028911	0.001500
2-4	0.153222	-0.015307	0.001415
2-5	0.484222	0.053322	0.009603
3-4	0.400464	0.019989	0.000951
4-5	0.126755	0.002453	0.001375

5.2.3. Test Results with UPFC (Bus 2 and 5)

The voltage profile of the system is:

Table 06. *Voltage profiles of the IEEE 5 bus system with UPFC (bus 2-5)*

Bus code	Voltage(p.u)	Angle(rad)	Angle(deg)
1	1.060000	0.000000	0.000000
2	0.998937	-0.015406	-0.882724
3	0.988461	-0.059093	-3.385767
4	0.985640	-0.061540	-3.526007
5	0.978559	-0.044272	-2.536618

The choice of "P_c" and "Q_c" are valid

The control setting of UPFC is

Table 07. *Control settings of UPFC (bus 2-5)*

Voltage (U_T in p.u)	Phase angle (φ_T in rad)	Phase angle (φ_T in deg)
0.018444	-1.555852	-89.143778

The Power flow profile of the system

Table 08. *Power flows of the IEEE 5 bus system with UPFC (bus 2-5)*

Bus code	Real power (p.u)	Reactive power(p.u)	Loss(p.u)
1-2	0.568953	0.857510	0.019900
1-3	0.329123	0.185785	0.010969
2-3	0.234625	-0.034794	0.003323
2-4	0.250920	-0.023983	0.003787
2-5	0.400231	0.019998	0.007340
3-4	0.099455	0.050129	0.000138
4-5	-0.053549	0.023245	0.000422

5.3. Test Results for 14 Bus System

The performance of UPFC on the IEEE 14 bus system shown in figure5. and the data as shown in appendix –II

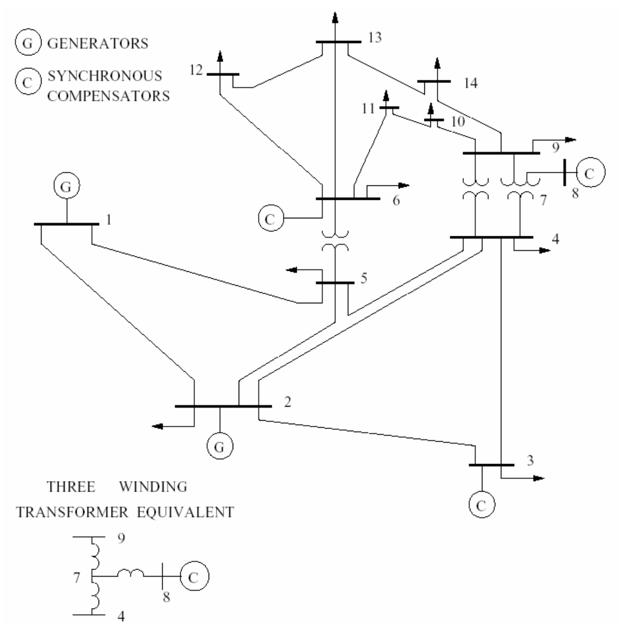

Fig. 5. *IEEE 14 bus system*

5.3.1. Test Results without UPFC

The voltage profile of the system is tabulated below

Table 09. *Voltage profile of the IEEE 14 bus system without UPFC in the system*

Bus code	Voltage(p.u)	Angle(rad)	Angle(deg)
1	1.060000	0.000000	0.000000
2	0.179331	-2.288247	-131.106867
3	3.003445	2.569834	147.240670
4	0.801914	1.153725	66.103578
5	0.557927	2.134085	122.274079
6	0.361504	0.632530	36.241286
7	1.205262	0.493703	28.287102
8	0.029187	0.237284	13.595389
9	0.200750	-1.509105	-86.465347
10	0.088059	1.616350	92.610029
11	0.095862	-1.698440	-97.313422
12	0.398357	1.836755	105.238306
13	1.116873	-0.412811	-23.652326
14	0.632956	2.982683	170.895172

and the Power flow profile of the system

Table 10. *Power profiles of the IEEE 14 bus system without UPFC in the system*

Bus no	Real power(p.u)	Reactive power(p.u)	Loss(p.u)
1-2	8.427942	18.311464	7.027357
1-5	-0.640964	6.581140	2.119981
2-3	2.496023	-0.825690	10.097645
2-4	0.503510	0.794991	1.601668
2-5	0.601350	0.152012	0.681603
3-4	29.240393	39.059395	17.718054
4-5	-5.324704	11.044104	3.120731
4-7	2.833800	-0.576041	0.000000
4-9	0.133342	1.413121	-0.000000
5-6	0.798388	1.179781	0.000000
6-11	0.404998	0.583696	0.366826
6-12	-0.306318	0.456276	0.284050
6-13	1.908977	-1.520838	3.015375
7-8	0.050649	8.053528	0.000000
7-9	1.997330	14.125655	0.000000
9-10	0.223268	0.602056	0.325453
9-14	0.472542	0.029734	0.707077
10-11	0.023820	0.073490	0.063149
12-13	1.870098	0.124471	4.890334
13-14	2.607364	4.269854	3.429823

5.3.2. Test Results with UPFC (Bus 2 and 5)

The voltage profile of the system is

Table 11. *Power profiles of the IEEE 14 bus system without UPFC in the system (bus 2-5)*

Bus code	Voltage(p.u)	Angle(rad)	Angle(deg)
1	1.060000	0.000000	0.000000
2	1.137716	0.085501	4.898831
3	1.197531	0.187757	10.757695
4	1.185627	0.165721	9.495116
5	1.167506	0.142518	8.165699
6	1.206837	0.219664	12.585838
7	1.208420	0.206742	11.845449
8	1.208420	0.206742	11.845449
9	1.221203	0.227689	13.045600
10	1.225012	0.229993	13.177616
11	1.218993	0.226622	12.984494
12	1.219505	0.230963	13.233204
13	1.223628	0.231860	13.284619
14	1.237072	0.242100	13.871284

The choice of "P_c" and "Q_c" are valid

The control setting of UPFC is

Table 12. *Control settings of the UPFC when installed in the IEEE-14 bus system*

Voltage ($U_T$in p.u)	Phase angle (φ_T in rad)	Phase angle (φ_T in deg)
0.032423	1.302547	74.630

and the Power flow profile of the system

Table 13. *Power profiles of the IEEE 14 bus sytem when UPFC is installed in the system (bus 2-5)*

Bus no	Real power(p.u)	Reactive power(p.u)	Loss(p.u)
1-2	-1.961689	-0.704930	0.074240
1-5	-0.848453	-0.276779	0.037601
2-3	-0.734209	-0.161881	0.020217
2-4	-0.637580	-0.096423	0.018498
2-5	-0.447139	-0.058455	0.008854
3-4	0.187574	0.002699	0.001651
4-5	0.842512	0.251929	0.007344
4-7	-0.280967	-0.123464	0.000000
4-9	-0.161216	-0.070842	0.000000
5-6	-0.430879	-0.165576	-0.000000
6-11	-0.070517	-0.039904	0.000428
6-12	-0.075997	-0.022882	0.000532
6-13	-0.172365	-0.067185	0.001554
7-8	0.000000	0.000000	0.000000
7-9	-0.280967	-0.137476	0.000000
9-10	-0.053867	-0.034732	0.000088
9-14	-0.093316	-0.027226	0.000805
10-11	0.036046	0.023035	0.000100
12-13	-0.015529	-0.007988	0.000045
13-14	-0.054493	-0.020275	0.000386

6. Conclusions

The unified power flow controller provides simultaneous or individual controls of basic system parameters like transmission voltage, impedance and phase angle, thereby controlling transmitted power. In this thesis an IEEE 5-bus system is taken into consideration to observe the effects of UPFC. Load flow studies were conducted on given system to find the nodal voltages, and power flow between the nodes. The MATLAB program is run with and without incorporation of UPFC. The UPFC is incorporated between buses (3, 4) and (2,5) to improve the power flow between the lines to a pre-specified value. From the results it has been observed that the power flow between the lines is improved to a pre-specified value. Depending on the pre-specified value the UPFC control settings were determined. The real power losses between the lines were decreased after the incorporation of UPFC.so, it can be concluded that after the incorporation of UPFC the voltage profile and power flow between the lines improves. Also by using this program, control setting of UPFC for different pre-specified power flows can be obtained

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