International Journal of Engineering Research and General Science Volume 3, Issue 2, Part 2, March-April, 2015
ISSN 2091-2730

Load Flow Study of A UPFC Embedded System

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Abstract— The Unified Power Flow Controller (UPFC) in its general form can provide simultaneous, real time control of all basic power system parameters (transmission, voltage, impedance and phase angle) or any combinations there-of determining transmitted power in AC transmissions. This paper addresses the steady-state modeling of UPFC, within the context of Load Flow study of a power system. This model is incorporated into an existing Newton – Raphson Load Flow algorithm. This proposed algorithm exhibits quadratic or near quadratic convergence characteristics, regardless of the size of the network and the number of FACTS devices.

Keywords— Unified Power Flow Controller, Flexible AC Transmission Systems (FACTS), Control Strategy, Interflow Power Flow Controller (IPFC), De-regulation, Newton-Raphson method, Jacobian , Power Flow Control, AC Power transmission, IPP

1. INTRODUCTION

Optimizing the use of power transfer capability of a transmission network is always a concern in the power supply industry. Expansion in power transmission networks has taken place not only due to the increase in generation and loads but also due to the extensive interconnection among different power utilities. Interconnection between various systems is done mainly to reduce generation reserves. However power flow congestion occurs in strategic routes because of inflexibility of their power control capability [1]. Upgrading existing transmission lines or enhancing their power controllability is common practical means of achieving a better utilization of their ultimate design limit. In modern power systems, much attention has been given to explore both capital and technical concepts on how to utilize existing transmission system better.

Line compensation in the past has primarily been for reactive power management. Switched or fixed shunt capacitors and reactors as well of series capacitors are typically applied. Synchronous condensers have also been used and continue to be used where dynamic voltage control is needed. In the 70’s, the Static Var Compensator (SVC) began to be applied. The first of these was the EPRI – Minnesota Power & Light and Westinghouse project commissioned in 1978[6]. Prior to this, SVC system had been applied for Voltage control primarily at locations with heavy industrial loads but not for transmission system stabilization. The amount of compensation is easily determined for steady state operation. However, in heavily compensated systems, the voltage profiles are much flatter and therefore there is almost no warning prior to reaching the point of voltage collapse. Thus voltage stability has to be continuously monitored to ensure is kept at an operating point which remains stable after a disturbance.
Advances have been made in high power semi-conductor devices, control technologies which have been instrumental in the broad application of HVDC transmission and power inertia schemes having significant impact on AC transmission.

The concept of Flexible AC Transmission System (FACTS) devices has gradually evolved as a new dimension in network analysis. The concept of FACTS was first proposed by Dr. Nori Hingorani, in 1988 when he was working in Electric Power Research Institute (EPRI), CA, and USA [1]. It involves application of high power electronic controllers in AC transmission networks, which enable fast and reliable control of power flows and voltages. FACTS don’t indicate a particular controller but a host of controllers, whom the system planner can choose, based on cost benefit analysis. This new dimension is the proper adjustment in parameters including transmission line impedance, bus voltage magnitudes and phase angles. By doing so, it is possible to regulate power flow and voltage in the network at will and it is also possible to render the dispatch of electricity more controllable, reliable and flexible[2]. The ability to regulate the power flows in certain paths in a network is of particular importance, especially in a de-regulated electricity market.

The FACTS devices enable the routing of power in the steady state in any desired manner independent of the impedance of the various paths. This has assumed considerable significance with the emergence of IPP (Independent Power Producers), who are willing to invest in power, provided they are assured of wheeling of the power generated by them, to the areas where power is in demand. The fast progress in power electronics has made power wheeling a technically feasible happening.

Some of the first generation FACTS devices which used conventional Thyristors can be listed as

1) SVC (Static Var Compensator)
2) TCSC (Thyristor Controlled Series Compensator)

Presently a new generation FACTS devices are developed. These controllers are based on self-commutated voltage source based converters (VSC) using GTO Thyristor technology. These controllers are:

1) STATCOM (Static Var Generator)
2) SSSC (Static Synchronous Series Compensator)
3) SPS (Static Phase Shiftor)
4) UPFC (Unified Power Flow Controller)
5) IPFC (Interline Power Flow Controller)

The objectives that are to be met by FATCS devices can be listed as below:

1) Power flow can be regulated in prescribed transmission routes
2) Loading of lines nearer their thermal limits
3) Prevention of cascading outages by contributing to emergency control
4) Damping of oscillation which can threaten security or limit the useable line capacity.

FACTS is the underpinning concept upon which are based promising means to avoid effectively power flow bottle necks and ways to extend the loadability of existing power transmission network. The Unified Power Flow Controller (UPFC) is a promising FACTS device for load flow control.

Power systems embedded with FACTS devices have become an integral part of power system. Hence it is essential to perform some basic studies like load flow study, stability study, fault analysis etc. to investigate the impact of FACTS devices on power systems.

2. UNIFIED POWER FLOW CONTROLLER

The Unified Power Flow Controller (UPFC) facilitates the real time control and dynamic compensation of AC transmission systems. It provides the necessary functional flexibility required for solving the problems faced by the utility industry. The UPFC could be considered as comprehensive real and reactive power flows in the line. UPFC concept provides a powerful tool for the 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.

The UPFC consists of two switching converters, which in implementation considered are Voltage - Source inverters using Gate Turn off (GTO) Thyristor values as shown in Fig.1.These inverters labeled, Inverter 1 and Inverter 2 are operated from a common DC link provided by a DC storage capacitor. This arrangement works as an ideal AC to AC power converter in which real power can freely flow in either directions between AC terminals of the two inverters and each inverter can independently generate (or absorb) reactive power at its own AC O/P terminal

Inverter 2 provides the main function of the UPFC by injecting as AC voltage V_{pq} with controllable magnitude and phase angle at the power frequency, in series with line via an insertion transformer. The basic function of Inverter 1 is to supply or absorb real power demand by Inverter 2 at the common DC link. This DC link is converted back to AC and coupled to transmission line via shunt connected transformer.

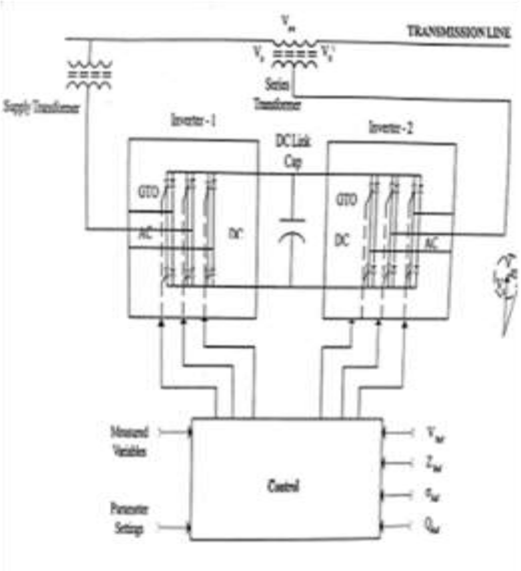
2.1 Operational features of UPFC

Operation of UPFC combines the functions of series compensator, shunt compensator and phase shifter, UPFC can fulfill all these functions there by meet multiple control objectives by adding the injected Voltage Vpq, with appropriate amplitude and phase angle to the terminal voltage. Using phasor representation, basic UPFC power flow control functions are shown in Fig. 2

a) **Voltage regulation:** This function is similar to that of regulation obtained with transformer tap changes having infinitely small steps. Here Vpq = ΔV is injected in phase or anti phase with Vo. That is, infact the shunt compensation is realized.
b) **Series Capacitive Compensation:** Here Vpq=Vc is injected in quadrature with the line current I
c) **Phase Angle regulation: Vpq**= Vσ is injected with an angular relationship with respect to Vo that achieves the desired σ phase shift (advance or retard) without any changes in magnitude.
d) **Multi-functional Power Flow Control:** Here Vpq = ΔV+Vc+Vσ. In this mode UPFC combines the functional features of voltage regulation, series compensation, shunt compensation and also phase angle regulation.

The powerful, hitherto unattainable, capabilities of the UPFC summarized above in terms of conventional transmission control concepts can be integrated into a generalized power flow controller that is able to maintain prescribed and independently controllable, real power P and reactive power Q in the line.

ISSN 2091-2730



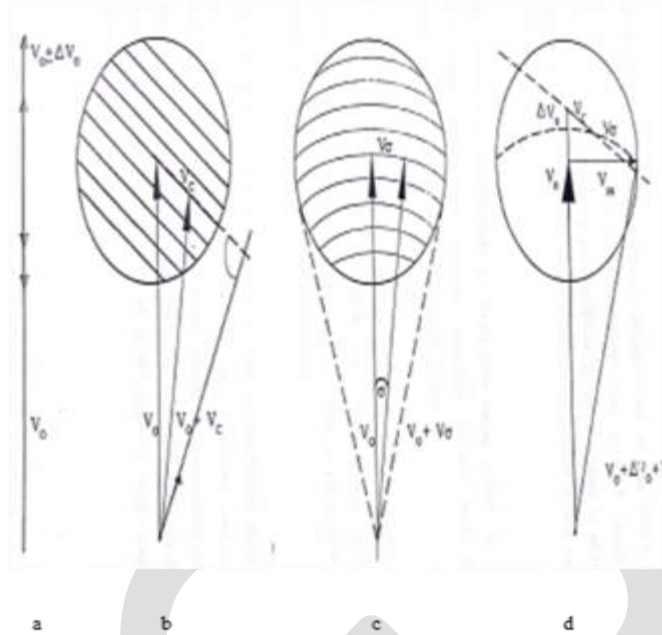


Fig. 2.Basic UPFC Control functions: a) Voltage regulation b) series compensation c) angle regulation d) multi-function power flow control

Fig. 1. Basic circuit arrangement of UPFC

2.2 Generalized power flow controller

In this context it is appropriate to show that using UPFC in a line, we can transmit more power and hitherto increase steady state stability limit. Consider a two machine model as shown in Fig.3 [1]. This figure shows the sending end generator with voltage Vs, the receiving end generator with voltage phasor V_r, the transmission line impedance X (assumed inductive) in two sections (X/2) and a generalized power flow controller operated at the middle of the line [2]

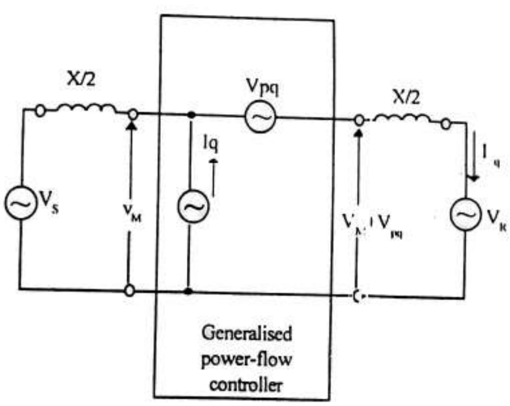


Fig. 3. Simple Two – machine power system with a generalized Power – Flow controller

The power flow controller consists of two controllable elements, a voltage source (Vpq) inserted in series with the line and a current source (Iq) connected in shunt with the line at the midpoint. Both the magnitude and the angle of Voltage (Vpq) and freely variable whereas only the magnitude of current (Iq) is variable. Its phase angle is fixed at 90 degrees with respect to midpoint voltage.
The four classical cases of power transmission

1. Without line compensation (P1)
2. With series capacitive compensation (P2)
3. With shunt compensation (P3)
4. With Phase angle control (P4)

Can be obtained by appropriately specifying Vpq and Iq in the generalized power flow controller.

In the above four classical cases of power transmission can be expressed by well- known formula by assuming suitable values according to the case mentioned for steady state operation of the system.

$$P = \frac{(V_r * V_s)}{X} \sin\delta$$

These classical four cases can be well explained for a two machine power system in the fig.4

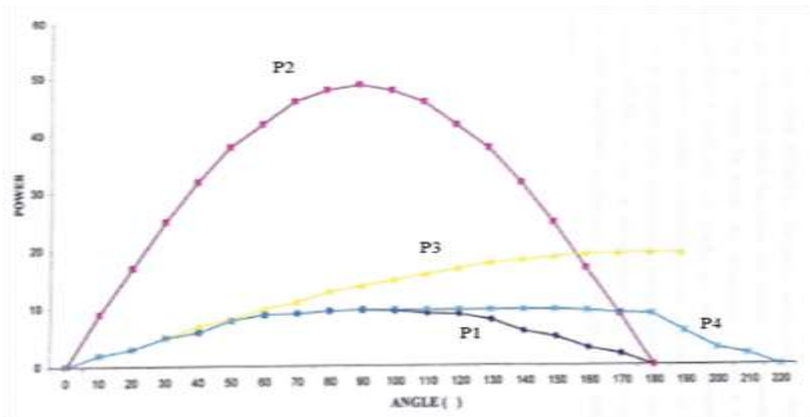


Fig.4. Power Transmission Characteristics for Two machine power system

3. STEADY STATE MODELING OF UPFC

Performance analysis and control synthesis of UPFC required its steady state and dynamic models. In this paper a steady state model of UPFC is presented [3]. The main assumptions in deriving the model is assuming the power system to be

1) Symmetrical
2) Operates under 3-phase balanced conditions

This steady state model is based on two ideal voltage source converters. One is in Series with the Line and one is in Shunt with the Line[15]. It is well suited for incorporation into an existing N-R load flow algorithm. In common with all other controllable plant component models available in the algorithm, UPFC state variables are incorporated inside Jacobian matrix and mismatch equations, leading to very robust iterative solution.

This UPFC model has been tested extensively in a wide range of power networks of varying size and degree of operational complexity [4]. A schematic representation of UPFC is shown in Fig. 5. The output voltage of series converter is added to AC terminal voltage V_o via the series connected coupling transformer. The injected voltage V_{cr} acts as an AC series voltage source changing the effective sending end voltage as seen from node m.

The product of transmission line current I_m and series voltage source V_{cr} determines the active and reactive power exchanged between the series converter and the AC system.

Then real power demanded by the series converter is supplied from AC power system by the shunt converter via the common DC link. The shunt converter is able to generate or absorb controllable reactive power in both operating modes (i.e. rectifier and inverter). The independently controlled shunt reactive compensation can be used to maintain the shunt converter terminal AC voltage magnitude at a specified value.

3.1 Mathematical Model of UPFC

The UPFC equivalent circuit shown in Fig.6 below is used to derive the steady state mathematical model.

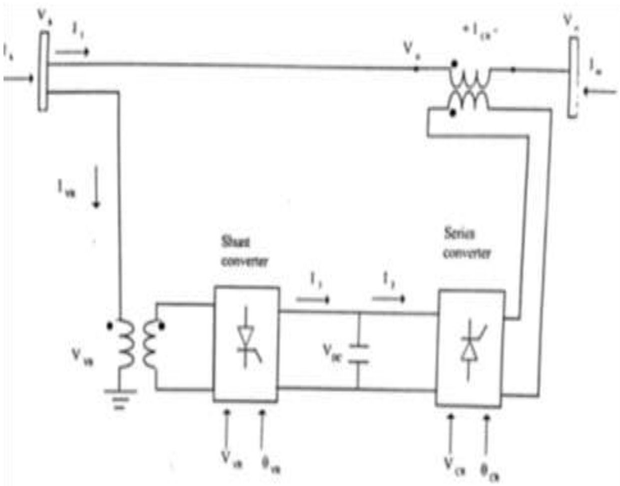


Fig.5. UPFC Schematic Diagram

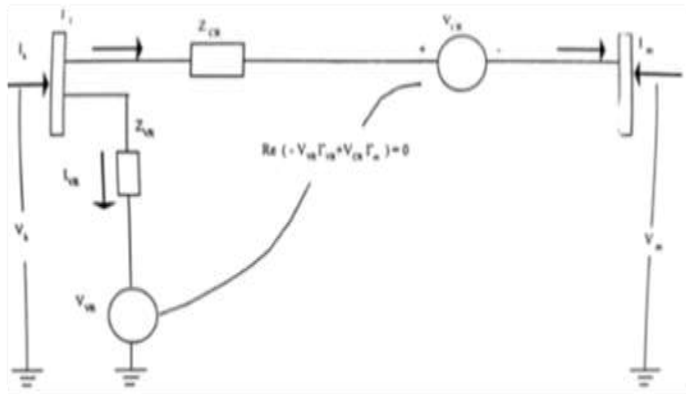


Fig. 6. UPFC Equivalent Circuit

The equivalent circuit consists of two ideal voltage sources representing the fundamental Fourier series component of the switched voltage wave forms at the AC converter terminals. The ideal voltage sources are

$V_{vr} = V_{vr} (\text{Cos}\theta_{vr} + j\ \text{Sin}\theta_{vr})$

$V_{cr} = V_{cr} (\text{Cos}\theta_{cr}+ j\ \text{Sin}\ \theta_{cr})$

Where V_{vr} and θ_{vr} are the controllable magnitude $V_{vrmin}<=V_{vr}<=V_{vrmax}$ and angle $(0<=\theta_{vr}=360^0)$ of the voltage source representing shunt converter. The magnitude V_{cr} and angle θ_{cr} of the voltage source of the series converter are controlled between the limits $V_{crmin} <= V_{cr} <= V_{crmax}$ and angle $(0<=\theta_{cr}=360^0)$ respectively. The real and reactive powers injected nodes k, m and also at series and shunt converters.

The real and reactive powers injected at nodes k,m and also at series converter and shunt converter.
At node k:
$S_k = V_k * I_K$

$P_k= (V_k * V_{cr} * b_1 * \text{Sin}\ (\theta_k - \theta_{cr})) + (V_k * V_m * b_1 * \text{Sin}\ (\theta_k – \text{Sin}\ \theta_m) + (V_k * V_{vr} * b_2 * \text{Sin}\ (\theta_k – \text{Sin}\ \theta_{vr}))$

$Q_k = (V_k^2 * b_1) + (V_k^2 * b_2) – (V_k * V_{cr} * b_1 * \text{Cos}\ (\theta_k – \theta_{cr})) - (V_k * V_m * b_1 * \text{Cos}\ (\theta_k – \theta_m)) - (V_k * V_{vr} * b_2 * \text{Cos}\ (\theta_k – \theta_{vr}))$

Where
$b_1 = |Zcr^{-1}|$ and $\theta_{cr} = /\_\ Zcr^{-1}$
$b_2 = |Zvr^{-1}|$ and $\theta_{vr} = /\_\ Zvr^{-1}$
At node m :
$Sm = V_m * Im$
$Pm= - (V_m * V_{cr} * b_1 * \text{Sin}\ (\theta_m - \theta_{cr})) + (V_m * V_k * b_1 * \text{Sin}\ (\theta_m – \text{Sin}\ \theta_k))$
$Qm = (V_m^2 * b_1) + (V_k^2 * b_2) – (V_m * V_k * b_1 * \text{Cos}\ (\theta_m – \theta_k)) + (V_m * V_{cr} * b_1 * \text{Cos}\ (\theta_m – \theta_{cr}))$

At Series Converter :
$S_{cr} = V_{cr} * I_m$

$P_{cr}= - (V_{cr} * V_m * b_1 * \sin(\theta_{cr} - \theta_m)) + (V_{cr} * V_k * b_1 * \sin(\theta_{cr} - \sin\theta_k))$

$Q_{cr} = (V_{cr}^2 * b_1) + (V_{cr} * V_m * b_1 * \cos(\theta_{cr} - \theta_m)) - (V_{cr} * V_k * b_1 * \cos(\theta_{cr} - \theta_k))$

At Shunt Converter :

$S_{vr} = V_{vr} * I_{vr}$

$P_{vr}= - (V_{vr} * V_k * b_2 * \sin(\theta_{vr} - \theta_k))$

$Q_{vr} = (V_{vr}^2 * b_2) + (V_{vr} * V_k * b_2 * \cos(\theta_{vr} - \theta_k))$

Assuming a free loss converter operation, UPFC neither absorbs nor injects active power with respect to the AC system. The DC link Voltage, V_{dc} remains constant. The active power associated with the series converter becomes the DC power $V_{dc} * I_2$. The Shunt converter must supply an equivalent amount of DC power to maintain V_{dc} constant. Hence, the active power supplied to the Shunt converter P_{vr}, must satisfy the active power demanded by the series converter P_{cr}

i.e. $P_{vr} + P_{cr} = 0$

$P_{bb}= P_{vr} + P_{cr} = 0$

4. LOAD FLOW ANALYSIS

Load flow studies are one of the most important aspects of power system planning and operation. The load flow gives us the sinusoidal steady state of the entire system - voltages, real and reactive power generated and absorbed and line losses. Since the load is a static quantity and it is the power that flows through transmission lines, the purists prefer to call this **Power Flow studies** rather than load flow studies.

Through the load flow studies we can obtain the voltage magnitudes and angles at each bus in the steady state. This is rather important as the magnitudes of the bus voltages are required to be held within a specified limit [13]. Once the bus voltage magnitudes and their angles are computed using the load flow, the real and reactive power flow through each line can be computed. Also based on the difference between power flow in the sending and receiving ends, the losses in a particular line can also be computed. Furthermore, from the line flow we can also determine the over and under load conditions.

The steady state power and reactive power supplied by a bus in a power network are expressed in terms of nonlinear algebraic equations. We therefore would require iterative methods for solving these equations.

4.1 Load Flow Analysis with Newton-Raphson Method

The load flow study is dealt with here is applied here with respect to balanced condition[9][10]. It mainly requires
1) Formulation of the network equation
2) Suitable mathematical technique for the solution of the network

Newton-Raphson method is an iterative method adopted using Y-bus in polar coordinates. The approach to Newton-Raphson load flow is similar to that of solving a system of nonlinear equations using the **Newton-Raphson method**: At each iteration we have to form a Jacobian matrix and solve for the corrections from an equation of the type given in (4.27)[13].
Load flow analysis involves the following steps:

- **Load Flow Algorithm**
- **Formation of the Jacobian Matrix**
- **Solution of Newton-Raphson Load Flow**

Let us assume that an n -bus power system contains a total n_p number of P-Q buses while the number of P-V (generator) buses be n_q such that $n = n_p + n_q + 1$. Bus-1 is assumed to be the slack bus. We shall further use the mismatch equations of ΔP_i and ΔQ_i given in (4.9) and (4.10) respectively [13].

4.2 Load Flow Equations with UPFC embedded branch

DEVELOPMENT OF LOAD FLOW EQUATION FOR A BRANCH BETWEEN NODE K, M IN WHICH UPFC IS EMBEDDED IS BASED ON THE EQUIVALENT REPRESENTATION OF THE UPFC. THESE LOAD FLOW EQUATIONS ARE THE REAL AND REACTIVE POWERS INJECTED AT NODES K, M AND ALSO AT SERIES CONVERTER AND SHUNT CONVERTER AS PRESENTED ABOVE.

4.2.1. UPFC JACOBIAN EQUATIONS

AS THE VARIOUS NETWORK CONTROLS INTERACT WITH EACH OTHER, THE RELIABILITY OF CONVERGENCE BECOMES THE MAIN CONCERN IN THE MODELING OF CONTROLLABLE DEVICES. THE STATE VARIABLES CORRESPONDING TO THE UPFC ARE COMBINED WITH THE NETWORK NODAL VOLTAGE MAGNITUDES AND ANGLES IN A SINGLE FRAME OF REFERENCE FOR A UNIFIED SOLUTION THROUGH A NEWTON-RAPHSON METHOD. THE UPFC STATE VARIABLES ARE ADJUSTED AUTOMATICALLY SO AS TO SATISFY SPECIFIED POWER FLOWS AND VOLTAGE MAGNITUDES.

THE UPFC LINEARIZED POWER EQUATIONS ARE COMBINED WITH LINEARIZED SYSTEM OF EQUATIONS CORRESPONDING TO THE REST OF THE NETWORK.

$[\,F(X)\,] = [J]\,[X]$ WHERE $[\,F(X)\,] = [\Delta P_K \Delta P_M \Delta Q_K \Delta Q_M \Delta P_{CR} \Delta Q_{CR} \Delta P_{BB}\,]^T$

P_{BB} IS THE POWER MISMATCH AND SUBSCRIPT T INDICATES TRANSPOSITION. X IS THE SOLUTION VECTOR AND [J] IS THE JACOBIAN MATRIX. FOR THE CASE WHEN THE UPFC CONTROLS VOLTAGE MAGNITUDE AT THE AC SHUNT CONVERTER TERMINAL (NODE K) ACTIVE POWER FLOWING FROM NODE K TO M AND REACTIVE POWER INJECTED AT NODE M AND ASSUMING NODE M IS PQ – TYPE THE SOLUTION VECTOR AND JACOBIAN MATRIX ARE

$[\,X\,] = [\Delta\theta_k \Delta\theta_m \Delta V_{vr} \Delta V_m \Delta\theta_{cr} \Delta V_{cr} \Delta\theta_{vr}\,]^T$

and [J] =

$$\begin{pmatrix}
\partial P_k/\partial\theta_k & \partial P_k/\partial\theta_m & \partial P_k/\partial V_{vr} & \partial P_k/\partial V_m & \partial P_k/\partial\theta_{cr} & \partial P_k/\partial V_{cr} & \partial P_k/\partial\theta_{vr} \\
\partial P_m/\partial\theta_k & \partial P_m/\partial Q_m & \partial P_m/\partial V_{vr} & \partial P_m/\partial V_m & \partial P_m/\partial\theta_{cr} & \partial P_m/\partial V_{cr} & \partial P_m/\partial\theta_{vr} \\
\partial Q_k/\partial\theta_k & \partial Q_k/\partial Q_m & \partial Q_k/\partial V_{vr} & \partial Q_k/\partial V_m & \partial Q_k/\partial\theta_{cr} & \partial Q_k/\partial V_{cr} & \partial Q_k/\partial\theta_{vr} \\
\partial Q_m/\partial\theta_k & \partial Q_m/\partial Q_m & \partial Q_m/\partial V_{vr} & \partial Q_m/\partial V_m & \partial Q_m/\partial\theta_{cr} & \partial Q_m/\partial V_{cr} & \partial Q_m/\partial\theta_{vr} \\
\partial P_{cr}/\partial\theta_k & \partial P_{cr}/\partial Q_m & \partial P_{cr}/\partial V_{vr} & \partial P_{cr}/\partial V_m & \partial P_{cr}/\partial\theta_{cr} & \partial P_{cr}/\partial V_{cr} & \partial P_{cr}/\partial\theta_{vr} \\
\partial Q_{cr}/\partial\theta_k & \partial Q_{cr}/\partial Q_m & \partial Q_{cr}/\partial V_{vr} & \partial Q_{cr}/\partial V_m & \partial Q_{cr}/\partial\theta_{cr} & \partial Q_{cr}/\partial V_{cr} & \partial Q_{cr}/\partial\theta_{vr} \\
\partial P_{bb}/\partial\theta_k & \partial P_{bb}/\partial Q_m & \partial P_{bb}/\partial V_{vr} & \partial P_{bb}/\partial V_m & \partial P_{bb}/\partial\theta_{cr} & \partial P_{bb}/\partial V_{cr} & \partial P_{bb}/\partial\theta_{vr}
\end{pmatrix}$$

4.3 INITIAL CONDITIONS OF UPFC VOLTAGE SOURCES

THE SOLUTION BY NEWTON – RAPHSON METHOD REQUIRE GOOD STARTING CONDITIONS FOR THE UPFC, A SET OF EQUATIONS WHICH GIVE GOOD INITIAL ESTIMATES ARE OBTAINED BY ASSUMING LOSS-LESS UPFC AND COUPLING TRANSFORMERS AND NULL VOLTAGE ANGLES IN POWER EQUATIONS AT NODES K, M.

1. SERIES SOURCE INITIAL CONDITIONS

$\Theta_{CR} = \mathrm{TAN}^{-1}((P_{MR})/C1$

$V_{cr} = ((X_{cr}/V^o_m) * \square\, (P_{mr}^2 / CI^2))$

Where $CI = Q_{mr}$ if $V^o_m = V^o_k$ otherwise $CI = (Q_{mr} - (V^o_m / X_{cr}) * (V^o_m - V^o_k)$

2. Shunt Source Initial conditions:

An equation for initializing the shunt voltage angle source can be obtained by substituting the real power equations of series and shunt converter into power mis-match equation and performing simple operations:

$$\Theta_{VR} = -\,\mathrm{SIN}^{-1}((V^{O}_{K} - V^{O}_{M}) * V^{O}_{CR} * X_{VR} * \mathrm{SIN}\,(\Theta_{CR}{}^{O}) / V^{O}_{VR} * V^{O}_{K} * X_{CR})$$

where X_{VR} is the inductive reactance of the shunt source .

When the shunt converter is acting as a voltage regulator, the voltage magnitude of it is initialized at its target value and the updated at each iterations and if it is not acting as voltage regulator its voltage magnitude is kept at fixed value within the prescribed limits for the

$(V_{VRMIN} <= V_{VR} <= V_{VRMAX})$

Here a purely inductive branch is assumed with series and shunt source impedance values of $X_{CR} = X_{VR} = 0.1$ (p.u)

A load flow study has been carried out by developing software in “C” Language for a UPFC embedded Power System network based on conventional NEWTON-RAPHSON Algorithm. In this paper, it is applied to a single branch of a power system embedded with UPFC.

5. RESULTS

The software developed in “C” language is applied to conventional Newton-Raphson algorithm to calculate load flow for a UPFC incorporated branch of 5 bus system whose details are in Table 1, 2 and 3. UPFC is embedded between the nodes 3 and 4 by creating another node labeled as 6 (m). The solution is converged in two iterations and given below in Table 4and Table 5.

Data for 5-bus

Table 1. Impedance and line charging for the sample 5-bus system

Bus Code p-q	Impedance (Zpq)	Line Charging Ypq/2
1-2	0.02+j0.06	0.0+j0.030
1-3	0.08+j0.24	0.0+j0.025
2-3	0.06+j0.18	0.0+j0.020
2-4	0.06+j0.18	0.0+j0.020
2-5	0.04+j0.12	0.0+j0.015
3-6	0.00+j0.10	0.0+j0.010
4-5	0.08+j0.24	0.0+j0.025
6-4	0.01+j0.03	0.0+j0.01

Table 2. Scheduled generation and loads and assumed bus voltages for the sample 5-bus system

Bus Code	Assumed Bus voltage (pu)	Generation MW	MVAR	Load MW	MVAR
1	1.06+j0.0	0	0	0	0
2	1.0+j0.0	40	30	20	10
3	1.0+j0.0	0	0	45	15
4	1.0+j0.0	0	0	40	5
5	1.0+j0.0	0	0	60	10
6	1.0+j0.0	0	0	0	0

Y-bus for the system
Table 3. Admittance to ground for sample system

Bus Code P	Admittance to ground Yp
1	0.0+j0.0550
2	0.0+j0.8500
3	0.0+j0.1450
4	0.0+j0.0550
5	0.0+j0.0400
6	0.0+j0.0100

Table 4. The final converged values of f(x) matrix

ΔP_k	0.001503
ΔPm	-0.001988
ΔQk	-0.009564
ΔQm	0.009522
ΔPcr	0.000485
ΔQcr	-0.000006
ΔPbb	0.000485

Table 5. The final converged values of [X] matrix

Bus Code	Voltage (pu)	Angle (rad)	Angle (degree)
K	1	0.0045	0.257
M	0.995	0.0148	0.8484
Series Converter	0.0501	-1.6058	-92.05
Shunt Converter	1.0194	0.0045	0.257

system

5.1 Case Studies

The developed software in "C" language for load flow analysis of system embedded with UPFC is used to perform case studies on a 5-bus system. The conventional Newton-Raphson algorithm for the load flow study is carried out. Power Flow solution converged in 5 iterations to tolerance of 0.01 starting from flat voltage profiles[11]. In this paper the functional capability of UPFC as shunt compensator is investigated[14]. A load flow program is used to incorporate the specified voltage at a specified bus in a given power system.

5.1.1 Case -1

With the load demand at bus 3 as 45MW and at bus 4 as 40 MW, the load flow program is conducted. The specified voltage magnitude at bus 3 is kept at 1.0 (pu). Thus the functional capability of UPFC as shunt compensator is tested. The results of the load flow solution at the end of 5^{th} iteration with tolerance level at 0.01 are shown in Table 6 to Table 9

Table No 6. The final converged values of change in real and reactive powers at each bus

ΔP_2	-0.0046200
ΔQ_2	-0.0000059
ΔP_3	0.0045060
ΔP_4	0.00000168
ΔQ_4	-0.00000317
ΔP_5	0.00000065
ΔQ_5	-0.00000046
ΔP_6	-0.00011300
ΔQ_6	-0.00000575
ΔP_{cr}	-0.00000727
ΔQ_{cr}	-0.00000309
ΔP_{bb}	-0.00000727
ΔQ_k	-0.00000856

Table No 7. The converged values of voltage and phase angle magnitudes at all buses

Bus Code	Voltage (pu)	Angle (rad)	Angle (degree)
1 (SLACK)	1.06	0	0
2	1.033	-0.0446	-2.5566
3	1.000	-0.0866	-4.9643
4	0.986	-0.0785	-4.5000
5	0.9953	-0.1014	-5.8120
6	0.9812	-0.0691	-3.9610

Table 8. The end values of voltage and angles of series and shunt converters are in

Voltage (pu)	Angle (rad)	Angle (deg)
V_{cr}	-0.8208	-47.05
V_{vr}	-0.0866	-4.96

Table 9. Nodal complex voltages of modified network

Bus Code	Complex Voltages V(pu)θ(deg)		Complex Voltages V(pu) θ (deg)	
1	1.060	0.000	1.060	0.000
2	1.000	-1.770	1.032	-2.562
3	1.000	-6.020	1.000	-4.970
4	0.992	-3.19	0.986	-4.505
5	0.972	-5.77	0.995	-5.818
6	0.997	-2.51	0.981	-3.966

In the above case the real and reactive power references are taken as per original network values at nodes 3 and 4. The shunt compensator capability of the UPFC is studied and the results obtained are in close agreement to the reference [4].

5.1.2 Case 2

UPFC's capability to meet the specified load demands is tested here. The load flow program is again conducted by increasing the load demands at bus 3 from its initial value to 65MW and the load at bus 4 from its original value to 50MW. Convergence is obtained at the end of 5th iteration within tolerance of 0.01. These changes are done apart from maintaining the bus voltage at node 3 as in case1 at 1.0 (pu). The results are shown in Tables 10, 11 and 12

Table 10. Load demands

ΔP_2	-0.00049800
ΔQ_2	-0.00002320
ΔP_3	0.00848800
ΔP_4	-0.00000685
ΔQ_4	-0.00000879
ΔP_5	0.00000214
ΔQ_5	-0.00000306
ΔP_6	-0.00041300
ΔQ_6	0.000017600
ΔP_{cr}	-0.00002980
ΔQ_{cr}	0.000011500
ΔP_{bb}	-0.00002980
ΔQ_{k}	-0.00000365

Table 11. The converged values of voltage and phase angle magnitudes at all nodes

Bus Code	Voltage (pu)	Angle (rad)	Angle (degree)
1	1.06	0	0
2	1.0315	-0.0559	-3.204
3	1.000	-0.1148	-6.580
4	0.9833	-0.1024	-5.870
5	0.9932	-0.1169	-6.701
6	0.9793	-0.0931	-5.331

Table 12. The end values of voltage and angles of series converter and shunt converter

Voltage (pu)	Angle (rad)	Angle (deg)
V_{cr}=-0.0621	-0.9069	-51.987
V_{vr}= 0.9952	-0.1148	-6.580

ACKNOWLEDGMENT

I am deeply thankful to all of our professors in the Osmania University. I sincerely thank all of them without whose co-operation; it would not have been possible to complete this work.

I also take immense happiness in thanking my parents, husband and especially my loving daughter.

Last, but not least, I thank THE GOD for giving an opportunity of life on this wonderful planet to see many technological happenings.

CONCLUSION

In this paper load flow study is performed on 5 bus system. A software is developed in "C" language for load flow analysis of a power system embedded with UPFC. This program is based on conventional polar co-ordinates Newton-Raphson Algorithm. UPFC provides simultaneous or individual control of basic system parameters like transmission voltage, impedance and phase angle, there by controlling transmitted power. In this paper the functional capability of UPFC to maintain specified voltage magnitude at a node where UPFC is connected is obtained. The shunt compensator capability is obtained in the first case and ability of UPFC to meet the specified node demands is obtained in the second case. The results obtained in both the cases are in close agreement to the values in [4].

All the capabilities of UPFC will hasten the broad application of UPFC concepts and achievement of its ultimate goal that is **"The higher utilization of existing Power Systems"**

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