A Review on Power Flow Analysis with UPFC and its Applicability

Adit Pandita
M.E Student,
Electrical and Instrumentation Engineering Department,
Thapar University, Patiala.

Dr. Sanjay K. Jain
Associate Professor,
Electrical and Instrumentation Engineering Department,
Thapar University, Patiala.

Abstract

The unified power flow controller (UPFC) is an advanced member of flexible AC transmission systems (FACTS) group. This paper is focused on three techniques for inclusion of the steady state models of the UPFC in power flow programs. This paper also presents a review of various benefits and applications of UPFC in power flow studies such as minimization of loss, enhancement of loadability, voltage stability etc. using various optimization techniques. A case study is also shown to analysis effect of UPFC using comprehensive NR method based power flow.

Keywords: *Unified Power Flow Controller (UPFC), Newton Raphson method, Steady state analysis, loadability, voltage stability.*

1. Introduction

Power flow calculations are performed in power systems for planning, operational planning, and operation/control. Power flow equations, commonly referred to as power flow are the backbone of power system analysis and design. The power flow problem consists of the calculation of power flows and voltages of a network for a specified terminal or bus conditions. Appropriate steady state model of power system is needed for writing the computer programs. The model includes non-linear algebraic equations, which must be solved iteratively. Power flow calculations are needed for both steady state analysis and initializations of different dynamic analysis.

Flexible AC Transmission systems (FACTS) is a concept based on power-electronic controllers, which enhance the value of transmission networks by increasing the use of their capacity. These controllers are used for enhancing dynamic performance of power systems in terms of voltage/angle stability while improving the power transfer capability and voltage profile in steady state.

The Unified Power Flow Controller (UPFC) is, arguably, the most comprehensive device to have emanated so far from the FACTS initiative. UPFC is capable of providing active and reactive power control, as well as adaptive voltage magnitude control.

UPFC is a versatile FACT'S device which can independently or simultaneously control the active power, reactive power, and the bus voltage to which it is connected. This controller offers substantial advantages for the static and dynamic operation of power system. However, to achieve such functionality it is important to find the optimal location of this device to be installed in power system with appropriate parameters. The active power loss reduction, the stability margin improvement, the power transmission capacity increasing, and the power blackout prevention, are some factors that can be considered in selecting the optimal installation and optimal parameters of UPFC. This controller also helps in increasing the loadability of the power system and providing better security and reliability to a power system network. It also helps in providing better voltage stability by setting appropriate control parameters. Fig.1 shows the schematic diagram of UPFC and its working.

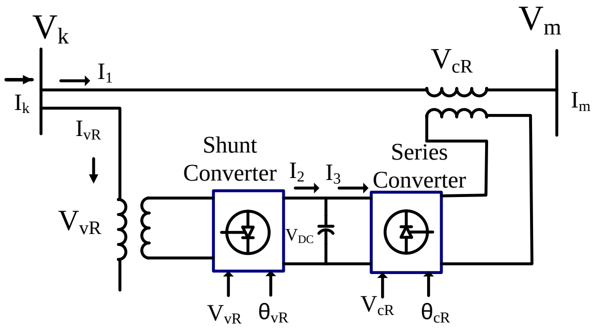


Fig.1: UPFC Schematic diagram

This paper presents a review on various benefits which UPFC provides in a power system, including improving steady state, transient stability, damping power swings, enhancing system loadability, which is provided by optimally locating and setting UPFC parameters. This paper also focuses on study of various UPFC models for power flow studies.

2. Benefits of UPFC

In past, researchers have used various techniques in power flow studies to incorporate UPFC to minimize losses, generation costs and maximize loadability, social welfare etc. To seek optimal allocation and parameter settings of UPFC in power system various evolutionary techniques have been applied recently. Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) techniques have been used to find out optimal location and parameter setting of UPFC device to minimize active power losses in a power system. Various such benefits have been surveyed herewith.

2.1 Minimization of Generation Cost

In the normal operation state of power system, the production costs of active power can be minimized by economic power dispatch, and delivery costs due to transmission system loss can be also minimized by active power control of UPFC, incorporated with minimization of production cost.

Lim *et al*. [3] presented UPFC operation for minimization of delivery cost and power production in normal operation state. The delivery cost due to transmission loss can be minimized by active power control of UPFC using uncoupled model of UPFC in power flow.

Vijayakumar *et al*. [4] developed an algorithm to simultaneously find the real power allocation of generators and to choose the type and the best location of UPFC device such that overall cost function which includes the generation cost of power plants and investment cost of FACTS is minimized. The combinatorial analysis is solved using Hybrid Genetic Algorithm on IEEE 9 bus system. The Optimal Power Flow problem formulated is as follow,

$$\text{Minimize } C_{Total} = C_1(f) + C_2(P_G) \qquad (1)$$

$$\text{Subjected to } E(f,g) = 0 \qquad (2)$$

$$B_1(f) < b_1,\ B_2(g) < b_2 \qquad (3)$$

E (f, g) is the conventional power flow equations. B_1 (f) and B_2 (g) are the inequality constraints for UPFC and the conventional power flow respectively.

Taher *et al*. [5] presented the application technique to find the optimal location of UPFCs (with installation cost) for getting minimum total active reactive power production cost of generators, and congestion management. Simulations were performed on IEEE-14 and IEEE-30 bus test systems and the optimal solutions found by IA were better than those of standard Genetic Algorithm (GA) and Particle Swarm Optimization (PSO).

Kiran *et al*. [6] proposed Particle swarm optimization method to solve the optimal power flow problem on power system by finding a location for UPFC device. The proposed algorithm is an effective method for finding the optimal choice and location of UPFC controller and also minimizing the overall system cost, which comprises of generation cost and the investment cost of the UPFC controller using PSO and conventional Newton Raphson's power flow method by verifying it on IEEE 14 bus test system.

2.2 Enhancement of System Loadability

Estimating loadability of a generation/transmission system is a generalized mathematical programming problem. It is not a standard mathematical programming problem because some of the constraints (specifically, dynamic security constraints) have to be expressed not in algebraic forms but in the form of differential equations. Loadability of power systems is dependent upon the pattern of load increasing.

Saravanan *et al*. [7] proposed the application of Particle Swarm Optimization to find the optimal location, settings, type and number of FACTS devices including UPFC to minimize its cost of installation and to improve system loadability for single and multi-type FACTS devices. While finding the optimal location, thermal limit for the lines and voltage limit for the buses are taken as constraints. This has been tested on IEEE 6 and IEEE 30 bus test systems. It is observed that system loadability cannot be improved further after placing certain number of devices. In IEEE test systems, UPFC gives maximum system loadability but the cost of installation is high when compared with all other cases.

Singh *et al.* [8] proposed a new variant to Genetic Algorithm, specialized in multi-objective optimizations problem known as Non-Dominated Sorting Genetic Algorithm II (NSGA II), to obtain optimal allocation of UPFC for enhancing loadability of the system within security and stability margins. This method to optimize the objective function of maximizing loadability is tested on IEEE 30 bus system with effective results.

Singh *et al.* [9] suggested the suitable locations of UPFC to enhance system loadability and tested it on IEEE 14 bus system. A sensitivity based approach has been developed for finding suitable placement of UPFC. The optimal power flow problem involves a nonlinear objective function and a set of nonlinear equality and inequality constraints. Sequential Quadratic Programming (SQP) has been used to obtain OPF solutions.

Shaheen *et al.* [10] presented application of evolutionary optimization techniques for optimal location and parameter setting of multiple UPFC devices for maximizing loadability and minimizing installation cost in power system with respect to line thermal limits and bus voltage magnitude limits. This proposed method was tested on IEEE 6 and IEEE 14 bus test power system with desired results. The results obtained by GA and PSO has stable convergence characteristic and good computational efficiency as the system loadability can be increased significantly by certain load factor by installing UPFC.

2.3 Minimization of Power Losses

One of the capabilities of UPFC is the power loss reduction in the power system. Farhangfar *et al.* [11] presented an injection model of UPFC to investigate its effect on power flow and loss reduction in power system. The best place for UPFC for loss reduction is in the main transmission line. It can be achieved by two methods. The first method is to increase the transition power in lines, which have low impedance. This can be implemented by inserting series voltage in phase with the sending end bus voltage. In this method, because of the increased transmission power, the size of the UPFC is greater, which makes it expensive. Another method is to decrease the transmission power in lines with high impedance. Hence, inverse series voltage with respect to the voltage of the sending end bus should he inserted to the line. Finally in order to decrease the loss in the power system, it is more economical to install UPFC in the lines with high impedances that are usually long lines.

Kothari *et al.* [12] formulated voltage phasor method and loss minimization including UPFC as an optimization problem. PSO is applied for real power loss minimization including UPFC and is tested with IEEE 14 and IEEE 57 bus test systems. The algorithm is easy to implement and is capable of finding the global optimum solution for the loss minimization giving decision about the minimal loss location is the location of the UPFC. For large power systems PSO could have a significant advantage compared to the exhaustive and other methods, by giving better solutions with less computational effort.

Rashed *et al.* [13] presented a Differential Evolutionary (DE) algorithm for finding the optimal location and the best parameter setting of Unified Power Flow Controller (UPFC) for minimizing the active and reactive power losses in the power system. Simulations have been implemented in MATLAB and the IEEE 14-bus and IEEE 30-bus systems have been used as a case study. Also for the purpose of comparison the proposed technique was compared with another optimization technique namely Particle Swarm Optimization (PSO). The results we have obtained indicate that DE is an easy to use, robust, and powerful optimization technique compared with particle swarm optimization (PSO). Installing UPFC in the optimal location determined by DE can significantly minimize the active and reactive power loss in the network.

2.4 Voltage Stability and Maximization of Transmission Capability

The voltage deviation due to load variation and power transfer limitation were observed due to reactive power unbalances has drawn attention to better utilize the existing transmission line. It also causes a higher impact on power system security and reliability in power system network. Thus UPFC plays a vital role in maintaining stable voltage profile and also maximizing the transmission capability of power system network without the need of building new transmission lines.

Abdullah *et al.* [14] presented the application of evolutionary computation technique for monitoring voltage profile of the power system network when UPFC is incorporated in the network. Evolutionary Programming and Artificial Immune system method have been applied in IEEE 30 bus RTS system to maintain stable voltage profile and minimize losses while increasing the power transfer capability.

Mori *et al.* [15] proposed a new method Two-Layered Tabu Search (TLTS) method for optimal allocation of UPFC. UPFC is employed to control power flows so that the transmission capability is maximized in different power system conditions. The proposed method is based on two layered tabu search (TLTS) that is effective for the nonlinear mixed integer problem. TLTS evaluates better solutions by repeating the process that Layer 1 determines the optimal integer variables while Layer 2 computes the optimal continuous ones. The proposed method was successfully applied to the IEEE 14-node system. A comparison was made between the proposed and the conventional methods in terms of solution accuracy and computational time.

Yap *et al.* [16] presented an effective utilization of UPFC in power flow control to improve existing transmission capability of the power system network. The IEEE 14-bus network system operating with common loads and generators is used to demonstrate the available controllability in the UPFC through computational monitoring.

Chen *et al.* [17] discussed control of UPFC to improve power system voltage stability. A dynamical UPFC model is presented. The impact of the UPFC model on voltage stability is clarified through bifurcation analysis. Robust techniques are employed for the series and shunt branches control and the DC capacitor voltage control. Different roles of the series and shunt branches of UPFC in voltage stability are studied on a three-machine power system. The effects of the UPFC controllers on voltage stability enhancement are examined on the three-machine power system. Bifurcation analysis shows that the feasibility region is significantly affected by the proposed UPFC control.

2.5 Power system Security and Transient Stability

Kim *et al.* [18] presented a new UPFC operation algorithm to find the operating point of UPFCs for the system security level Enhancement. The proposed algorithm iteratively minimizes the security index which indicates the overload level of transmission lines. The sensitivity representing the change of the index for a given set of changes in the UPFC real power outputs is derived. In each iteration, with this sensitivity, the proposed algorithm finds a new UPFC operating point that reduces the index or increases the security margin. The algorithm is verified by IEEE 39 bus system with multiple UPFCs. The proposed algorithm is tested with 3 UPFCs on the normal operating system and on the same system with a line fault. The study results show two things. The first is UPFCs operated by the algorithm can provide the normal operating system with the relief of the power flow congestion in the system and enhance the system security level. And the second is by applying the algorithm the UPFCs with a proper capacity can enlarge the security margin to prevent the overload problem of the system in an increased load or faulted condition.

Gerbex *et al.* [19] presented a comparison between three heuristic methods (Simulated Annealing, Tabu Search method, Genetic Algorithms) applied to the optimal location of UPFC in order to enhance the system security. The optimizations are made on three parameters: the location of the UPFC, their types and their sizes. The three methods lead to similar results, but generally Tabu Search method and Genetic Algorithm converge faster than Simulated Annealing. IEEE 118 bus test system is applied for the comparative study.

Taki *et al.* [20] discussed the application of neuro – fuzzy controlled UPFC to improve transient stability of power system. Neuro-fuzzy control method the membership function parameters of fuzzy controller can be computed with learning information about a data set. This Adaptive Network Fuzzy Inference System (ANFIS) can track the given input-output data the best. The process of training data generation is based on maximizing the energy function of UPFC. Proposed method is tested on a single machine infinitive bus system to confirm its performance through simulation. The purpose of maximizing the transient stability margin has been achieved by maximizing the injected energy of UPFC by using its energy function. Consequently, the ANFIS controller operation is based on energy function optimization. By keeping the series (shunt) branch inactive, UPFC can operate as a STATCOM (SSSC) and the corresponding behavior is also evaluated and compared. The superiority of the proposed controlled UPFC over a STATCOM or a SSSC in improving transient stability of a single machine infinitive bus has been demonstrated.

Hosseini *et al.* [21] proposed a transient model and control system of UPFC to enhance the voltage regulation and transient stability of a radial AC transmission system using UPFC. The control scheme has the fast dynamic response and therefore, improves the transient behavior of power system after a transient condition. Simulation results demonstrate that the presented control system acts properly in steady state and transient condition. The presented UPFC control system can regulate line active and reactive power flow and voltage at line midpoint. The presented control system of UPFC not only responses to the step changing in the active and reactive power, but also is able to exchange the direction of line active power flows. Also, the proposed control system is regulating the DC link capacitor voltage. The simulation results indicate the fast dynamic response, validity and effectiveness of the presented control scheme.

2.6 Damping Power Swings

Tambey *et al.* [22] suggested a comprehensive approach to the design of UPFC controllers (power-flow controller, DC Voltage regulator and damping controller). Studies reveal that damping is adversely affected by the incorporation of a DC-voltage regulator. Investigations were carried out to understand the relative effectiveness of modulation of the UPFC control signals m_B, δ_B, m_E and δ_E on damping of the system oscillations, using a controllability index. Dual damping controller based on simultaneous modulation of UPFC control signals m_B and δ_E is proposed. Investigations reveal that alternative damping controllers (damping controller m_B, damping controller δ_E and dual damping controller) provide robust dynamic performance under wide variations in loading condition and system parameters.

Gharibpour *et al.* [23] presents the control methods to damp the power swings using UPFC. The first control algorithm is based on energy and equivalent energy criterion that works only at the presence of disturbance. The second one is adding an active damper to the system and affecting on the system damping. In this algorithm in order to increase the damping of a system of the machine. This function is used to determine the angle in which a proper damping is added to the system. This angle can be set as the reference and by using the angle compensation mode, the voltage injection is done in that angle. In this algorithm by using an angle feedback it doesn't need to exchange a lot of information which is used in other algorithms. Finally the power swing is observed in the simulation by selecting a power flow model for UPFC.

3. UPFC models for Power Flow Studies

There are various techniques for inclusion of steady state models of the UPFC in power flow programs. This paper is focused on three techniques for incorporating UPFC in power flow studies. They are: Decoupled UPFC model, Injection UPFC model and comprehensive NR UPFC model. A comparative study is also presented in this paper for the mentioned models.

3.1 Decoupled UPFC Model

A sequential UPFC power flow model proposed by Nabavi-Niaki and Iravani [24] is capable of regulating the power flow from node m to node k and to regulate the nodal voltage magnitude at node k. in this situation, assuming a loss free UPFC operation and neglecting the resistance in voltage source impedances, the UPFC and coupling transformers can be modeled by means of a load at bus k and a generator at bus m. This is shown in figure (3).

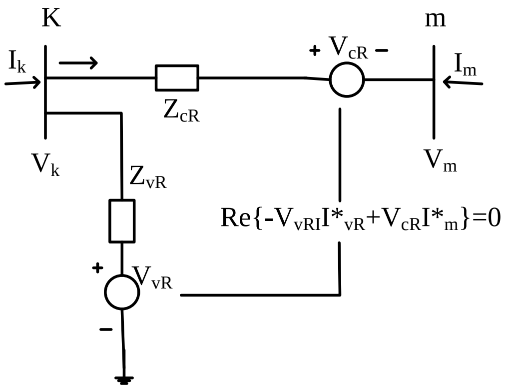


Fig.2: Equivalent Circuit of UPFC

The sending end of UPFC is transformed into a PQ bus, while the receiving end is transformed into PV bus. The active and reactive power loads in PQ bus are set to the values being controlled by UPFC. The standard power flow solution is carried out with an equivalent model given by fig.3 (b). After power flow convergence a set of non-linear equations is solved by iteration to compute the UPFC parameters.

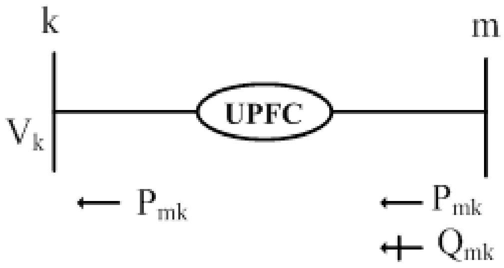


Fig.3 (a): UPFC model schematic

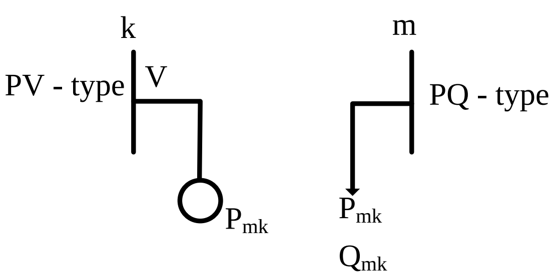


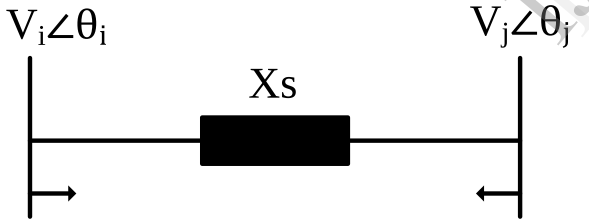
Fig.3 (b) UPFC model equivalent

3.1.1 Drawbacks of Decoupled UPFC Model

Although this sequential method is simple but it is not clear from it how the model can be used in situations when the UPFC is not controlling the voltage magnitude, line active power and line reactive power simultaneously. Moreover since UPFC parameters are computed after power flow converged, there is no way of knowing during this iterative process whether or not the UPFC parameters are within limits. The UPFC parameters are computed iteratively by Newton-Raphson method, no guidelines are given to select suitable UPFC parameters starting values.

3.2 UPFC Injection Model

Reference [25] presents an approach of modelling the UPFC as a series fixed reactance X_s together with a set of active and reactive nodal power injections at each end of the series reactance P_{si}, Q_{si}, P_{sj}, Q_{sj} . These powers are expressed as a function of the terminal, nodal voltages, and a voltage of a series source, which represents the UPFC series converter. The fig. (4) Shows complete injection model of UPFC connected between buses i and j. The series voltage source V_{ser} is taken equal to $rVi\angle\gamma$ where $0 < r < r_{max}$ and $o < \gamma < 2\pi$. r and γ represent the control parameters of UPFC.



$$P_{si} = rb_s V_i V_j \sin(\theta_{ij} + \gamma)$$
$$P_{sj} = -rb_s V_i V_j \sin(\theta_{ij} + \gamma)$$
$$Q_{si} = rb_s V_i^2 \cos\gamma$$
$$Q_{sj} = -rb_s V_i V_j \cos(\theta_{ij} + \gamma)$$

Fig.4: UPFC Injection model

The UPFC injection model is implemented into a full Newton-Raphson power flow program by adding the UPFC power injections and their derivatives with respect to the AC network state variables, i.e., nodal voltage magnitude and angles, at the appropriate locations in the mismatch vector and Jacobian matrix. The original dimensions of the mismatch vector and Jacobian matrix are not altered at all.

3.2.1 Advantages of UPFC Injection Model

The attraction of this formulation is that it can be implemented easily in existing power flow program and UPFC can be adjusted to work as a voltage regulator, series compensator or phase shifter.

3.2.2 Drawbacks of UPFC Injection Model

The major drawback of this model is that all important aspect of the automatic UPFC parameter adjustment has not been addressed. Also the series voltage course parameters are adjusted by trial and error in order to achieve certain power flow solution, which will match the target power flow.

3.3 Comprehensive NR UPFC Model

Trying to circumvent the limitations in the decoupled and injection UPFC model, reference [26] developed a new and comprehensive UPFC model. This model is straightforward extension of the power flow equations and hence, it is suitable for incorporation into an existing Newton-Raphson power flow algorithm. The UPFC equivalent circuit used to derive this steady state is shown in fig. (2). The equivalent circuit consists of two ideal voltage sources representing the fundamental Fourier series of the switched voltage waveforms at the AC converter terminals. The source impedances included in the model represent the positive sequence leakage inductances and resistances of the coupling UPFC transformers. The ideal voltage sources are:

$$V_{vr} = |V_{vr}| \left(cos\theta_{vr} + jsin\theta_{vr}\right) \quad (4)$$
$$V_{cr} = |V_{cr}| \left(cos\theta_{cr} + jsin\theta_{cr}\right) \quad (5)$$

Here V_{vR} and θ_{vR} are the controllable magnitude $\left(V_{vRmin} \le |V_{vR}| \le V_{vRmax}\right)$ and $\left(0 \le \theta_{vR} \le 2\pi\right)$ phase angle of the voltage source representing the shunt converter. The magnitude V_{cR} and phase angle θ_{cR} of the voltage source representing the series converter are controlled between these limits : $\left(V_{cRmin} \le |V_{cR}| \le V_{cRmax}\right)$ and $\left(0 \le \theta_{cR} \le 2\pi\right)$. Assuming a loss free converter operation, the 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. The shunt converter must apply an equivalent amount of DC power to maintain V_{dc} constant. Hence the active power supplied to the shunt converter, must satisfy the active power demanded by the the series converter,

$$P_{vR} + P_{cR} = 0 \qquad (6)$$

The UPFC linearized power equations are combined with the linearized system of equations corresponding to the rest of the network,

$$[F(x)] = [J][\Delta X] \qquad (7)$$

Where,

$$\left[f\left(x\right) \right] = \left[\Delta P_k \Delta P_m \Delta Q_k \Delta Q_m \Delta Q_{mk} \Delta P_{bb} \right]^T \qquad (8)$$

ΔP_{bb} is the power mismatch given by equation (6) and superscript T indicates the transposition. ΔX is the solution vector and J is the Jacobian matrix. The power mismatch equations are used as the guiding principle for conducting limit revisions. The mismatch provides an accurate indicator for determining the activation of limits revision for a controllable device parameters. The revision criterion of the UPFC is based on its active power converter mismatch. For the case when the UPFC controls voltage magnitude at the AC shunt converter terminal (node *k)*, active power flowing from node *m* to node ***k*** and reactive power injected at node ***m,*** and assuming that node ***m*** is PQ-type, the solution vector and Jacobian matrix are,

$$\left[\Delta X \right] = \left[\Delta\theta_k \Delta\theta_m \frac{\Delta V_{vR}}{V_{vR}} \frac{\Delta V_m}{V_m} \Delta\theta_{cR} \frac{\Delta V_{cR}}{V_{cR}} \Delta\theta_{vR} \right]^T \qquad (9)$$

$$\left[J\right] = \begin{bmatrix} \frac{\partial P_k}{\partial \theta_k} & \frac{\partial P_k}{\partial \theta_m} & \frac{\partial P_k}{\partial V_{vR}} V_{vR} & \frac{\partial P_k}{\partial V_m} V_m & \frac{\partial P_k}{\partial \theta_{cR}} & \frac{\partial P_k}{\partial V_{cR}} V_{cR} & \frac{\partial P_k}{\partial \theta_{vR}} \\ \frac{\partial P_m}{\partial \theta_k} & \frac{\partial P_m}{\partial \theta_m} & 0 & \frac{\partial P_m}{\partial V_m} V_m & \frac{\partial P_m}{\partial \theta_{cR}} & \frac{\partial P_m}{\partial V_{cR}} V_{cR} & 0 \\ \frac{\partial Q_k}{\partial \theta_k} & \frac{\partial Q_k}{\partial \theta_m} & \frac{\partial Q_k}{\partial V_{vR}} V_{vR} & \frac{\partial Q_k}{\partial V_m} V_m & \frac{\partial Q_k}{\partial \theta_{cR}} & \frac{\partial Q_k}{\partial V_{cR}} V_{cR} & \frac{\partial Q_k}{\partial \theta_{vR}} \\ \frac{\partial Q_m}{\partial \theta_k} & \frac{\partial Q_m}{\partial \theta_m} & 0 & \frac{\partial Q_m}{\partial V_m} V_m & \frac{\partial Q_m}{\partial \theta_{cR}} & \frac{\partial Q_m}{\partial V_{cR}} V_{cR} & 0 \\ \frac{\partial P_{mk}}{\partial \theta_k} & \frac{\partial P_{mk}}{\partial \theta_m} & 0 & \frac{\partial P_{mk}}{\partial V_m} V_m & \frac{\partial P_{mk}}{\partial \theta_{cR}} & \frac{\partial P_{mk}}{\partial V_{cR}} V_{cR} & 0 \\ \frac{\partial Q_{mk}}{\partial \theta_k} & \frac{\partial Q_{mk}}{\partial \theta_m} & 0 & \frac{\partial Q_{mk}}{\partial V_m} V_m & \frac{\partial Q_{mk}}{\partial \theta_{cR}} & \frac{\partial Q_{mk}}{\partial V_{cR}} V_{cR} & 0 \\ \frac{\partial P_{bb}}{\partial \theta_k} & \frac{\partial P_{bb}}{\partial \theta_m} & \frac{\partial P_{bb}}{\partial V_m} V_{vR} & \frac{\partial P_{bb}}{\partial V_m} V_m & \frac{\partial P_{bb}}{\partial \theta_{cR}} & \frac{\partial P_{bb}}{\partial V_{cR}} V_{cR} & \frac{\partial P_{bb}}{\partial \theta_{vR}} \end{bmatrix} \qquad (10)$$

If the UPFC voltage control is deactivated, the third column of eqn. (10) is replaced by partial derivatives of the nodal and UPFC mismatch powers with respect to the nodal voltage magnitude V_k. Moreover, the shunt source voltage magnitude increment in eqn.(9), $\Delta V_{vR} / V_{vR}$, is replaced by the nodal voltage magnitude increment at node *k*, $\Delta V_k / V_k$,. In this case, V_{vR} is maintained at a fixed value within prescribed limits, $V_{vR\min} \le V_{vR} \le V_{vR\max}$.

3.3.1 Advantages of Comprehensive NR Model

The main advantages that this UPFC model has over the Decoupled and injection model is that UPFC state variables are incorporated inside the Jacobian and mismatch equations leading to very robust iterative solution. In this unified solution, the UPFC state variables are adjusted simultaneously with the nodal network state variables in order to achieve the specified control targets. Hence, the interaction between the network and UPFC is better represented and the UPFC state variables can be identified inside the power flow program. This model also gives the ability to control the active and reactive power simultaneously as well as the voltage magnitude. The losses of the UPFC coupling transformers are taken into consideration.

3.3.2 Drawbacks of Comprehensive NR UPFC Model

The drawback of this model is that the UPFC cannot be adjusted to work in voltage regulation, impedance compensation, and phase shift mode. Moreover, the model needs good initial conditions for UPFC state variables for better convergence. Bad initial conditions may cause divergence.

4 Case Study

A small five- node network [27] has been used to show quantitavely, how the UPFC performs. We have modified the original network to include a UPFC which compensates the transmission line connected between Nodes Lake and main in case 1 and, between Main and Elm for case 2. This is shown in Fig. (5) and Fig. (6) respectively. The UPFC shunt converter is set to regulate the Lake's nodal voltage at 1 p.u. Initial conditions of UPFC voltage sources are, V_{vR} = 1 p.u , θ_{vR} = 0°, V_{cR}= 0.04 p.u, θ_{vR} = -87.13°. The source impedance has values of $X_{cR}=X_{vR}$ = 0.1 p.u. Convergence in case 1 and case 2 was attained in 5 iterations to a power mismatch tolerance of 10^{-12}. The UPFC upheld its target values.

Case -1

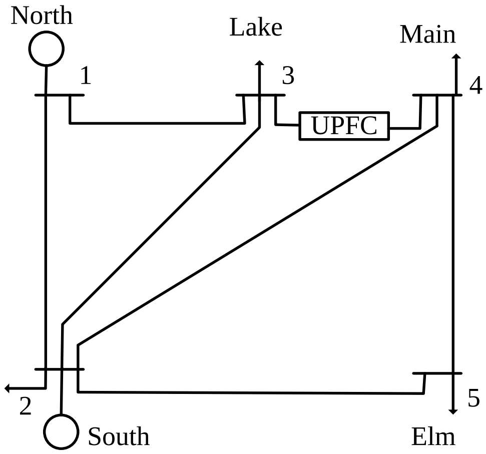


Fig. (5): Modified Test Network for Case 1.

Table 1: Nodal Complex Voltage of Modified Network for case 1

Complex Voltages	**System Nodes**				
	North	**South**	**Lake**	**Main**	**Elm**
V (p.u)	1.06	1.00	1.00	0.998	0.977
θ (deg)	0	-1.988	-5.095	-4.756	-5.633

After the convergence in five iterations the UPFC sending end active and reactive power from node 3 is 40MW and 21.68MVARs respectively. Also the active and reactive receiving end power at node 4 is 40MW and 2MVAR's. Moreover, after five iterations the value of voltage sources of series and shunt converter are, $V_{cR} = 0.046$ p.u, $\theta_{cR} = -94.947°$, $V_{vR} = 1.023$ p.u, $\theta_{vR} = -5.090°$. Table 1 shows the voltage magnitudes and voltage angles at all the nodes when UPFC is incorporated between node 3 and node 4.

Case – 2

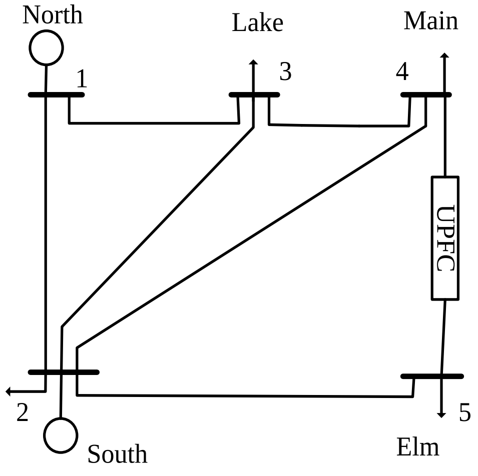


Fig. (6): Modified Test Network for Case 2.

Table 2: Nodal Complex Voltage of Modified Network for case 2

Complex Voltages	**System Nodes**				
	North	**South**	**Lake**	**Main**	**Elm**
V (p.u)	1.06	1.00	0.999	1.00	0.991
θ (deg)	0	-1.886	-5.532	-6.151	-4.170

After the convergence in five iterations the UPFC sending end active and reactive power from node 4 is 40MW and 34.31MVARs respectively. Also the active and reactive receiving end power at node 5 is 40MW and 2MVAR's. Moreover, after five iterations the value of voltage sources of series and shunt converter are, $V_{cR} = 0.075$ p.u, $\theta_{cR} = -88.99°$, $V_{vR} = 1.035$ p.u. $\theta_{vR} = -6.128°$. Table 2 shows the voltage magnitudes and voltage angles at all the nodes when UPFC is incorporated between node 4 and node 5.

Conclusion

This paper gives the review of UPFC device, its benefits and various optimization techniques used for optimal allocation of UPFC converter for damping oscillations, power loss minimization, enhancement of system loadability, power transfer capability etc. The three steady state models namely UPFC Decoupled model, UPFC injection model and UPFC comprehensive NR model are compared. A case study is also presented to show the effectiveness of UPFC device to regulate voltage magnitude and also controls the power flow between the two busses. It is expected that this review will be helpful to researchers working in the area of power flow and optimal allocation of UPFC.

References

[1] N. G. Hingorani and L. Gyugyi, "Understanding FACTS Concepts and Technology of Flexible AC Transmission Systems", *IEEE Press, Wiley-Interscience Publication*, 1999.

[2] L.H. Hasaan, M. Moghavvemi, H.A.F. Almurib, O. Steinmayer, "Application of genetic algorithm in optimization of unified power flow controller parameters and its location in the power system network", *Electric Power and Energy Systems*, Page 89-97 Vol. 46, 2013.

[3] J.U. Lim and S. Moon, "UPFC Operation for the Minimization of Power Production and Delivery Costs", *IEEE Power Engineering Society Meeting*, Page 331-335 Vol. 1, 2000.

[4] K. Vijayakumar, R.P. Kumudinidevi and D. Suchithra, "A Hybrid Genetic Algorithm for Optimal Power Flow incorporating FACTS

Devices", *International Conference on Computational Intelligence and Multimedia Applications*, Page 463-467 Vol. 1, 2007.

[5] S.A. Taher, M.K. Amooshahi, "Optimal Placement of UPFC in Power Systems using Immune Algorithm", *Simulation Modelling Practise and Theory,Elsevier, Page 1399-1412 Vol. 19*, 2011.

[6] S.H. Kiran, C. Subramani, S.S. Dash, M. Arunbhaskar and M. Jagdishkumar, "Particle Swarm Optimization Algorithm to find the Location of Facts controllers for a Transmission Line", *International Conference on Process Automation, Control and Computing (PACC)*, Page 1-5, 2011.

[7] M. Sarvanan, S. Mary Raja Slochanal, P. Venkatesh and Prince Stephen Abrahim J., "Application Of PSO Technique For Optimal Location Of FACTS Devices Considering System Loadability And Cost Of Installation", *Power Engineering Conference*, Page 716-721 Vol. 2, 2005.

[8] I.M. Wartana, J.G. Singh, W. Ongsakul, K Buayai and S. Sreedharan, "Optimal Placement of UPFC for Maximizing System Loadability and Minimize Active Power Losses by NSGA-II", *International Conference and Utility Exhibition on Power and Energy Systems: Issues and Prospects of Asia*, Page 1-8, 2011.

[9] S.N. Singh and I. Erlich, "Locating Unified Power Flow Controller for Enhancing Power System Loadability", *International conference on Future Power Systems*, Page 5, 2005.

[10] H. I. Shaheen, G. I. Rashed "Application of Evolutionary Optimization Techniques for Optimal Location and Parameters Setting of Multiple UPFC devices", *Third International Conference on Natural Computation*, Page 688-697 Vol. 4, 2007.

[11] A. Farhangfar, S. J. Sajjadi and S. Afsharnia, "Power Flow Control and Loss Minimization with Unified Power Flow Control (UPFC)", *Canadian Conference on Electrical and Computer Engineering*, Page 385 – 388 Vol. 1, 2004.

[12] M. Kowsalya, K.K. Ray and D.P. Kothari, "Loss Optimization for Voltage Stability Enhancement Incorporating UPFC Using Particle Swarm Optimization", *Journal of Electrical Engineering and Technology*, Page 492-298 Vol. 4 No. 4, 2009.

[13] G.I. Rashed, Y. Sun, K.A. Rashed and H.I. Shaheen, "Optimal Location of Unified Power Flow Controller by Differential Evolution Algorithm Considering Transmission Loss Reduction", *IEEE International Conference on Power System Technoloy (POWERCON)*, Page 1-6, 2012.

[14] N.R.H. Abdullah, I. Musirin and M.M. Othman, "Transmission Loss Minimization and UPFC Installation Cost using Evolutionary Computation for Improvement of Voltage Stability", *Proceedings of the 14th International Middle East Power Systems Conference (MEPCON'10)*, Page 825-830, 2010.

[15] H. Mori and Y. Maeda, "Application of Two-Layered Tabu Search to Optimal Allocation of UPFC for Maximizing Transmission Capability*", IEEE International Symposium on Circuits and Systems*, 2006.

[16] E.M. Yap, M. Al-Dabbagh and P.C. Thum, "Applications of FACTS Controller for Improving Power Transmission Capability*", TENCON 2005 IEEE Region 10*, Page 1-6, 2005.

[17] H. Chen, Y. Wang and R. Zhou, "Analysis of Voltage Stability Enhancement via Unified Power Flow Controller", *International Conference on Power System Technology, 2000. Proceedings. PowerCon 2000,* Page 403-408 *Vol.*1, 2000.

[18] S.H. Kim, J.U. Lim and S. Moon, "Enhancement of Power System Security Level through the Power Flow Control of UPFC", *Power Engineering Society Summer Meeting, 2000. IEEE*, Page 38-43 Vol. 1, 2000.

[19] S. Gerbex, R. Cherkaoui and A.J. Germond, "Optimal Location of FACTS Devices to Enhance Power System Security", *Power Tech Conference Proceedings IEEE*, Vol. 3, 2003.

[20] F. Taki, S. Abazari and G. R. Arab Markadeh, "Transient Stability Improvement Using ANFIS Controlled UPFC Based on Energy Function", *18th Iranian Conference on Electrical Engineering (ICEE)*, Page 944-988, 2010.

[21] S.H. Hosseini and A. Ajami, "Voltage Regulation and Transient Stability Enhancement of a Radial AC Transmission System Using UPFC", *30th Annual Conference of the IEEE Industrial Electronics Society*, Page 1150-1154 Vol. 2, 2004.

[22] N. Tambey and M.L. Kothari, "Damping of power system oscillations with unified power flow controller (UPFC)", *IEE- Proceedings Generation, Transmission and Distribution*, Page 129-140 Vol. 150 Issue: 2, 2003.

[23] H. Gharibpour, H. Monsef and M. Ghanaatian, "The Comparison of Two Control Methods of Power Swing Reduction in Power System with UPFC Compensator", *20th Iranian Conference on Electrical Engineering (ICEE)*, Page 386-391, 2012.

[24] A. Nabavi-Niaki and M. R. Iravani, "Steady-state and Dynamic Models of Unified Power Flow Controller(UPFC) for Power System Studies", *IEEE Transactions on Power Systems*, Vol. 11, No. 4, 2006.

[25] M. Noroozian, L. Angquist, M. Ghandhari and G. Andersson, "Use of UPFC for Optimal Power Flow", *IEEE Transactions on Power Delivery*, Page 1629-1634 Vol.12 No. 4, 1997.

[26] C.R. Fuerte-Esquivel and E.Acha, "Unified power flow controller: a critical comparison, of Newton-Raphson UPFC algorithms in power

flow studies", *IEE Proc.-Gener. Transm. Distrib*, Vol. 144, No. 5, September 1997.

[27] Stagg and El-Abiad, "Computer Methods in Power System Analysis", *McGraw Hills Ltd. Publication*, 1968.

[28] A. Berrizi, M. Delfanti, P. Marannino, M.S. Pasquadibisceglie and A. Silvestri, "Enhances Security Constrained OPF with FACTS Devices", *IEEE Transactions on Power Systems,* Vol. 20, No. 3, August 2005.

[29] L. J. Cai, I. Erlich and G. Stamtsis, "Optimal Choice and Allocation of FACTS Devices in Deregulated Electricity Market using Genetic Algorithms", *Power System Conference and Exposition, IEEE PES*, Page 201-207 Vol. 1, 2004.

[30] Xiao - Ping Zhang, Christian Rehtanz and Bikash Pal, "Flexible AC Transmission Systems: Modelling and Control", *Springer-Verlag Publication*, 2005.

[31] M. Mashayekh, A. Kazemi and S. Jadid, "A New Approach for Modelling of UPFC In Power Flow and Optimum Power Flow Studies", *IEEE Conference on Industrial Electronics and Applications*, Page 1-6, 2006.

[32] John J. Grainger and William D. Stevenson, Jr., "Power System Analysis", *Tata McGraw Hill Publication*, 1994.