ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Website: www.ijareeie.com

Vol. 6, Issue 3, March 2017

Power Flow Solution with Optimal Unified Power Flow Controller

Srilatha Dande[1], Sivanagaraju Sirigiri[2]

Associate Professor, Department of EEE, Prakasam Engineering College, Kandukur, A.P, India

Professor, Department of EEE, University College of Engineering, JNTUK, Kakinada, A.P, India

ABSTRACT: A comprehensive load flow model for the Optimal unified power flow controller (OUPFC) is presented. The OUPFC model is incorporated into an existing FACTS Newton–Raphson load flow algorithm. Critical comparisons are made against existing UPFC and OUPFC models, which shows developed model to be far more flexible and efficient. The algorithm exhibits quadratic or near-quadratic convergence characteristics, regardless of the size of the network and the number of FACTS devices.

KEYWORDS: Phase shifting transformer, Optimal unified power flow controller , Newton raphson load flow, convergence, Power flow.

I. INTRODUCTION

The control of an AC power in real time is involved because power flow is a function of the transmission line impedance, the magnitude of sending end and receiving end voltages, and the phase angle between these voltages. Years ago electric power systems were relatively simple and were designed to be self-sufficient. Furthermore, it was generally understood that Ac transmission systems could not be controlled fast enough. Transmission systems were designed with fixed or mechanically switched series and shunt reactive compensators, together with voltage regulating and phase Shifting transformer tap changer, to optimize line impedance, minimize voltage variation and control power flow under steady state or slowly changing load conditions. All these resulted in the under utilization of transmission systems. During the last two decades, advances have been made in high power semiconductor device and control technologies [1,2]. Hingorani proposed the concept of Flexible AC Transmission Systems or FACTS, which includes the use of high power electronics, advanced control centers, and communication link to increase the usable power transmission capacity. The possibility that current through a line can be controlled at a reasonable cost enables a large potential of increasing the capacity of existing lines with larger conductors and use of one of the FACTS controllers enable corresponding power to flow through such lines under normal and contingency conditions. The advent of flexible ac transmission systems (FACTS) devices has given a system operator additional leverage to control a power system. While FACTS devices like static var compensator (SVC) and thyristor controlled series compensator (TCSC) are variable reactance devices based on thyristors, the new generation of devices like static synchronous compensator (STATCOM), static synchronous series compensator (SSSC), unified power flow controller (IPFC), and interline power flow controller (IPFC) are based on voltage source converter (VSC) topology[6-11]. STATCOM and SVC are shunt connected; SSSC,IPFC, and TCSC are series connected; and UPFC is a hybrid connected (i.e., have components connected both in series and shunt) FACTS device.

II. MODELLING OF OUPFC

Optimal Unified Power Flow Controller (OUPFC) consists of two triple winding transformers such as injecting and exciting transformers connected in series and shunt with the line as shown in Fig.1. It is the combination of PST and UPFC having two voltage source converters[3,4]. PST is to shift the transmission angle based on the system condition. Series and shunt converters of UPFC are connected to injects a current with controllable magnitude and phase angle in

DOI:10.15662/IJAREEIE.2017.0603109

series with the line via an injecting transformer and Shunt converter either supply or consumes the real power demanded by the series converter to balance the real power between converters.

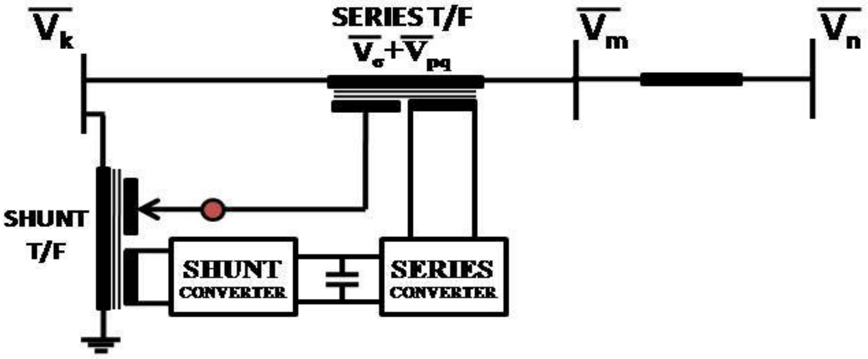

Fig.1 Basic schematic diagram of OUPFC

Mathematical model of phase shifting transformer

The Phase Shifting Transformer (PST) is used to advance the phase angle of the bus voltage. It is represented by an ideal transformer as in previous cases but with a turns ratio which is a complex number. Let the turns ratio be (*as* + *jbs*). The configuration of phase shifting transformer is shown in Fig.2.

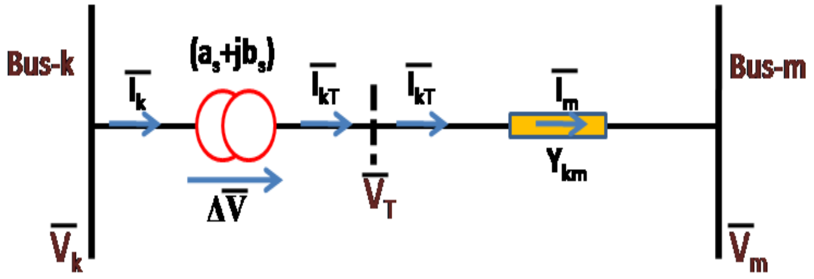

Fig.2 Basic configuration of PST

The elements of admittance matrix between the buses where PST is connected are modified as

$$Y_{kk}=\frac{Y_{km}}{\left(a^2+b^2\right)};\ Y_{km}=-\frac{Y_{km}}{\left(a_s-jb_s\right)};\ Y_{mk}=-\frac{Y_{mk}}{\left(a_s+jb_s\right)};\ Y_{mm}=Y_{mk} \qquad (1)$$

Mathematical model of upfc

The general structure of UPFC contains “back-to-back" AC to DC voltage source converters through a common DC link capacitor shown in Fig.1. First converter (CONVERTER-I) is connected in shunt and the second one (CONVERTER-II) in series with the line.

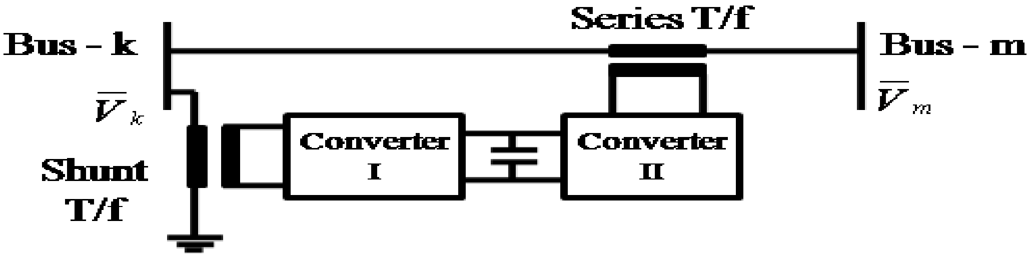

Fig.3 Basic schematic diagram of UPFC

The complete power injection model for UPFC is given below. The final power injection model of UPFC is shown in Fig.4 and the power injections at the UPFC connected buses can be expressed as

$$P_k^{UPFC} = 0.02 r V_k^2 B_{se} \sin\gamma - 1.02 r V_k V_m B_{se} \sin(\delta_{se} + \gamma) \tag{2}$$

$$Q_k^{UPFC} = -r V_k^2 B_{se} \cos\gamma + Q_{sh}^{UPFC} \tag{3}$$

$$P_m^{UPFC} = r V_k V_m B_{se} \sin(\delta_{se} + \gamma) \tag{4}$$

$$Q_m^{UPFC} = r V_k V_m B_{se} \cos(\delta_{se} + \gamma) \tag{5}$$

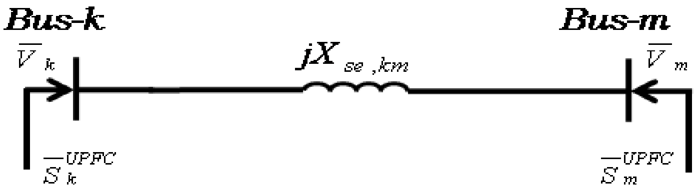

Fig.4 Power injection model of UPFC

Modelling of oupfc

The basic configuration of OUPFC incorporated transmission line is shown in Fig.5.

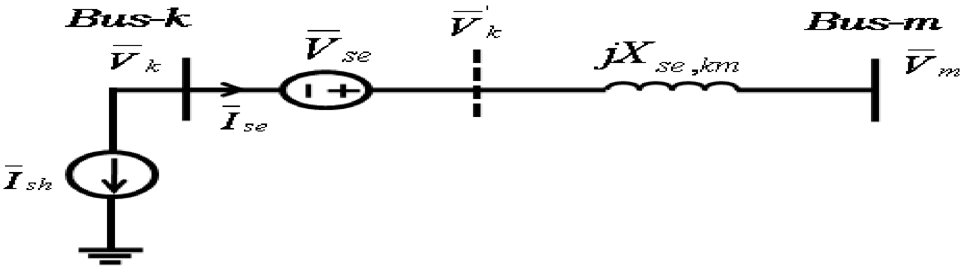

Fig.5 Basic configuration of OUPFC

The complete mathematical model of OUPFC is developed by combining the following series and shunt converter models explained below:

Series converter model

Let $\overline{V}_{se}$ is the voltage injected into the line by UPFC is given as

$$\overline{V}_{se} = r e^{j\rho} \overline{V}_k \tag{6}$$

Where, r and ρ are the radius of operating region and phase angles of UPFC.

Let $\overline{V}_\sigma$ is the voltage injected by PST into the line is given by,

$$\overline{V}_\sigma = t\,e^{j\sigma}\,\overline{V_k} \tag{7}$$

Where, t and σ are the transfer ratio and phase angles of PST.

Total voltage injected by both UPFC and PST are given by,

$$\overline{V}_{inj} = \overline{V}_{se} + \overline{V}_\sigma \tag{8}$$

and voltage at the fictitious bus ($\overline{V}_k'$) can be expressed as

$$\overline{V}_k' = \overline{V}_{inj} + \overline{V}_k \tag{9}$$

Current flowing through the line can be calculated as,

$$\overline{I}_{se} = \frac{\left(\overline{V_k}' - \overline{V_m}\right)}{jX_{se,km}} \tag{10}$$

Where, $jX_{se,\,km}$ is the line reactance.

Shunt converter model

In PIM, exciting transformer of OUPFC (i.e. shunt converter transformer) is modeled as an ideal shunt current source

$$I_{sh} = (I_{re} + jI_{img}).e^{j\delta_k} \tag{11}$$

Where, I_{re} and I_{img} are the magnitude of currents in phase and in quadrature with $\overline{V}_k$.

For an ideal model of transformers, OUPFC does not exchange real and reactive powers with system.

$$\overline{V}_{tinj} \times \overline{I}_{se}^{*} = \overline{V}_k \times \overline{I}_{sh}^{*} \tag{12}$$

From equations (1), (4) and (6), we get

$$I_{re} = b_s\,tV_m Sin\,(\varphi+\sigma) + b_s\,rV_m Sin\,(\varphi+\rho) - b_s\,tV_k Sin\,(\sigma) - b_s\,rV_k Sin\,(\rho) \tag{13}$$

$$\begin{aligned} I_{img} = {} & b_s\,tV_m Cos\,(\varphi+\sigma) + b_s\,rV_m Cos\,(\varphi+\rho) - b_s\,tV_k Cos\,(\sigma) - b_s\,rV_k Cos\,(\rho) \\ & - b_s\,V_k(r^2+t^2) - 2b_s t\,r\,V_k Cos\,(\sigma-\rho) \end{aligned} \tag{14}$$

Where, $\varphi = \delta_k - \delta_m$

Combined model

Device injecting voltage $\overline{V}_{inj}$ is converted into a current source in series with line with a parallel impedance of $jX_{se,\,km}$ therefore injected currents at kth and mth buses can be as follows

$$\overline{I}_k = \overline{I}_{inj} + \overline{I}_{sh} \;\; ; \;\; \overline{I}_{inj} = \overline{V}_{inj}\,.\left(-jb_{se,km}\right) \;\; ; \;\; \overline{I}_m = \overline{I}_{inj} \tag{15}$$

The combined model of OUPFC is shown in Fig.6. The power injections at kth and mth buses with OUPFC are calculated as follows.

$$\overline{S}_k^{OUPFC} = \overline{V}_k \times \left(-\overline{I}_k\right)^{*} \text{ and } \overline{S}_m^{OUPFC} = \overline{V}_m \times \left(\overline{I}_m\right)^{*} \tag{16}$$

The expanded form of real and reactive power equations at kth bus can be expressed as

$$P_k = -b_s\,t.V_k.V_m Sin\,(\varphi+\sigma) - b_s\,r.V_k.V_m Sin\,(\varphi+\rho) \tag{17}$$

$$Q_k = -b_s .V_k.^2(t^2 + r^2) - 2.b_s t.r.V_k.^2 \text{ Cos}(\sigma - \rho) - 2.b_s t..V_k.^2 \text{ Cos}(\sigma\sigma - 2.b_s t..V_k.^2 \text{ Cos}(\rho\rho + b_s r t.V_k.V_m \text{ Cos } (\varphi + \sigma) + b_s r t.V_k.V_m \text{ Cos } (\varphi + \rho) \tag{18}$$

Similarly, at mth bus can be expressed as

$$P_m = -P_k \tag{19}$$

$$Q_m = b_s t.V_k.V_m \text{Cos } (\varphi + \sigma) + b_s r.V_k.V_m \text{Sin } (\varphi + \rho) \tag{20}$$

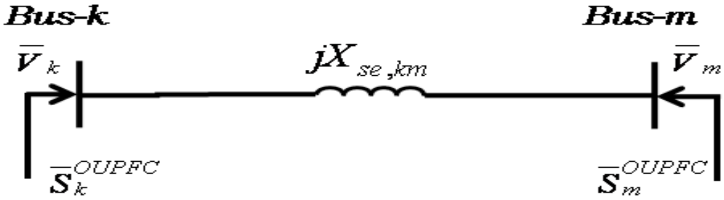

Fig.2.6 Power injection model of OUPFC

III.POWER FLOW INCORPORATION PROCEDURE

To analyze the effect of UPFC/OUPFC on a given power system, this device is incorporated in Newton-Raphson (NR) load flow solution. The developed power injection model of UPFC/OUPFC is easily incorporated into the system by modifying Jacobian elements and power mismatch equations related to device connected buses .

The final steady state network equation in NR load flow in the presence of UPFC can be expressed as

$$\left(\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} + \begin{bmatrix} P^{FACTS} \\ Q^{FACTS} \end{bmatrix}\right) = \left(\begin{bmatrix} H & N \\ J & L \end{bmatrix} + \begin{bmatrix} H^{FACTS} & N^{FACTS} \\ J^{FACTS} & L^{FACTS} \end{bmatrix}\right)\begin{bmatrix} \Delta\delta \\ \Delta V \\ \hline |V| \end{bmatrix} \tag{21}$$

Where, 'ΔP, ΔQ' are the vector corresponds to real and reactive power mismatches, 'Δδ, ΔV' are the vector of incremental changes in angles and voltages, 'H, N, J, L' are the partial derivatives of P and Q w.r.to δ and V.

The corresponding Jacobian elements related to OUPFC connected buses are expressed as follows.

Device control parameters

For PST: The transfer ratio $\left(k = \sqrt{\left(a^2 + b^2\right)}\right)$ of PST voltage injection is varied from 0 p.u to 0.1 p.u. While phase angle $\left(\sigma = \tan^{-1}\left(\frac{b}{a}\right)\right)$ is varied from -45 deg to 45 deg

For UPFC: The radius of the operating region (r) is varied from 0 p.u. to 0.1 p.u and respective phase angle (γ) is varied from -180 deg to 180 deg.

For OUPFC: The control parameters variation for both PST (k, σ) and UPFC (r, γ) are considered as this device is a combination of PST and UPFC.

IV. RESULTS

An IEEE-5 bus system with two generators, seven transmission lines is considered. The total load on this system is 165 MW. To show effect of these devices, device is connected between buses 4 and 5.The reactance of the series converter transformer is considered to be 0.1 p.u. OUPFC control parameters k and σ are taken 0 to 0.1 pu, -45 to 45 deg and the parameters r is varied from 0 p.u. to 0.1 p.u and γ is varied from -180 deg to 180 deg. The variation of bus voltage magnitudes with OUPFC is shown in Fig.7, variation of power flow, power losses and number of iterations is shown in Figs. 8 and 9. From these figures, it is identified that, value of the system parameters (voltage magnitude, power flow, losses) is increasing as the device control parameters value is varied from minimum setting (r=0 p.u) to maximum setting (r=0.1 p.u). The power flow in the device connected line (7th line) and nearby line (5th line) has got major variations. It is also observed that, the power flow in line-5 can be varied up to its maximum limit.

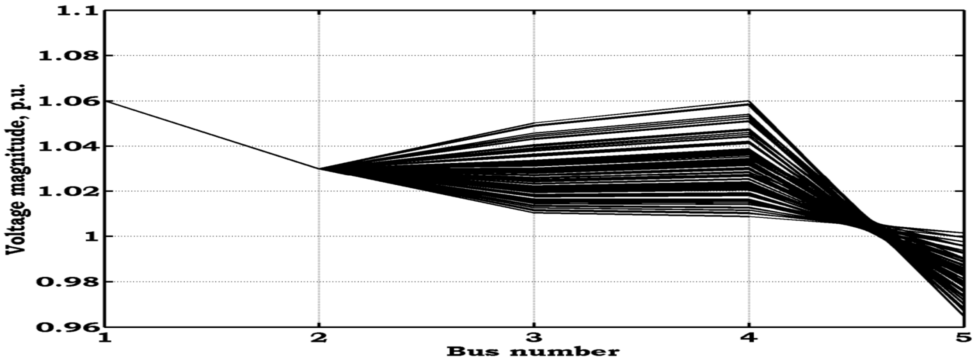

Fig.7 Consolidated variation of bus voltage magnitude by varying OUPFC control parameters for HALE network

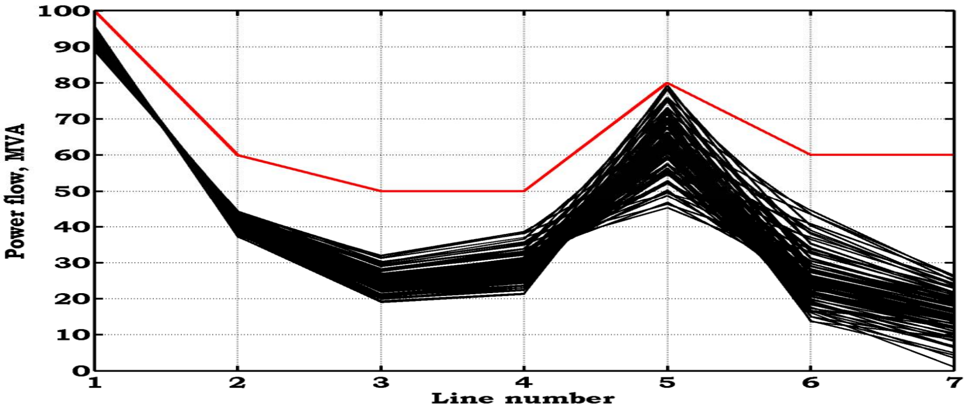

Fig.8 Consolidated variation of line power flow by varying OUPFC control parameters for HALE network

The numerical results of the losses with respective PST, UPFC and OUPFC control parameters are tabulated in Table.1

Table.1 Numerical results of the losses and respective device control parameters for HALE network

Device	Total power loss			
	Min. value (control parameters)	Number of Iterations	Max. value (control parameters)	Number of Iterations
PST	4.723836 (k=0.01 p.u, σ=-24.54 deg)	04	5.029837 (k=0.1 p.u, σ=43.76 deg)	18
UPFC	4.803002368 (r=0.02 p.u, γ=-20 deg)	04	5.2735 (r=0.1 p.u, γ=140 deg)	27
OUPFC	4.7728371 (r=0.089 p.u, γ=153 deg, k=0.08 p.u, σ=-18.28 deg)	11	6.57487312 (r=0.042 p.u, γ=88 deg, k=0.08 p.u, σ=-18.28 deg)	59

V. CONCLUSIONS

In this chapter, modeling of OUPFC with supporting mathematical derivation has been presented with its incorporation procedure to solve load flow problem. The effectiveness of OUPFC on system parameters such as bus voltages, power flow in transmission lines and total power losses have been analyzed and compared with the existing PST and UPFC. From the analysis, it has been identified that, due to controlling of multiple parameters with OUPFC, the voltage magnitude at the device shunt converter connected bus and the power flow in the device series converter connected line have been enhanced to minimize the total power losses. The numerical results along with supporting graphical results have been presented for the considered IEEE-5 bus test systems.

REFERENCES

1. N. G. Hingorani “Flexible AC Transmission Systems (FACTS) – Overview”, IEEESpectrum, pp. 40 – 45, April 1993
2. [29] S. Kamel, F. Jurado, J.A. Pecas Lopes,” Comparison of various UPFC models for power flow controls”, Electrical Power and Energy Systems, 2014, vol.121, pp.243-251.
3. [30] R. Srinivasa Rao, V. Srinivasa Rao.,” A generalized approach for determination of optimal location and performance analysis of FACTs devices”, Electrical Power and Energy Systems, 2015, vol.73, pp.711-724
4. L. Gyugyi “Dynamic Compensation of AC Transmission Lines by Solid-State Synchronous Voltage Sources”, IEEE Transactions on Power Delivery, Vol. 9, No. 2, pp. 904 – 911, April 1994.
5. C. W. Edwards, K. E. Mattern, P. R. Nannery, and J. Gubernick “Advanced Static Var Generator Employing GTO Thyristors”, IEEE Transactions on Power Delivery, Vol. 3, No. 4, pp. 1622 – 1627, October 1988.
6. L. Gyugyi, C. D. Schauder, and K. K. Sen “Static Synchronously Series Compensator: A Solid-State Approach to the Series Compensation of Transmission Line”, IEEE Transactions on Power Delivery, Vol. 12, No. 1, pp. 406 – 417, January1997.
7. B. T. Ooi, S. Z. Dai, and X. Wang “Solid-State Series Capacitive Reactance Compensators”, IEEE Transactions on Power Delivery, Vol. 7, No. 2, pp. 914 – 919, April 1992.
8. L. Gyugyi, C. D. Schauder, S. L. Williams, T. R. Rietman, D. R.Torgerson,andA Edris “The Unified Power Flow Controller: A New Approach to Power Transmission Control”, IEEE Transactions on Power Delivery, Vol. 10, No. 2, pp. 1085 – 1093, April 1995.
9. .H. Mehta, R. K. Johnson, D. R. Torgerson, L. Gyugyi, and C. D. Schauder “Unified Power Flow Controller for FACTS”, Modern Power Systems, Vol. 12, No. 12, December 1992, United Kingdom
10. L. Gyugyi, C. D. Schauder, M. R. Lund, D. M. Hammai, T. R. Reitman, D. R. Torgerson, and A. Edris “Operation of Unified Power Flow Controller Under Practical Constraints”, IEEE Winter Meeting, PE-511- PWRD-0-11-1996, February 1997.
11. L. Gyugyi “Power Electronics in Electric Utilities: Static Var Compensators”, Proceedings of IEEE, Vol. 76, No. 4, pp. 483 – 494, April 1988.