VOL. 3, NO. 6, DECEMBER 2008 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

CONTROL SETTING OF UNIFIED POWER FLOW CONTROLLER THROUGH LOAD FLOW CALCULATION

Ch. Chengaiah, G. V. Marutheswar and R. V. S. Satyanarayana
Department of Electrical and Electronics Engineering, S. V. University College of Engineering, Tirupati, India
E-Mail : chinthapudi_ch@rediffmail.com

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) 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 aims to present a reliable method to meet the requirements by developing a Newton-Raphson based load flow calculation program through which control setting of UPFC can be determined directly. A MATLAB program has been developed to calculate the control setting parameters of the UPFC after the load flow is converged. Case studies have been performed on IEEE 5-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.

Keywords: UPFC, FACTS, load flow, Newton-Raphson method, MATLAB.

1. INTRODUCTION

With the development of power systems, especially the opening of electric energy markets, it becomes more and more important to control the power flow along the transmission line, thus to meet the needs of power transfer. On the other hand, the fast development of electronic technology has made FACTS (Flexible A.C. Transmission Systems) a promising path for future power system needs.

The UPFC is an advanced power systems 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 while enhancing considerably transient and dynamic stability.

In this paper UPFC is treated to operate in closed loop form and the control parameters of the UPFC are derived to meet the required power flow along the line. This paper finds the control setting of UPFC i.e., the magnitude and angular position of the injected voltage, through a robust load flow calculation. The calculation involved is robust in the sense that the number of equations to be solved is more, time taking and complicated.

2. OPERATING PRINCIPLES OF UPFC

The unified power flow controller consists of two switching converters. These converters are operated from a common link provided by a dc storage capacitor (Figure-1).

Converter 2 provides the main function of the UPFC by injecting an ac voltage with controllable magnitude and phase angle in series with the transmission line via a series transformer. The basic function of converter 1 is to supply or absorb the real power demand by converter 2 at the common dc link. It can also generate or absorb controllable reactive power and provide independent shunt reactive compensation. The injection model is obtained by replacing the voltage for the line. Converter 2 supplies or absorbs locally required reactive power and exchanges the active power as a result of the series injection voltage.

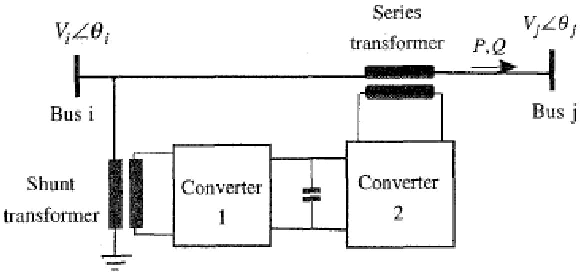

Figure-1. Basic circuit arrangement of UPFC.

3. UPFC MODEL FOR POWER FLOW STUDIES

In the following section, a model for UPFC which will be referred as UPFC injection model is derived. This model is helpful in understanding the impact of the UPFC on the power system in the steady state. Furthermore, the UPFC injection model can easily be incorporated in the steady state power flow model. Since the series voltage source converter does the main function of the UPFC, it is appropriate to discuss the modeling of a series voltage source converter first.

3.1. Series connected voltage source converter model

Suppose a series connected voltage source is located between nodes i and j in a power system. The series voltage source converter can be modeled with an ideal series voltage Vs in series with a reactance *Xs*. In Figure-2, *Vs* models an ideal voltage source and represents a fictitious voltage behind the series reactance:

$$\overline{V}'_i = \overline{V}_s + \overline{V}_i \qquad \text{........ (1)}$$

The series voltage source is controllable in magnitude and phase, i.e.:

$$\overline{V}_s = r\overline{V}_i e^{j\gamma} \qquad \text{............... (2)}$$

where $0 < r < r_{max}$ and $0 < \gamma < 2\pi$.

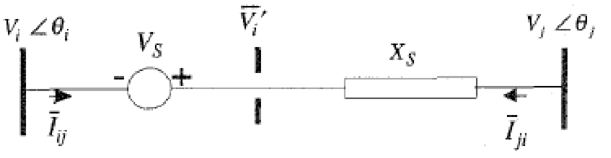

Figure-2. Representation of a series connected VSC.

The equivalent circuit vector diagram is shown in Figure-3.

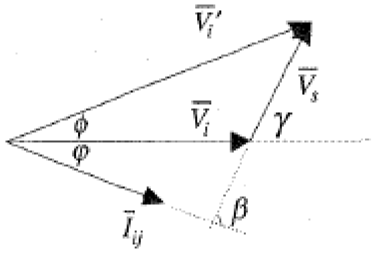

Figure-3. Vector diagram of the equivalent circuit of VSC.

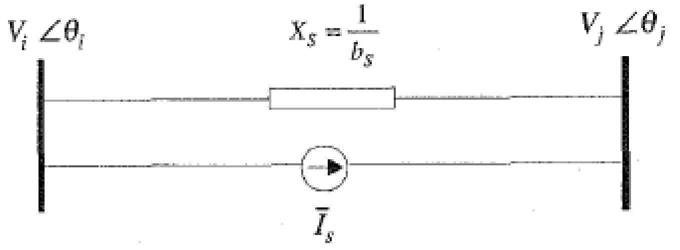

Figure-4. Replacement of a series voltage source by a current source.

The current sources I_s corresponds to the injection powers S_{is} and S_{js}, where

$$\overline{S}_{is} = \overline{V}_i\left(-\overline{I}_s\right)^* \qquad \text{.................. (3)}$$

$$\overline{S}_{js} = \overline{V}_j\left(\overline{I}_s\right)^*$$

The injection powers $\overline{S}_{is}$ and $\overline{S}_{js}$ are simplified to:

$$\begin{aligned} S_{is} &= \overline{V}_i\left(jb_s r\overline{V}_i e^{j\gamma}\right)^* \\ &= -b_s rV_i^2 \sin\gamma - jb_s rV_i^2 \cos\gamma \end{aligned} \qquad \text{.................. (4)}$$

If we define:

$$\theta_{ij} = \theta_i - \theta_j$$

We have,

$$\begin{aligned} S_{js} &= \overline{V}_j\left(-jb_s r\overline{V}_i e^{j\gamma}\right)^* \\ &= b_s rV_iV_j \sin\left(\theta_{ij} + \gamma\right) + jb_s rV_iV_j \cos\left(\theta_{ij} + \gamma\right) \end{aligned} \qquad \text{.... (5)}$$

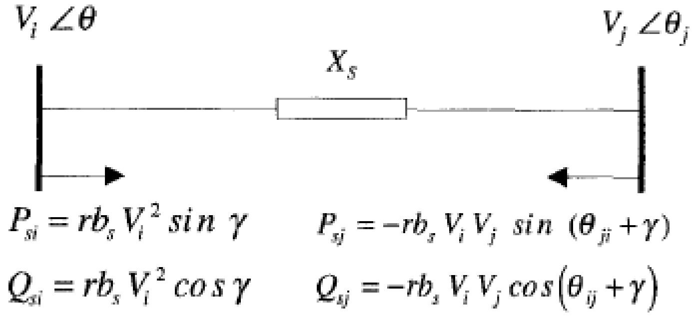

Figure-5. Injection model for a series connected VSC.

3.2. UPFC model

In UPFC, the shunt connected voltage source (Converter 1) is used mainly to provide the active power which is injected to the network via the series connected voltage source:

$P_{CONV1} = P_{CONV2}$

The equality above is valid when the losses are neglected. The apparent power supplied by the series voltage source converter is calculated from:

$$S_{CONV2} = \overline{V}_s \overline{I}_{ij}^{\,*} = re^{j\gamma}\overline{V}_i\left(\frac{\overline{V}_i' - \overline{V}_j}{jx_s}\right)^* \quad \text{..................} (6)$$

Active and reactive powers supplied by Converter 2 are distinguished as:

$$P_{CONV2} = b_s r V_i V_j \sin(\theta_i - \theta_j + \gamma) - b_s r V_i^2 \sin\gamma \quad (7)$$

$$Q_{CONV2} = -b_s r V_i V_j \cos(\theta_i - \theta_j + \gamma) + b_s r V_i^2 \cos\gamma + r^2 b_s V_i^2 \quad \text{............}(8)$$

The reactive power delivered or absorbed by converter 1 is independently controllable by UPFC and can be modeled as a separate controllable shunt reactive source. In view of above, we assume that Q_{CONV1} = O (In Sec. 3.2, the possibility to control Q_{CONV1} is investigated). Consequently, the UPFC injection model is constructed from the series connected voltage source model (Figure-5) with the addition of a power equivalent to $P_{CONV} + j0$ to node i. Thus, the UPFC injection model is shown in Figure-6. The model shows that the net active power interchange of UPFC with the power system is zero, as is it expected for a lossless UPFC.

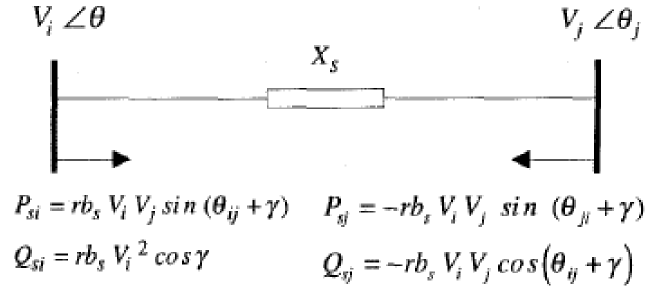

Figure-6. UPFC model.

3.3. UPFC injection model for load flow studies

The UPFC injection model can easily be incorporated in a load flow program. If a UPFC is located between node i and node j in a power system, the admittance matrix is modified by adding a reactance equivalent to *Xs* between node i and node j**.** The Jacobian matrix is modified by addition of appropriate injection powers. If we consider the linearised load flow model as:

$$\begin{bmatrix}\Delta P \\ \Delta Q\end{bmatrix} = \begin{bmatrix} H & N \\ J & L\end{bmatrix}\begin{bmatrix}\Delta\Theta \\ \Delta V / V\end{bmatrix} \quad \text{.......} (9)$$

The Jacobian matrix is modified as given in Table-1 (The superscript o denotes the Jacobian elements without UPFC).

Table-1. Modification of Jacobian matrix.

$H_{(i,i)} = H^o(i,i) - Q_{sj}$	$N_{(i,i)} = N^o(i,i) - P_{sj}$
$H_{(i,j)} = H^o(i,j) + Q_{sj}$	$N_{(i,j)} = N^o(i,j) - P_{sj}$
$H_{(j,i)} = H^o(j,i) + Q_{sj}$	$N_{(j,i)} = N^o(j,i) + P_{sj}$
$H_{(j,j)} = H^o(j,j) - Q_{sj}$	$N_{(j,j)} = N^o(j,j) + P_{sj}$
$J_{(i,i)} = J^o(i,i)$	$L_{(i,i)} = L^o(i,i) + 2Q_{si}$
$J_{(i,j)} = J^o(i,j)$	$L_{(i,j)} = L^o(i,j)$
$J_{(j,i)} = J^o(j,i) - P_{sj}$	$L_{(j,i)} = L^o(j,i) + Q_{sj}$
$J_{(j,j)} = J^o(j,j) + P_{sj}$	$L_{(j,j)} = L^o(j,j) + Q_{sj}$

4. CASE STUDY

An IEEE 5-bus network has been used to show quantitatively, how the UPFC performs. The original network is modified to include UPFC as shown in Figure-7, which compensates the line between the buses 3 and 4. The UPFC is used to regulate the active and reactive power flowing in the line at a pre specified value. The load flow equations are modified correspondingly at bus 3 and

4. The load flow solution for the modified network is obtained by using Newton-Raphson method. Depending on the pre specified value of the active and reactive power the UPFC control setting is determined after the load flow is converged.

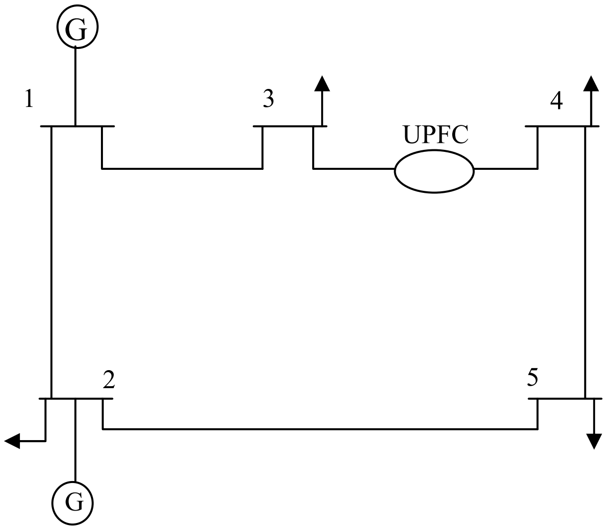

Figure-7. Single line diagram of UPFC embedded five bus system.

5. RESULTS

A MATLAB program was developed to find the control setting of UPFC when pre specified power flow is defined from bus 3 to bus 4. For the same pre specified power flow, UPFC is connected between buses 2 and 5. The results are compared and it is advantageous to keep the UPFC connected to the bus which is having low voltage profile.

Case-1. Results without UPFC

Table-2. Nodal voltages in the system.

Bus code (p)	**Voltage** (PU)	**Angle** (rad)	**Angle** (deg)
1	1.06	0.0	0.0
2	0.992546	-0.033943	-1.944762
3	0.981424	-0.079984	-4.582736
4	0.977920	-0.085544	-4.901328
5	0.964432	-0.099612	-5.707344

Case-2. Results with UPFC between buses 3 and 4

Table-3. Nodal voltages in the system.

Bus code (p)	**Voltage** (PU)	**Angle** (rad)	**Angle** (deg)
1	1.06	0.0	0.0
2	0.998416	-0.034417	-1.971973
3	0.990050	-0.086497	-4.955889
4	0.992753	-0.081996	-4.698007
5	0.973622	-0.097996	-5.614737

Table-4. Control setting of UPFC.

Voltage (V_T in PU)	**Phase angle** (Φ_T in rad)	**Phase angle** (Φ_T in deg)
0.0072	-1.588023	-90.98701

Case-3. Results with UPFC between buses 2 and 5

Table-5. Nodal voltages in the system.

Bus code (p)	**Voltage** (PU)	**Angle** (rad)	**Angle** (deg)
1	1.06	0.0	0.0
2	0.997828	-0.039400	-2.257446
3	1.000222	-0.065911	-3.776416
4	1.000845	-0.066499	-3.810121
5	0.976170	-0.096000	-5.500414

Table-6. Control setting of UPFC.

Voltage (V_T in PU)	**Phase angle** (Φ_T in rad)	**Phase angle** (Φ_T in deg)
0.012935	-1.434259	-82.176987

6. CONCLUSIONS

The Unified Power Flow Controller provides simultaneous or individual controls of basic system parameters like transmission voltage, impedance and phase angle, there by controlling the transmitted power. In this paper, a 5-bus system is considered and power flow program is run with and without UPFC. The UPFC is incorporated

i) Between buses 3 and 4
ii) Between buses 2 and 5

to control the transmission power to a specified value. Based on the specified transmission power, the UPFC control setting is determined for both cases. From the results it is concluded that the system performs better when the UPFC is connected to a bus which is having low voltage profile.

REFERENCES

[1] N. Hingorani. 1991. FACTS, Flexible Transmission Systems. In: Proceedings of 5th International Conference on AC and DC Power Transmission. London. September. pp. 1-7.

[2] E. Lerch *et al.* 1994. Simulation and performance analysis of Unified Power Flow Controller. Cigre. pp. 14-205.

[3] M. Noroozian, G. Andersson. 1993. Power Flow Control by Use of Controllable Series Components. IEEE Transactions on Power Delivery. 8(3): 1420-1429.

[4] G. W. Stagg and A. Abiad. Computer Methods in Power System Analysis. McGraw-Hill, New York. First Edition.

[5] W. L. Fang, H. W. Ngan. 1999. Control setting of Unified Power Flow Controllers through a robust load flow calculation. IEEE proceedings on generation, transmission, distribution. Vol. 146. July.

APPENDIX-I

Bus code p-q	**Impedance** Z_{pq}	**Line charging** $Y_{pq}/2$
1-2	0.02+j0.06	0+j0.030
1-3	0.03+j0.24	0+j0.025
2-3	0.06+j0.18	0+j0.020
2-4	0.06+j0.18	0+j0.020
2-5	0.04+j0.12	0+j0.015
3-4	0.01+j0.03	0+j0.010
4-5	0.08+j0.24	0+j0.025

APPENDIX-II

Bus code p	**Assumed Bus voltage**	**Generation**		**Load**	
		MW	**MVAR**	**MW**	**MVAR**
1	1.06+j0.0	0	0	0	0
2	1.0+j0.0	40	-75	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