UPFC FOR CONTROLLING POWER FLOW IN POWER SYSTEMS

A. M. Vural M. Tümay

University of Gaziantep, Department of Electrical and
Electronics Engineering, 27310 Gaziantep / Turkey
vural@gantep.edu.tr tumay@gantep.edu.tr

Abstract

This paper deals with controlling power flow by the use of unified power flow controller (UPFC) in power systems. The UPFC mathematical model is developed for power flow studies. The model is incorporated to the power flow program, "Power System Analysis Software Package", (PSASP) in order to investigate the capabilities of UPFC under steady-state operating conditions. The effectiveness and the reliability of the model are investigated in a simple 5-bus test system.

1. Introduction

Transmission compensation techniques have been used to control transmission line parameters for a long time. Phase shifters perform controlling phase angle difference between voltages of two buses, and series compensation devices, such as series capacitor is used to change the effective reactance of the line. However these compensation techniques are not sufficient fast enough to keep the system in stable operation in some contingency situations. Because they are mechanically controlled. In order to overcome the operation limitations of conventional compensation techniques, a new concept is introduced as "Flexible AC Transmission Systems" (FACTS) [1]. This new technology has capability of making the transmission and distribution of electricity more reliable, more controllable, and more efficient [2]. FACTS technology offers greater control of power to manage the direction of power flow on prescribed routes, an important task with the advent of privatization of electric power industry, secure loading of transmission lines up to their thermal limits, prevention of cascading outages by limiting the impacts of faults and equipment failure, damping of power system oscillations.

Among the FACTS family, thyristor-controlled series capacitor (TCSC) and thyristor-controlled static phase shifter (TCSPS) could provide fast and real-time control of active power through a transmission line [3-4]. Recent advances in high power technology has made it possible to implement all solid state power flow controllers using power switching converters. UPFC is a new device in FACTS family, which consists of series and shunt connected converters [5-6]. It can provide real-time and simultaneous control of power flow. This approach allows the combined application of phase angle control with controlled series and shunt reactive compensation. Also, the operation mode can be changed from one state into another without hardware alterations to adapt particularly changing system conditions. This paper aims to represent UPFC in steady-state analysis and to demonstrate the capabilities of UPFC in controlling active power flow within any electrical network. An injected power model method is used to represent UPFC in load flow program, PSASP [7].

2. UPFC Modeling

The equivalent circuit of a UPFC can be modeled with two ideal voltage sources, V_{se} and V_{sh}, respectively in series with the reactances, X_{se} and X_{sh}, as shown in Fig. 1. The series injection branch, a series injection voltage source, performs the main functions of controlling power flow while the shunt branch is used to provide the real power demanded by the series branch and the losses in the UPFC system. V_{se} and V_{sh} are representing the output voltages of series and shunt branches respectively, while X_{se} and X_{sh} respectively denote the leakage reactance of the two coupling transformers, T_{se} and T_{sh}.

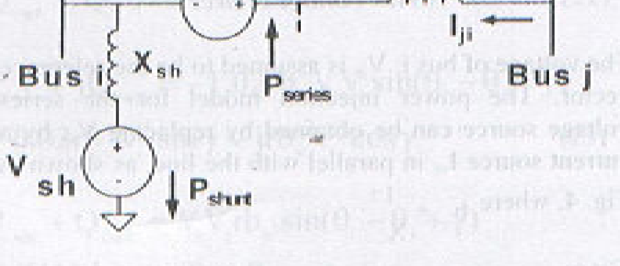

Fig. 1 The Equivalent Circuit of a UPFC

2.1 Representation of Series Connected Voltage Source of UPFC

Since the UPFC is composed of two converters, first, the mathematical modeling of the series connected converter is derived. It is assumed that the series connected converter is located between nodes i and j in a power system. The series converter can be represented with an ideal voltage source V_{se} in series with a reactance X_{se} as shown in Fig. 2. V_{se} represents an ideal voltage source. and V_i is the phasor equivalent of two phases.

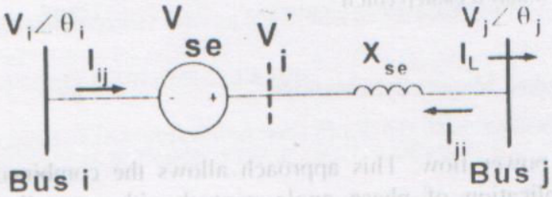

Fig. 2 Series Connected Voltage Source of the UPFC

$$\tilde{V}_i' = \tilde{V}_{se} + \tilde{V}_i \tag{1}$$

The series voltage source. V_{se} is controllable both in magnitude and phase angle. i.e..

$$\tilde{V}_{se} = r\tilde{V}_i e^{j\gamma} \tag{2}$$

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

The related phasor diagram of the concerned parameters in Fig. 2 is shown in Fig. 3.

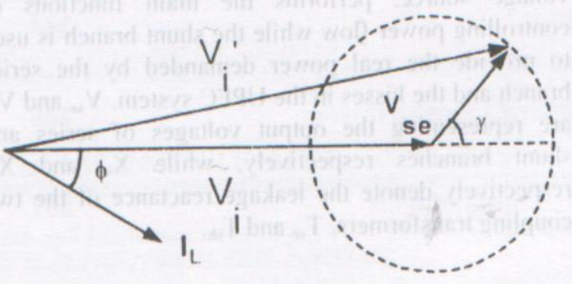

Fig. 3 Phasor Diagram of the Equivalent Circuit of Series Voltage Source

The voltage of bus i. V_i, is assumed to be the reference vector. The power injection model for the series voltage source can be obtained by replacing V_{se} by a current source I_{se} in parallel with the line. as shown in Fig. 4. where $b_{se} = \frac{1}{X_{se}}$.

$$\tilde{I}_{se} = -jb_{se}\tilde{V}_{se} \tag{3}$$

The current source I_{se} can be modeled by injection powers at the two nodes i and j. i.e..

$$\tilde{S}_{is} = \tilde{V}_i(-\tilde{I}_{se})^* \tag{4}$$

$$\tilde{S}_{js} = \tilde{V}_j(\tilde{I}_{se})^* \tag{5}$$

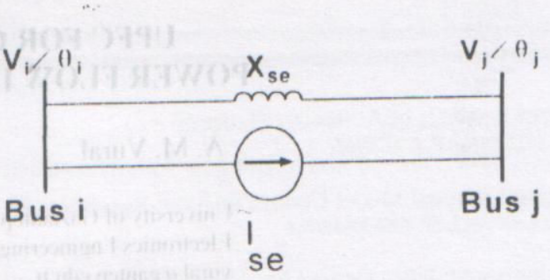

Fig. 4 Replacement of Series Voltage Source by a Current Source

The injected complex powers S_{is} and S_{js} can be simplified as substituting Eqns 2 and 3 into Eqn. 4.

$$\tilde{S}_{is} = \tilde{V}_i(jb_{se}r\tilde{V}_i e^{j\gamma})^* \tag{6}$$

$$\tilde{S}_{is} = \tilde{V}_i(e^{-j\gamma}e^{-j90}b_{se}r\tilde{V}_i^*) \tag{7}$$

$$\tilde{S}_{is} = V_i^2 b_{se} r[\cos(-\gamma - 90) + j\sin(-\gamma - 90)] \tag{8}$$

By using trigonometric identities. Eqn. 8 reduces to

$$\tilde{S}_{is} = -rb_{se}V_i^2\sin\gamma - jrb_{se}V_i^2\cos\gamma \tag{9}$$

Eqn. 9 can be divided into its real and imaginary components

$$\tilde{S}_{is} = P_{is} + jQ_{is}$$

where

$$P_{is} = -rb_{se}V_i^2\sin\gamma \tag{10}$$

$$Q_{is} = -rb_{se}V_i^2\cos\gamma \tag{11}$$

Similarly. for the bus j. the apparent power equation can be written as

$$\tilde{S}_{js} = \tilde{V}_j(-jb_{se}r\tilde{V}_i e^{j\gamma})^* \tag{12}$$

Finally. real and reactive power components can be derived as

$$\tilde{S}_{js} = P_{js} + jQ_{js}$$

where

$$P_{js} = V_iV_jrb_{se}\sin(\theta_i - \theta_j + \gamma) \tag{13}$$

$$Q_{js} = V_iV_jrb_{se}\cos(\theta_i - \theta_j + \gamma) \tag{14}$$

Based on the Eqns 10. 11. 13. and 14. the power injection model of the series connected voltage source can be seen as two dependent power injections at nodes i and j as shown in Fig. 5.

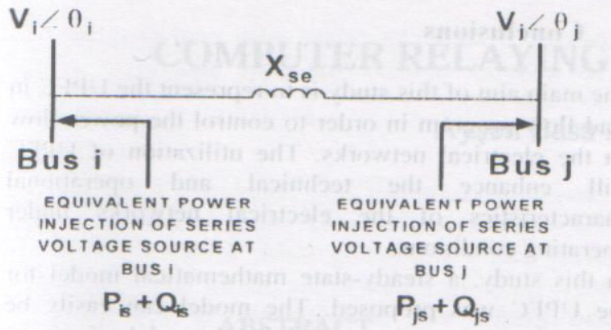

Fig. 5 Equivalent Power Injection of Series Voltage Source

2.2 Representation of Shunt Connected Voltage Source of the UPFC

The shunt branch converter is controlled to provide both the real power, which is injected to the system by the series branch, P_{SERIES}, and the total losses within the UPFC system. The total switching losses of the UPFC is estimated to be about 2 % of the power transferred. If the losses are to be included in the real power injection of the shunt connected voltage source at bus i, P_{SHUNT} is equal to 1.02 times the injected series real power P_{SERIES} through the series connected voltage source to the system.

$$P_{SHUNT} = -1.02P_{SERIES} \qquad (15)$$

The apparent power supplied by the series voltage source is calculated from

$$\tilde{S}_{SERIES} = \tilde{V}_{se}\tilde{I}_{ij}^{*} = re^{\prime}\tilde{V}_i\left(\frac{\tilde{V}_i'^{*}-\tilde{V}_j^{*}}{-jX_{se}}\right) \qquad (16)$$

Eqn. 16 can be divided into real and reactive components as follows

$$P_{SERIES} = rb_{se}V_iV_j\sin(\theta_i-\theta_j+\gamma) - rb_{se}V_i^2\sin\gamma \qquad (17)$$

$$Q_{SERIES} = -rb_{se}V_iV_j\cos(\theta_i-\theta_j+\gamma) + rb_{se}V_i^2\cos\gamma + r^2b_{se}V_i^2 \qquad (18)$$

The reactive power delivered or absorbed by the shunt connected voltage source is not considered in this model, but its impact on system can be considered as a separate controllable shunt reactive source, the main function of this reactive power is to maintain the voltage level at node i within acceptable limits. In view of the above explanations, it functions at unity power factor. We assume that $Q_{SHUNT}=0$. Consequently, the injected power model of the shunt connected voltage source is implemented with the addition of a power injection equivalent to P_{SHUNT} + j0 to node i, as shown in Fig. 6.

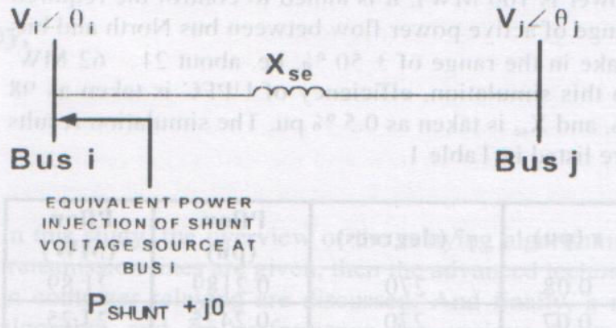

Fig. 6 The Equivalent Power Injection of the Shunt Connected Voltage Source

Finally, the complete UPFC power injection model can be constructed by combining all the series and shunt power injections at both bus i and bus j as shown in Fig. 7.

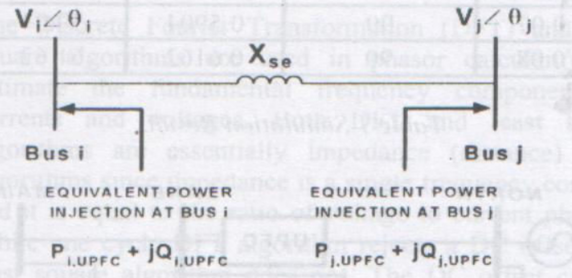

Fig. 7 Complete UPFC Power Injection Model

Where $P_{i,upfc}$ + $jQ_{i,upfc}$ and $P_{j,upfc}$ + $jQ_{j,upfc}$ are formulated as follows

$$P_{i,upfc} = P_{is} + P_{SHUNT} \qquad (19)$$

$$Q_{i,upfc} = Q_{is} \qquad (20)$$

$$P_{j,upfc} = P_{js} \qquad (21)$$

$$Q_{j,upfc} = Q_{js} \qquad (22)$$

$$P'_{i,upfc} + jQ_{i,upfc} = -1.02rb_{se}V_iV_j\sin(\theta_i-\theta_j+\gamma) + 0.02rb_{se}V_i^2\sin\gamma - jrb_{se}V_i^2\cos\gamma \qquad (23)$$

$$P_{j,upfc} + Q_{j,upfc} = V_iV_jrb_{se}\sin(\theta_i-\theta_j+\gamma) + jV_iV_jrb_{se}\cos(\theta_i-\theta_j+\gamma) \qquad (24)$$

3. Simulation Examples

According to the injection power model method and to perform the analysis of UPFC incorporated in load flow program, UPFC is located on the line between North-Lake in Hale Network [8]. The active power flow in line North-Lake in Hale 5-Bus system is equal to 0.4184 pu, which corresponds to 41.84 MW (base power is 100 MW); it is aimed to control the required range of active power flow between bus North and bus Lake in the range of ± 50 %, i.e. about 21 - 62 MW. In this simulation, efficiency of UPFC is taken as 98 %, and X_{se} is taken as 0.5 % pu. The simulation results are listed in Table 1.

r (pu)	γ° (degrees)	Pflow (pu)	Pflow (MW)
0.08	270	0.2189	21.89
0.07	270	0.2425	24.25
0.07	290	0.2737	27.37
0.05	290	0.3117	31.17
0.03	200	0.3527	35.27
0.01	290	0.3918	39.18
0.02	135	0.4393	43.93
0.03	110	0.4777	47.77
0.04	65	0.5132	51.32
0.06	90	0.5646	56.46
0.07	90	0.5904	59.04
0.08	90	0.6162	61.62

Table 1 Simulation Results

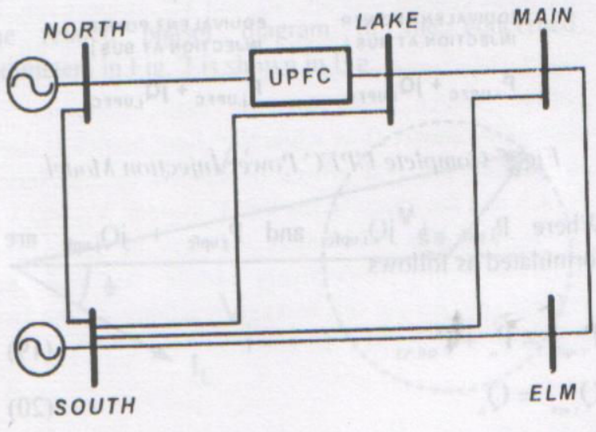

Fig. 8 Hale 5-Bus Test System with UPFC

The results show that the required active power flow control range in the line between North and Lake, i.e., ±50 % of the base power flow was obtained. It was shown that a UPFC could be controlled in an example power system to satisfy regulating and managing power flow through a transmission line. The effects of regulating power flow will not only change the reactive flows, but also it will effect on magnitudes and phase angles of bus voltages, total real and reactive power losses as well.

4. Conclusions

The main aim of this study is to represent the UPFC in load flow program in order to control the power flow on the electrical networks. The utilization of UPFC will enhance the technical and operational characteristics of the electrical networks under operating conditions.

In this study, a steady-state mathematical model for the UPFC was proposed. The model can easily be incorporated into the user-defined model of power flow program, PSASP. The capability of UPFC in power flow applications was demonstrated by the simulation examples. The required active power flow control range was successed.

5. References

[1] G.N. Hingorani, "High Power Electronics and Flexible AC Transmission System", IEEE's Power Engineering Review, July 1988, pp. 3-4.

[2] G.N. Hingorani, "Flexible AC Transmission", IEEE Spectrum, April 1993, pp. 40-45.

[3] J. Urbanek, R.J. Piwko, E.V. Larsen, B.L. Damsky, B.C. Furumasu, W. Mittlestadt, J.D. Eden, "Thyristor Controlled Series Compensation Prototype Installation At The Slatt 500 kV Substation", IEEE Transactions on Power Delivery, Vol. 8, No. 3, July 1993, pp. 1460-1469.

[4] M.R. Iravani, D. Maratukulam, "Review of Semiconductor-Controlled (Static) Phase Shifters For Power System Applications", IEEE Transactions on Power Systems, Vol. 9, No. 4, November 1994, pp. 1833-1839.

[5] L. Gyugyi, C.D. Schauder, S.L. Williams, T.R. Rietman, D.R. Torgerson, A. Edris, "The Unified Power Flow Controller: A New Approach To Power Transmission Control", IEEE Transactions on Power Delivery, Vol. 10, No. 2, April 1995, pp. 1085-1097.

[6] L. Gyugyi, "Unified Power-Flow Control Concept For Flexible AC Transmission Systems", IEE Proceedings-C, Vol. 139, No. 4, July 1992, pp. 323-331.

[7] Power System Analysis Software Package (PSASP) User Manual, Electric Power Research Institute (China), 1993.

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