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Modelling and Analysis of U.P.F.C Device in Interconnected Power Systems

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***Abstract*—Today's power generation systems are growing in size and complexity of operation with introducing of large generating units, EHV class AC transmission system, interconnection to neighboring systems, HVDC systems and more sophisticated control device such as flexible AC transmission system (FACTS) the unified power flow controller (U.P.F.C) is most superior device to have emanated from the FACTS family. They provide the fast and reliable control over the three main parameters i,e. voltage magnitude, real and reactive power flows.**

***Index Terms*—AC/DC system, FACTS, L-index, Newton-Raphson, UPFC, Voltage stability.**

I. Introduction

The U.P.F.C is an advanced power systems device capable of providing simultaneous control of voltage magnitude, active and reactive power flows, all this in adaptive fashion. Owing to its almost 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 [1]

The basic principal of operation of the U.P.F.C are well described in open literature. Readers with an interest in the internal working mechanism of the U.P.F.C are referred to some of the seminal work published in this area [1,2]. This paper is concerned with U.P.F.C models suitable for steady-state solution of large scale power network. Considerable progress has been made in this direction [3,4] and a realistic U.P.F.C model suitable for efficient load flow studies has recently been accepted for publication [5] . All these models, however, are only valid for the purpose of conventional load flow studies, and no attempt has been made so far to tackle the more complex issues of optimal power flow (OPF) solutions of power network where U.P.F.Cs are included. A comprehensive U.P.F.C model is suitable for OPF solutions is presented for the first time in this paper.

Using the U.P.F.C-OPF model presented in this paper, very robust iterative solutions are achieved since the optimization process is carried out via Newton's method [6,7]. Hence large scale power networks are solved very reliably. The U.P.F.C model has been developed to control active and reactive power flow at either the sending or receiving end nodes. Furthermore, the model is very flexible and can be set to simulate different U.P.F.C operating modes very easily.

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For instance, to deactivate one or even two operational functions, it is only necessary to add second derivate of large, quadratic penalty weight factor into the appropriate weight locations of the linearized system of equations. The dimension of the system remains unchanged as does the elimination order in the Gaussian elimination process, hence very efficient iterative solution are achieved.

II. UNIFIED POWER FLOW CONTROLLER

The basic principles of U.P.F.C operation are already well established in open literature [1-4]. A schematic representation of a U.P.F.C as shown in fig.1.

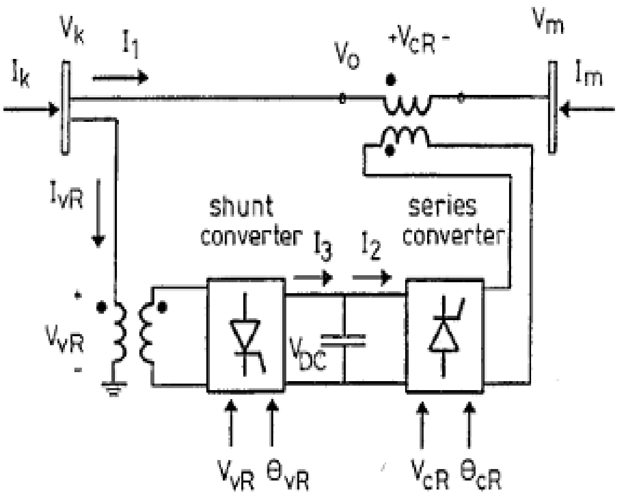

Fig. 1 UPFC schematic diagram

The output voltage of the 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 the series voltage source V_{cR}, determines active and reactive power exchanged between series converter and the AC system.

The real power demanded by the series converter is supplied from the 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.

III. U.P.F.C EQUIVALENT CIRCUIT

The U.P.F.C equivalent circuit shown in Fig. 2 is used to derive the steady-state model.

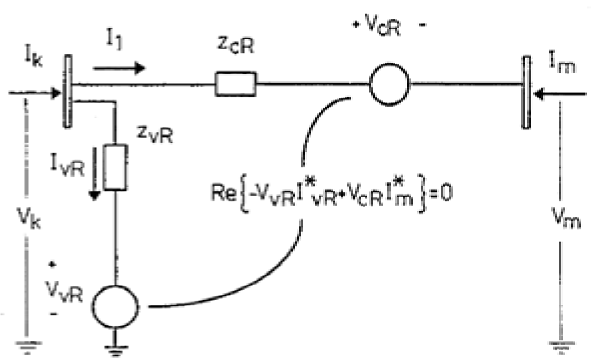

Fig. 2 UPFC equivalent circuit

The equivalent circuit consists of two ideal voltage source representing the fundamental Fourier series component of the switched voltage waveforms at the AC converter terminals, the ideal voltage sources are:

$$V_{vR} = V_{vR}\,(\cos\theta_{vR} + j\sin\theta_{vR}) \qquad (1)$$
$$V_{cR} = V_{cR}\,(\cos\theta_{cR} + j\sin\theta_{cR}) \qquad (2)$$

Where V_{vR} and θ_{vR} are the controllable magnitudes ($V_{vRmin} \le V_{vR} \le V_{vRmax}$) and angle ($0 \le \theta_{vR} \le 2\pi$) of the voltage source representing the shunt converter. The magnitude V_{cR} and the angle θ_{cR} of the voltage source of the series converter are controlled between the limits ($V_{cRmin} \le V_{cR} \le V_{cRmax}$) and angle ($0 \le \theta_{cR} \le 2\pi$), respectively.

IV. U.P.F.C POWER EQUATIONS

Based on equivalent circuit diagram shown in Fig. 2, the active and reactive power equations are:

At node k:

$$\begin{aligned} P_k &= V_k^2 G_{kk} + V_k V_m\,(G_{km}\cos(\theta_k - \theta_m) + B_{km}\sin(\theta_k - \theta_m)) \\ &\quad + V_k V_{cr}\,(G_{km}\cos(\theta_k - \theta_{cr}) + B_{km}\sin(\theta_k - \theta_{cr})) \\ &\quad + V_k V_{vr}\,(G_{vr}\cos(\theta_k - \theta_{vr}) + B_{vr}\sin(\theta_k - \theta_{vr})) \end{aligned} \qquad (3)$$

$$\begin{aligned} Q_k &= -V_k^2 B_{kk} + V_k V_m\,(G_{km}\sin(\theta_k - \theta_m) - B_{km}\cos(\theta_k - \theta_m)) \\ &\quad + V_k V_{cr}\,(G_{km}\sin(\theta_k - \theta_{cr}) - B_{km}\cos(\theta_k - \theta_{cr})) \\ &\quad + V_k V_{vr}\,(G_{vr}\sin(\theta_k - \theta_{vr}) - B_{vr}\cos(\theta_k - \theta_{vr})) \end{aligned} \qquad (4)$$

At node m:

$$\begin{aligned} P_m &= V_m^2 G_{mm} + V_m V_k\,(G_{mk}\cos(\theta_m - \theta_k) + B_{mk}\sin(\theta_m - \theta_k)) \\ &\quad + V_m V_{cr}\,(G_{mm}\cos(\theta_m - \theta_{cr}) + B_{mm}\sin(\theta_m - \theta_{cr})) \end{aligned} \qquad (5)$$

$$\begin{aligned} Q_m &= -V_m^2 B_{mm} + V_m V_k\,(G_{mk}\sin(\theta_m - \theta_k) - B_{mk}\cos(\theta_m - \theta_k)) \\ &\quad + V_m V_{cr}\,(G_{mm}\sin(\theta_m - \theta_{cr}) - B_{mm}\cos(\theta_m - \theta_{cr})) \end{aligned} \qquad (6)$$

Series converter:

$$\begin{aligned} P_{cR} &= V_{cR}^2 G_{mm} + V_{cR} V_k\,(G_{km}\cos(\theta_{cR} - \theta_k) + B_{km}\sin(\theta_{cR} - \theta_k)) \\ &\quad + V_{cR} V_m\,(G_{mm}\cos(\theta_{cr} - \theta_m) + B_{mm}\sin(\theta_{cR} - \theta_m)) \end{aligned} \qquad (7)$$

$$\begin{aligned} Q_{cR} &= -V_{cR}^2 B_{mm} + V_{cR} V_k\,(G_{km}\sin(\theta_{cR} - \theta_k) - B_{km}\cos(\theta_{cR} - \theta_k)) \\ &\quad + V_{cR} V_m\,(G_{mm}\sin(\theta_{cR} - \theta_m) - B_{mm}\cos(\theta_{cR} - \theta_m)) \end{aligned} \qquad (8)$$

Shunt converter:

$$P_{vR} = -V_{vR}^2 G_{vR} + V_{vR} V_k\,(G_{vR}\cos(\theta_{vR} - \theta_k) + B_{vR}\sin(\theta_{vR} - \theta_k)) \qquad (9)$$

$$Q_{vR} = V_{vR}^2 B_{vR} + V_{vR} V_k\,(G_{vR}\sin(\theta_{vR} - \theta_k) - B_{vR}\cos(\theta_{vR} - \theta_k)) \qquad (10)$$

Assuming a free loss converter operation. The U.P.F.C 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.

$$P_{vR} + P_{cR} = 0 \qquad (11)$$

V. DECOUPLED U.P.F.C MODEL

A sequential U.P.F.C power flow model proposed by Nabavi-Niaki and Iravani [6] is capable of regulating the power flowing from node *m* to *k* and to regulate the nodal voltage magnitude at node *k*. In this situation, assuming a free loss U.P.F.C operation and neglecting the resistance in the voltage source impedances, the U.P.F.C and coupling transformers can be modeled by means of a load and a generator. This is shown in fig. 3

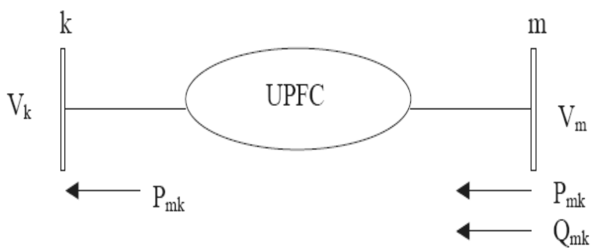

Fig. 3 Schematic U.P.F.C model.

Fig. 4 Equivalent U.P.F.C model.

The sending end of the U.P.F.C is transformed into a PQ bus, whilst the receiving end is transformed into a PV bus.

The active and reactive power loads in the PQ bus are set to the values being controlled by the U.P.F.C. The voltage magnitude at the PV bus is set at the value to be controlled by the U.P.F.C.**A** standard load flow solution is carried out with the equivalent model given in Fig. 4. After load flow convergence, an additional set of nonlinear equations is solved by iteration to compute the U.P.F.C parameters. This method is simple but will only work if the U.P.F.C is used to control voltage magnitude, active power and reactive power, simultaneously. If one only wishes to control one or two variables, the method is no longer applicable. Moreover, since the U.P.F.C parameters are computed after the load flow has converged, there is no way of knowing during the iterative process whether or not the U.P.F.C parameters are within limits.

VI. LOAD FLOW TEST CASES

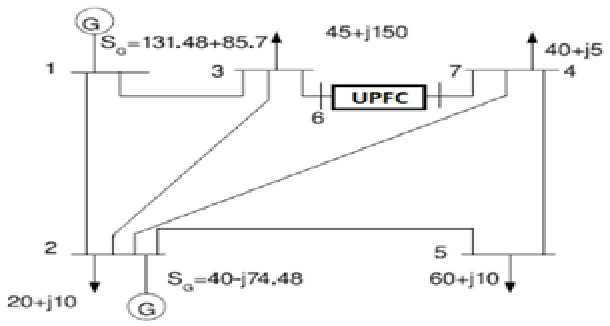

Fig.5 Single line diagram of 5-bus equivalent system with UPFC

VII. POWER FLOW CONTROL BY U.P.F.C

A small network is considered to analyze how the U.P.F.C performs. The original network is modified to include U.P.F.C which compensates the transmission line connected between nodes 3 and 4. An additional nodes, termed 6 and 7, are created to connect the U.P.F.C as shown in Fig.1. The U.P.F.C is used to maintain active and reactive powers leaving the U.P.F.C, towards 4, at 40 MW and 2MVARs, respectively. Moreover, the UPFC's shunt converter is set to regulate 3 nodal voltage magnitude at lpu. The initial conditions of the U.P.F.C voltage sources are computed. They are V_{cr}= 0.04pu, θ_{cr}= -87.13, V= 1puand V_{vr}= 1p.u and θ_{vr} =0. The source impedances have values of X_{cr}= X_{vr}= 0.1pu. Convergencewas obtained in three iterations to a power mismatch tolerance of The U.P.F.C upheld its target values. The final power flow results are shown in Fig. 1. The final nodal complex voltages are given in following Table 1.

Table 1: Nodal complex voltages of network with UPFC

Complex voltages	SYSTEM NODES 1	2	3	4	5	6	7
V(pu)	1.06	1	0.99	0.99	0.97	1	0.99
θ(deg)	0	-1.76	-6	-3.19	-4.97	-6.03	-2.53

Table 2. Shows the variation of the controllable voltage sources during the iterative process. Identical solutions were obtained with the general UPFC model discussed and the decoupled UPFC model since no limit violations occurred.

Table 2: Variation of ideal voltage sources

	Series source		Shunt source	
Iteration	V_{Cr} (p.u)	θ_{cr} (deg)	V_{VR} (p.u)	θ_{Vr} (deg)
0	0.02123	-87.46095	0.99332	4.6293
1	0.10113	-92.74664	1.01716	-6.02086
2	0.10087	-92.73934	1.01723	-6.0069

VIII. RESULTS ANALYSIS

This section presents simulation results aimed at showing the effects of the U.P.F.C models presented below. The active and reactive powers specified at U.P.F.C buses are same values as in Table 1 . Table 3. shows results for the following cases:

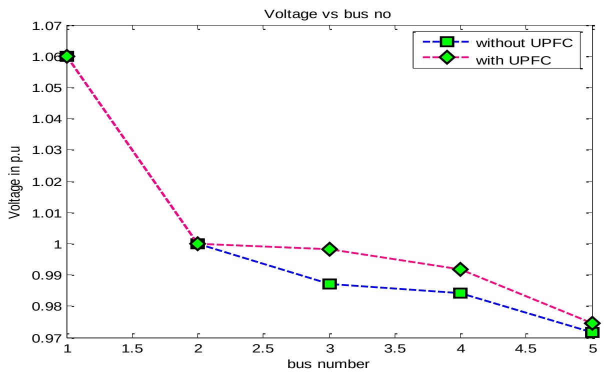

Fig. 6 UPFC regulating voltage

- UPFC controlling node 3 voltage magnitude at 1.0 pu;
- UPFC controlling node 3 voltage magnitude at 0.95 pu;
- UPFC controlling node 3 voltage magnitude at 1.05 pu;
- UPFC with shunt source voltage magnitude fixed at 0. 95 pu;
- UPFC with shunt source voltage magnitude fixed at 1.0 pu;
- UPFC with shunt source voltage magnitude fixed at 1.05 pu;

If the U.P.F.C is connected to a weak system, the reactive power generated by the shunt converter is mainly used for voltage support purposes in order to establish a strong bus bar at the point where the power system is supplying active power to the U.P.F.C. In these simulator (i.e.it does not operate at unity power factor), and the SVS model of the U.P.F.C[2] will not yield realistic results.

IX. EFFECT OF UPFC IMPEDANCES

The effect of source impedances on the U.P.F.C final parameters is shown in this Section. These studies were carried out using the network shown in Fig. 5. The U.P.F.C is set to control voltage magnitude and active and reactive power flows at the same values as those specified in Table 1. The U.P.F.C parameters corresponding to different combinations of source impedances are presented in Table 5. Voltage profile of equivalent system as shown in Fig 6. And Table 4. respectively.

Table 5: Effect of UPFC impedances

Imped ance	Series source				Shunt source		
X_{cR}	X_{vR}	V_{cR} (p.u)	θ_{cr} (deg)	Q_{cR} (MVARs)	V_{vR} (pu)	θ_{Vr} (deg)	Q_{vR} (MVARs)
0.10	0.10	0.1011	−92.7501 8	4.07	1.0171	−6.025 45	17.48845
0.05	0.05	0.0811	−92.0944 9	3.25507	1.0086	−6.030 69	17.34089

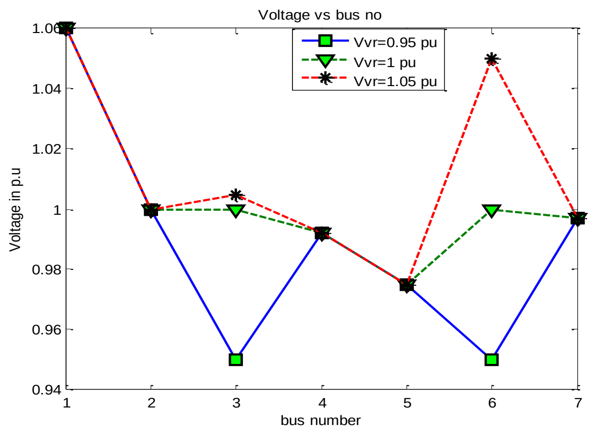

Fig 7: Nodal Voltage Magnitude Profile of 5 bus Equivalent system(VvR)

X. Conclusions

Modeling and analysis of HVDC and UPFC in interconnected power systems has been presented and tested under normal and contingency conditions on typical sample systems i.e.1. Sample 5 Bus System.2. 12 Bus equivalent, a part of Southern Indian System.3. UP equivalent system of a 100-bus AC comprising of two DC systems and two U.P.F.C. The modeling is giving encouraging results and fulfilling the task of maintaining voltage profiles and power flows and requirements.

ACKNOWLEDGMENTS

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