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PERFORMANCE COMPARISON OF OPEN AND CLOSED LOOP OPERATION OF UPFC

Sarat Kumar Sahu[1], S. Suresh Reddy[1] and S. V. Jayaram Kumar[2]
[1]Department of Electrical and Electronics Engineering, NBKRIST, Vidyanagar, Nellore, Andhraparadesh, India
[2]Department of Electrical Engineering, JNTU, Hyderabad, Andhraparadesh, India
E-Mail: sarata1@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 is a FACTS device that can control all the three system variables namely, line reactance, magnitude and phase angle difference of the voltages across the line. The Unified Power flow controller 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 addresses comparison of the two steady-state modeling of U.P.F.C within the context of Load flow study of a power system. This model is incorporated into an existing Newton-Raphson Load flow algorithm.

Keywords: FACTS, Load flows, UPFC.

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 power electronic technology has made FACTS (Flexible A.C. Transmission Systems) a promising path for future power system. With the FACTS technology such as STATCON (Static Condenser), TCSC (Thyristor Controlled Series capacitor), TCPR (Thyristor controlled phase angle regulator), UPFC [1] (Unified Power Flow Controller) etc, the bus voltages, line impedances, and phase angles in the power system can be regulated rapidly and flexibly. FACTS do not indicate a particular controller, but a host of controllers whom the system planner can choose based on cost benefit analysis.

The UPFC is an advanced power systems device capable of providing simultaneous control of voltage magnitude and 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.
There are two aspects in handling the UPFC in steady state analysis [7].

- When the UPFC parameters are given, a power flow program is used to evaluate the impact of the given UPFC on the system under various conditions. In this case UPFC is operated in open loop form.
- As UPFC can be used to control the line flow and bus voltage, control techniques are needed to derive the UPFC control parameters to achieve the required objective. In this case UPFC is operated in closed loop form.

In this paper UPFC is treated to operate in both forms and the both the modeling methods are compared with each other.

2. CLOSED LOOP OPERATION

2.1. Circuit description

Considering the well-established modeling principle [1] and the steady state UPFC models suggested in [2] the one shown in Figure-1 was adopted for the study. The three controllable variables namely voltage magnitude (V_T) injected by the booster transformer, voltage phase angle difference (Φ_T) and the exciting transformer reactive current (I_q) can be regulated independently with in the region defined by

$\Gamma = \{V_T , \Phi_T, I_q\}$
$V_T \in (0, V_{Tmax})$
$\Phi_T \in (0, 2\Pi)$
$I_q \in (-I_{qmax}, I_{qmax})$.

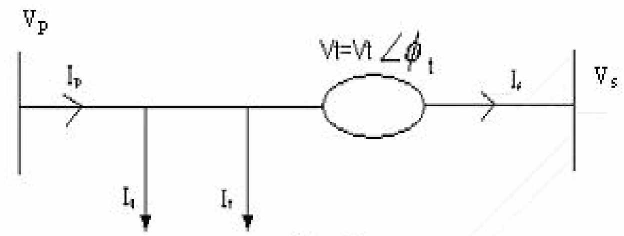

Fig. 1.

The mathematical relations of UPFC control variables are

$$V_s = V_p + V_t \quad (1)$$

$$I_s = I_p - I_q - I_t \quad (2)$$

$$\arg(I_t) = \arg(V_p) \quad (3)$$

$$I_t = \mathrm{Re}(V_t I_s^*)/V_p \quad (4)$$

$$\arg(I_q) = \arg(V_p) \pm \pi/2 \quad (5)$$

2.2. Power equations of the UPFC connected branch

Consider a UPFC with its boost transformer connected in series with a transmission line. Assume that the exciting transformer is connected to the bus ‘l’ and the

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two terminals of the transmission line are denoted as bus‘s’ and ‘m’ respectively. By using the UPFC model [3] illustrated in Figure-1 and ‘pi’ equivalent circuit of the transmission line, the branch with the UPFC connected between bus ‘l’ and ‘m’ can be modeled as shown in Figure-2. $Z_{lm} = R_{lm} + jX_{lm}$ and jB_{lm} denote the parameters of the transmission line. Y_l and Y_m represent the system shunt admittance at bus ‘l’ and ‘m’, respectively.

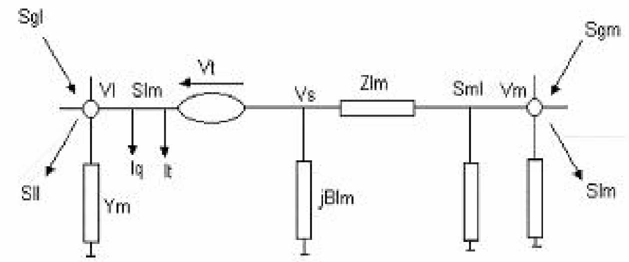

Fig. 2.

$$S_{ml} = P_c + jQ_c = P_f + jQ_f + \Delta S_e \quad (6)$$

$$P_f + jQ_f = \left(\frac{V_m - V_l}{R_{lm} + jX_{lm}} + jB_{lm} V_m \right)^* V_m \quad (7)$$

$$\Delta S_e = P_e + jQ_e = -\left(\frac{V_t}{R_{lm} + jX_{lm}} \right)^* V_m \quad (8)$$

$$S_{lm} = P_{lm} + jQ_{lm} \quad (9)$$

$$P_{lm} = R_{lm}\left(\frac{P_c^2 + Q_c^2}{V_m^2} + B_{lm}^2 V_m^2 + 2B_{lm} Q_c \right) - p_c \quad (10)$$

$$Q_{lm} = -I_q V_l - \left[\begin{array}{l} \left(E_1 V_m^{-1} + F_1 V_m\right)\sin\delta_{lm} \\ -\left(E_2 V_m^{-1} + F_2 V_m\right)\cos\delta_{lm} \end{array} \right] V_l \quad (11)$$

$$E_1 = C_x P_c + C_y Q_c \quad 12)$$

$$E_2 = C_y P_c - C_x Q_c \quad (13)$$

$$F_1 = B_{lm} C_y \quad (14)$$

$$F_2 = -B_{lm}(1 + C_x) \quad (15)$$

$$C_x = 1 - B_{lm} X_{lm} \quad (16)$$

$$C_y = B_{lm} R_{lm} \quad (17)$$

$\delta_{lm} = \delta_l - \delta_m$, δ_{lm} is the phase angle difference between bus ‘l’ and ‘m’

2.3. Load flow equations

Assume that for a given control strategy the power S_{ml} on the UPFC controlled transmission line l-m is set to constant $P_c + jQ_c$. By means of substitution theorem, this branch l-m can be detached as shown in Figure-3 in which S_{ml} represents power from bus ‘m’ and S_{lm} represents power from bus’l’. For each other additional UPFC, its corresponding branch can be dealt with similarly.

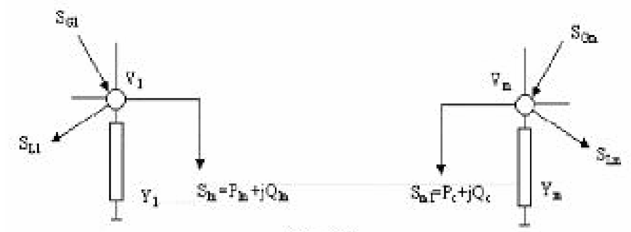
Fig. 3.

After modifying all of the UPFC embedded branches the load flow equations can be written as follows:

$$Q_{Gi} - Q_{Li} = \sum V_i V_j \left(G_{ij}\cos\delta_{ij} - B_{ij}\sin\delta_{ij} \right) \quad (18)$$

$$P_{Gi} - P_{Li} = \sum V_i V_j \left(G_{ij}\cos\delta_{ij} + B_{ij}\sin\delta_{ij} \right) \quad (19)$$

i=1,2,3…………………n; but i≠l,m

$$P_{Gl} - P_{Ll} = \sum V_l V_j \left(G_{lj}\cos\delta_{lj} + B_{lj}\sin\delta_{lj} \right) + P_{lm} \quad (20)$$

$$Q_{Gm} - Q_{Lm} = \sum V_m V_j \left(G_{mj}\cos\delta_{mj} - B_{mj}\sin\delta_{mj} \right) + Q_c \quad (21)$$

$$P_{Gm} - P_{Lm} = \sum V_m V_j \left(G_{mj}\cos\delta_{mj} + B_{mj}\sin\delta_{mj} \right) + P_c \quad (22)$$

$$Q_{Gl} - Q_{Ll} = \sum V_l V_j \left(G_{lj}\cos\delta_{lj} - B_{lj}\sin\delta_{lj} \right) + Q_{lm} \quad (23)$$

2.4. Load flow computation

Since $S_{ml} = P_c + jQ_c$ is set as constant for the given control requirement, $S_{lm} = P_{lm} + jQ_{lm}$ can be treated as a special load varying with respect to the voltages V_l and V_m. As a result, the UPFC’s have already been decoupled from the system and the load flow equations (18-23) can be solved by standard Newton Raphson load flow program.

2.5. Computation for the UPFC control setting

After the load flow computation converges, the control setting of the UPFC can be computed as follows. First P_f and Q_f are computed from (7). Note that P_c and Q_c are given and (6) gives

$$\Delta S_e = P_e + jQ_e = P_c + jQ_c - P_f - jQ_f \quad (24)$$

$$V_t \angle \varphi_t = -(P_e - jQ_e)(R_{lm} + jX_{lm})/(V_m \angle \delta_m) \quad (25)$$

$$V_t = \left[\left(P_c^2 + Q_c^2\right)\left(R_{lm}^2 + X_{lm}^2\right) \right]^{1/2} / V_m \quad (26)$$

$$\varphi_t = \gamma - \beta + \delta_m \quad (27)$$

$$\gamma = \mathrm{arctg}[Q_e/(-P_e)], \beta = \mathrm{arctg}\left[X_{lm} / R_{lm} \right] \quad (28)$$

From (25) and (26) V_T and Φ_T can be determined readily once the load flow calculation converges for the given (P_c, Q_c).

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3. OPEN LOOP OPERATION

3.1. Circuit description

The steady state model is based [4] on two ideal voltage source converters. One in series with the line and one are in shunt with the line. The output voltage of the series converter is added to the AC terminal voltage V_o via the series connected coupling transformer. The injected voltage V_{cr} acts as an AC series system voltage source changing the effective sending end voltage as seen from node m. The product of transmission line current Im and series voltage source V_{cr}, determines the active and reactive power exchanged between the series converter and AC system. The real power demanded by the series converter is supplied form the AC power system by the shunt converter via the common DC link.

3.2. Equivalent circuit and power equations

The UPFC equivalent circuit shown in Figure-4 is used to derive steady state model. The equivalent circuit consists of two ideal voltage sources representing the fundamental Fourier series component of the switched voltage waveforms at the AC converter terminals. The ideal voltage sources are:

$$V_{vr} = Vvr\,(\cos\theta_{vr} + j\sin\theta_{vr}) \qquad (29)$$

$$V_{cr} = Vcr\,(\cos\theta_{cr} + j\sin\theta_{cr}) \qquad (30)$$

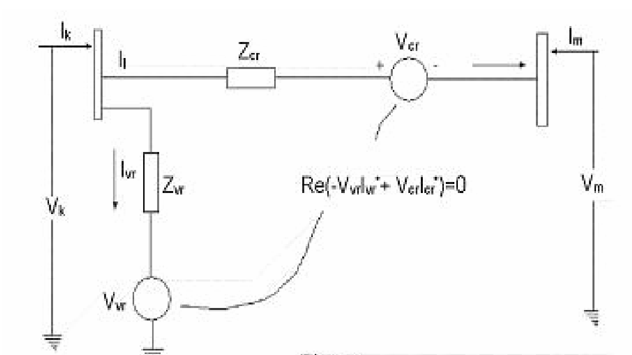

Fig. 4.

The real and reactive powers injected at the nodes k, m and also at series converter and shunt converter.

At node k,

$$\begin{aligned}P_k = V_k^2 G_{kk} &+ V_k V_m (G_{km}\cos(\theta_k - \theta_m) \\ &+ B_{km}\sin(\theta_k - \theta_m)) \\ &+ V_k V_{cr} (G_{km}\cos(\theta_k - \theta_{cr}) \\ &+ B_{km}\sin(\theta_k - \theta_{cr})) \\ &+ V_k V_{vr} (G_{vr}\cos(\theta_k - \theta_{vr}) \\ &+ B_{vr}\sin(\theta_k - \theta_{vr}))\end{aligned} \qquad (31)$$

$$\begin{aligned}Q_k = -V_k^2 B_{kk} &+ V_k V_m (G_{km}\sin(\theta_k - \theta_m) \\ &- B_{km}\cos(\theta_k - \theta_m)) \\ &+ V_k V_{cr} (G_{km}\sin(\theta_k - \theta_{cr}) \\ &- B_{km}\cos(\theta_k - \theta_{cr})) \\ &+ V_k V_{vr} (G_{vr}\sin(\theta_k - \theta_{vr}) \\ &- B_{vr}\cos(\theta_k - \theta_{vr}))\end{aligned} \qquad (32)$$

At node 'm',

$$\begin{aligned}P_m = V_m^2 G_{mm} &+ V_m V_k (G_{mk}\cos(\theta_m - \theta_k) \\ &+ B_{mk}\sin(\theta_m - \theta_k)) \\ &+ V_m V_{cr} (G_{mm}\cos(\theta_m - \theta_{cr}) \\ &+ B_{mm}\sin(\theta_m - \theta_{cr}))\end{aligned} \qquad (33)$$

$$\begin{aligned}Q_m = -V_m^2 B_{mm} &+ V_m V_k (G_{mk}\sin(\theta_m - \theta_k) \\ &- B_{mk}\cos(\theta_m - \theta_k)) \\ &+ V_m V_{cr} (G_{mm}\sin(\theta_m - \theta_{cr}) \\ &- B_{mm}\cos(\theta_m - \theta_{cr}))\end{aligned} \qquad (34)$$

At series converter,

$$\begin{aligned}P_{cr} = V_{cr}^2 G_{mm} &+ V_{cr} V_k (G_{km}\cos(\theta_{cr} - \theta_k) \\ &+ B_{km}\sin(\theta_{cr} - \theta_k)) \\ &+ V_{cr} V_m (G_{mm}\cos(\theta_{cr} - \theta_m) \\ &+ B_{mm}\sin(\theta_{cr} - \theta_m)\end{aligned} \qquad (35)$$

$$\begin{aligned}Q_{cr} = -V_{cr}^2 B_{mm} &+ V_{cr} V_k (G_{km}\sin(\theta_{cr} - \theta_k) \\ &- B_{km}\cos(\theta_{cr} - \theta_k)) \\ &+ V_{cr} V_m (G_{mm}\sin(\theta_{cr} - \theta_m) \\ &- B_{mm}\cos(\theta_{cr} - \theta_m))\end{aligned} \qquad (36)$$

At shunt converter,

$$\begin{aligned}P_{vr} = -V_{vr}^2 G_{vr} &+ V_{vr} V_k (G_{vr}\cos(\theta_{vr} - \theta_k) \\ &+ B_{vr}\sin(\theta_{vr} - \theta_k))\end{aligned} \qquad (37)$$

$$\begin{aligned}Q_{vr} = V_{vr}^2 B_{vr} &+ V_{vr} V_k (G_{vr}\sin(\theta_{vr} - \theta_k) \\ &- B_{vr}\cos(\theta_{vr} - \theta_k)\end{aligned} \qquad (38)$$

Where

$$Y_{kk} = G_{kk} + jB_{kk} = Z_{cr}^{-1} + Z_{vr}^{-1} \qquad (39)$$

$$Y_{mm} = G_{mm} + jB_{mm} = Z_{cr}^{-1} \qquad (40)$$

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$$Y_{km} = G_{km} + jB_{km} = -Z_{cr}^{-1} \quad (41)$$

$$Y_{vr} = G_{vr} + jB_{vr} = -Z_{vr}^{-1} \quad (42)$$

Assuming a free loss converter operation, the UPFC neither absorbs nor injects active power with respect to the A.C system. The dc line voltage V_{dc}, remains constant. The active power associated with 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 series converter, P_{cr} i.e.,

$$P_{cr} + P_{vr} = 0 \quad (43)$$

The UPFC linearised power equations are combined with the linearised system of equations corresponding to the rest of network as

$$[f(X)] = [J][X] \quad (44)$$

where

$$f(X) = [\Delta P_k \Delta P_m \Delta Q_k \Delta Q_m \Delta P_{cr} \Delta Q_{cr} \Delta P_{bb}]^T \quad (45)$$

ΔP_{bb} is the power mismatch and superscript 'T' indicates transposition. 'X' is the solution vector and 'J' is the jacobian matrix, where

$$[X] = [\Delta\theta_k \Delta\theta_m \Delta V_{vr} \Delta V_m \Delta\theta_{cr} \Delta V_{cr} \Delta\theta_{vr}]^T \quad (46)$$

This steady state model is suitable for interpolation into an existing Newton-Raphson load flow algorithm. In common with all other controllable plant component models available in algorithm, the UPFC state variables and interpolation inside the Jacobian matrix and mismatch equations, leading to a best iterative solution.

4. CASE STUDY

4.1. Open loop control

A five-bus network has been used to show quantitatively, how the UPFC performs. The power system model was drawn in simulink and it was simulated using PSAT/SIMULINK. The original network is modified to include UPFC as shown in Figure-5**,** which compensates the line between buses 3 and 4 The UPFC is used to regulate the active and reactive power flowing in the line at a pre specified value.

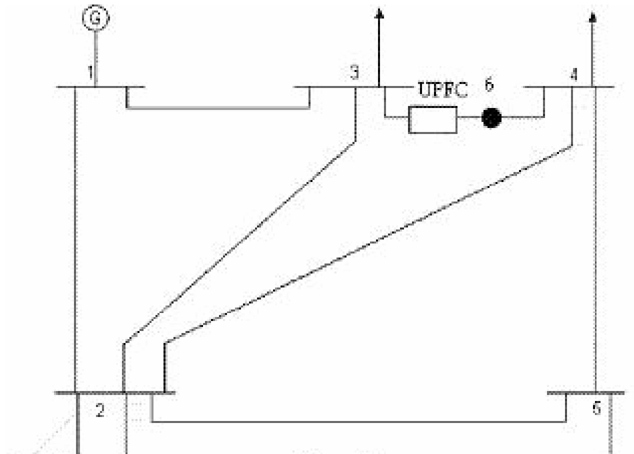

Fig. 5.

The load flow solution for the modified network is obtained by using Newton-Raphson method. Once the load flow is converged the final values of voltages at 3rd and 4th node are taken and the UPFC control setting is determined. The maximum amount of active power exchanged between the UPFC and the AC system will depend on the robustness of UPFC shunt bus i.e., bus '3'.Since the UPFC generates its own reactive power, the generator at the 1st bus reduces its reactive power as observed from the simulation studies It must be noted that selected UPFC initial conditions have a good impact on the convergence of load flow problem in open loop system. If the initial values of UPFC are not chosen in a proper way, the load flow problem diverges, because the initial conditions are estimated by using the pre specified power flows.

4.2. Closed loop control

The original network is modified to include UPFC which compensates the line between buses 3 and 4 . The UPFC is used to regulate the active and reactive powers leaving UPFC towards node '4' at specified values. Moreover the UPFC shunt converter is set to regulate the node voltage at bus 3 at 1 p.u. (Or any other specified value).The converged load flow results can be used to determine the control settings of UPFC. In closed loop control, the control setting of UPFC can be determined directly without iteration and hence have no need for any assumption of initial values. Keeping the load demand at the buses where UPFC is connected, the pre specified real and reactive power flows are gradually increased to see how the control setting of UPFC is changed. As the pre specified real power is increased, the UPFC series voltage is increasing in quadrature with the system voltage. The results of both the close loop and open loop systems are given in Tables 1 and 2, respectively. The final converged values of UPFC series and shunt voltage sources are also mentioned in Table-2. In both the cases to compare the results the pre specified power flow from bus '3' to bus'4' is kept same and studies are carried out. The number of iterations for convergence in open loop system is more when compared with the closed loop system. It is because of the factor that the number of non linear equations in open loop system is more when compared with closed loop system.

Table-1. Closed loop control.

Load demand (MW)		**Pre-specified line flow** (p.u)		**UPFC voltage**	**Angle** (Φ_t)
Bus '3'	Bus '4'	P_c	Q_c	(V_t) pu	radians
45	40	0.2	0.01	0.0072	-1.9828
45	40	0.24	0.01	0.0091	-1.8323
45	40	0.34	0.02	0.1474	-1.683
45	40	0.40	0.03	0.0181	-1.650
45	40	-0.34	0.02	0.0259	-1.150

Table-2. Open loop control.

Load demand (MW)		**UPFC parameters**			
Bus'3'	Bus'4'	V_{cr}	θ_{cr}	V_{vr}	θ_{vr}
45	40	0.0648	-1.5917	1.0493	-0.0950
45	40	0.0590	-0.8272	0.9783	-0.0853
45	40	0.0488	-0.5791	0.9191	-0.0703
45	40	0.0403	-0.4594	0.8611	-0.0583
45	40	0.0646	-1.8515	1.0566	-0.1171

5. CONCLUSIONS

In this paper a steady state model based on power flow between two buses is presented. It is observed that in closed loop operation as the pre specified real power flow is increased the voltage angle (Φ_T) is reaching near -90^o. In open loop operation prior to the incorporation of UPFC the power transfer between bus '3' and '4' is 18-j5.2.After the UPFC is incorporated the power flow has been changed to 34-j5. This is done by appropriately choosing the initial conditions of the UPFC. The disadvantage in open loop operation is that we have to choose appropriate initial conditions other wise we may not get the solution for the load flow.

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