Development of Power Flow Model of Hybrid Power Flow Controller

SonalRanjan Patel and DheemanChatterjee

Abstract – This paper presents the development of steady state power flow model of Hybrid Power Flow Controller (HPFC) – a newly introduced member of flexible AC transmission systems (FACTS) family. It comprises of both switching converter based and thyristor controlled variable impedance based FACTS devices. Its power flow control capability is described through the equations representing it in a transmission line. The Newton Raphson power flow program is then modified to incorporate the effects of HPFC without changing the basic computational algorithm. The power flow model is used for steady state control of active power flow and voltages at the point of connections to the transmission line. The modelling technique presented in this paper for controlled power flow is tested on WSCC 9-bus test system.

Keywords – Flexible AC transmission systems, Hybrid Power FlowController, Power flow model.

I. INTRODUCTION

The demand for electrical power is growing day by day. Economic and environmental constraints are proving to be a major hurdle in the establishment of new power generation and transmission infrastructure. One viable way to overcome this is focusing on better utilization of the existing system. Application of power electronic devices in the form of flexible AC transmission system (FACTS) helps in achieving this target – operating the existing transmission system closer to its thermal limit.

FACTS devices are broadly classified into two types as (a) thyristor controlled variable impedance type devices e.g. Static Var Compensator (SVC) or Thyristor Controlled Series Capacitor (TCSC) and (b) switching converter type devices e.g. Static Synchronous Compensator (STATCOM), Static Synchronous Series Compensator (SSSC) or Unified Power Flow Controller (UPFC). The dynamic performance of the switching converter type FACTS devices is better than that of the variable impedance type FACTS devices [1]. Among the various FACTS devices, UPFC is the most comprehensive one [2]. It is capable of controlling voltage, impedance and phase angle either simultaneously or selectively, but the main constraint in using it is its cost.

The current situation of power system presses for new installation of UPFC and/or replacement of existing SVC and TCSC by the UPFC. This makes the idea of the Hybrid Power Flow Controller (HPFC) proposed in [3] an alternative solution without substantial compromise on versatility. The HPFC makes combined use of both variable impedance type devices which may be already existing in the system and switching converter type FACTS devices. The investment cost is considerably reduced by using an existing FACTS device. Also, the existing SVC or TCSC is fully utilised with enhanced compensating functions.

Computer modelling of power system incorporating FACTS devices is necessary for operation/control analysis. Power flow solution is a most frequently performed key tool of power system network calculations. It is essential to determine steady state operating conditions in the presence of FACTS devices through solution of power flow problem for power system operation and planning studies.

This paper focuses on steady state power flow model of HPFC. The concept of HPFC and its steady state analysis has been presented in [3]. The dynamic models of HPFC presented in [4-5] are based upon detail 3-phase converter design and firing scheme. The power flow model of STATCOM, TCSC and UPFC discussed in [6] provides the knowledge of combining multiple series or shunt FACTS controller into a combined series-shunt FACTS controller. The power flow model of HPFC is developed based on the foundation of power flow models of STATCOM and TCSC discussed in [7-10]. The model so obtained is used to steady state control of following parameters a) the active power flow through transmission line b) the voltage magnitudes at the point of connections to the transmission line. Numerical examples are used to study the effect of HPFC on the steady state of power systems through WSCC 9-bus test system. The complete system has been simulated using MATLAB.

II. HYBRID POWER FLOW CONTROLLER

The basic concept of HPFC is that it injects a voltage source in series with the line whose magnitude and phase angle are controllable, as the UPFC does. It improves the dynamic performance of the existing variable impedance type FACTS devices co-ordination with switching converter based FACTS devices. The followed configuration of HPFC is shown in Fig.1. It is composed of two shunt converters (STATCOM) connected to the transmission line across a series impedance controller (TCSC) through coupling transformers. The converters are coupled through a common DC-link exchanging active power in between them. The rating of each converter is half the rated size of shunt converter of UPFC. Similar to UPFC, the HPFC offers control over real and reactive power flow through the line by varying the magnitude and phase angle of the injected series voltage. This is executed by the coordination between the two STATCOMs and the TCSC.

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The injected series voltage magnitude $|V_c|$ is varied by varying the impedance of the series compensator through firing angle control of the thyristors. However, the purpose of the two shunt converters is to maintain controllable voltage magnitudes $|V_u|$ and $|V_v|$ across the TCSC to help injecting voltage at a variable phase angle $\theta_c$. $V_c$ is actually represented as $V_u - V_v$. The magnitudes of $V_u$ and $V_v$ are controlled by controlling the VAR outputs of the shunt converters. As shown in Fig. 2, considering a constant bus voltage $V_s$ and a particular injected voltage magnitude $|V_c|$, the angle $\theta_c$ of injected voltage will vary along a locus of points on the circle depending on the bus voltage $V_v$. The two circles represent the maximum and minimum possible value of injected voltage depending on the maximum and minimum value of TCSC reactance respectively.

III. HPFC FOR POWER FLOW CONTROL IN A SINGLE TRANSMISSION LINE

The real and reactive power flow control capability of the HPFC can be illustrated by the injected voltage magnitude and angle characteristics of the two-machine system shown in Fig. 3. The current flowing through the line and apparent power at the receiving end are given by

$$ I = \frac{V_r - V_s - V_c}{jX} $$

$$ S_r = V_r \cdot I $$

where $jX$ represents the actual impedance of the transmission line.

Substituting (1)-(3) in (4)-(5), following equations of the receiving end active and reactive power flow are obtained.

$$ P_r = \frac{|V_r|^2}{2} \sin(\delta) - \frac{|V_s|^2}{2} \sin(\delta + \theta_c) $$

$$ Q_r = \frac{|V_r|^2}{2} \cos(\delta) - \frac{|V_s|^2}{2} \cos(\delta + \theta_c) $$

To obtain certain amount of active power flow $P_r$ and reactive power flow $Q_r$, the values of injected voltage magnitude $|V_c|$ and angle $\theta_c$ can be calculated from (6)-(7) with known values of the $|V_s|, |V_r|, \delta, X, P_r, & Q_r$. Being $V_r$ (or $V_s$) as constant, the injected voltage $|V_c|$ and $\theta_c$ is controlled by the HPFC by appropriate control over the $|V_r|$ and $X_{tsc}$, which can be calculated using (8)-(9).

$$ |V_c| \angle \theta_c = |V_r| \angle \theta_r - |V_s| \angle \theta_s $$

$$ I = \frac{|V_r| \angle \theta_r - |V_s| \angle \theta_s}{jX_{tsc}} $$
Considering a numerical example, the sending and receiving end voltages are 1.06±5.73pu and 1.0±5.73pu respectively. The transmission line impedance is j0.1008 pu. The sending voltage \( V_s \) being constant, the HPFC controls reactance of TCSC \( X_{tcsc} \) and bus \( v \) voltage magnitude\( |V_v| \) to obtain certain amount of \( P_r \) and \( Q_r \) as shown in Table I.

In Case 1, specified values of \( P_r \) as 4.62 pu and \( Q_r \) as 1.65 pu are considered, which are obtained by maintaining \( |V_v| \) as 1.256 pu and \( X_{tcsc} \) as -0.0535 pu. These values of \( |V_v| \) and \( X_{tcsc} \) are calculated using (6)-(9). The actual injected voltage becomes 0.263±115°pu, which is the voltage across the TCSC. The phasor representation of voltages \( V_r \), \( V_v \), \( V_e \) and \( V_s \) are shown in Fig. 4(a).

In Case 2, the objective of HPFC is to increase the power flows through the link and thus \( P_r \) is increased by 10% to 5.08 pu while keeping \( Q_r \) as earlier. \( |V_v| \), \( X_{tcsc} \) and \( V_e \) are obtained as 1.274pu, -0.0585pu and 0.307±112°pu respectively. Fig. 4(b) shows the corresponding phasor diagram. It shows that the injected voltage adjusts itself according to requirement.

For Case 3, the receiving end active power \( P_r \) is decreased by 10% to 4.16 pu while \( Q_r \) is increased to 1.98 pu by 20%. The values of \( |V_v| \), \( X_{tcsc} \) and \( V_e \) are obtained as 1.287pu, -0.0519pu and 0.267±121°pu respectively to control \( P_r \) and \( Q_r \) at above specified values.

### TABLE I

| \( P_r \) (pu) | \( Q_r \) (pu) | \( |V_v| \angle \theta_v \) | \( |V_e| \angle \theta_e \) | \( X_{tcsc} \) (pu) |
|---|---|---|---|---|
| 4.62 | 1.65 | 0.263±115 | 1.256±16 | -0.0535 |
| 5.08 | 1.65 | 0.307±112 | 1.274±18 | -0.0585 |
| 4.16 | 1.65 | 0.239±117 | 1.247±15 | -0.0504 |
| 4.62 | 1.98 | 0.276±121 | 1.287±15.5 | -0.0519 |

Fig 4. Phasor diagram representing \( V_r \), \( V_v \), \( V_e \) and \( V_s \) for case 1 and case 2

### IV. POWER FLOW MODEL FOR MULTIMACHINE SYSTEM

In the equivalent circuit of HPFC shown in Fig. 5, each STATCOM is represented by a controllable voltage source in series with coupling transformer impedance and connected in shunt to the transmission line. The TCSC is symbolised as a variable capacitance. As shown in Fig. 5 the HPFC is modelled by putting the TCSC in the middle of a line by creating two new buses \( a \) and \( v \) and connecting the voltage sources to bus \( a \) through coupling transformer impedance and internal bus \( u_t \) and \( v_l \).

The equations of net injected active and reactive power for power flow solution of a network without including HPFC are given by (10)-(11).

\[
P_r = \sum_{i=1}^{n} |V_i| |V_l| \cos(\theta_i - \theta_j - \alpha_{ij}), k = 1, \ldots, n - 1 \tag{10}
\]

\[
Q_r = \sum_{i=1}^{n} |V_i| |V_l| \sin(\theta_i - \theta_j - \alpha_{ij}), k = 1, \ldots, n - m - 1 \tag{11}
\]

where \( n \) is the number of buses and \( m \) is the number of PV buses in the network. \( |V| \) and \( \theta \) represent the bus voltage magnitudes and angles. \( |V| \) and \( \theta \) represent the magnitude and angle of \( Y \)-bus elements.

In the practical operation of HPFC, \( |E_{sh1}| \) and \( |E_{sh2}| \) can be regulated to control the bus voltage magnitudes \( |V_v| \) and \( |V_e| \) respectively. In the process, the converters do not exchange any active power with the network. To model this behaviour, the two buses \( u \) and \( v \) are considered as PV bus with \( |V_u| \) and \( |V_v| \). The injection of active power at these buses. The reactance of TCSC \( X_{tcsc} \) is regulated to control the active power flow \( P_w \) in the line \( u - v \).

To include HPFC in Newton Raphson power flow solution, bus \( u_t \) and \( v_l \) are considered initially for the solution. Three constraint equations of \( P_w \), \( P_r \), and \( P_{inj} \) given by (12)-(14) are included with (10)-(11) to solve for \( \theta_u \), \( \theta_v \), and \( X_{tcsc} \) along with existing state variables as shown in Table II. After convergence of power flow solution, voltages at bus \( u \) and \( v \) are calculated as per (15)-(16). The procedure is explained in flow chart shown in Fig. 6.
Here. Buses - For Case 3, the active - .

\[ P_\alpha = \sum_{j=1}^{n+2} V_j |Y| \cos(\theta_\alpha - \theta_j - \alpha_j) \] (12)

\[ P_\nu = \sum_{j=1}^{n+2} V_j |Y| \cos(\theta_\nu - \theta_j - \alpha_j) \] (13)

\[ P_{\nu\nu} = \frac{|V| |V|}{X_{tcsc}} \sin(\theta_\nu - \theta_\nu) \] (14)

\[ I_{\nu,k} = \frac{P_k - jQ_k}{V_k}, k = u, v \] (15)

\[ V_{\nu1} = V_s + I_{\alpha,k} Z_{tcsc}, k = u, v \] (16)

A. Effect of HPFC in different lines of WSCC 9-bus system

The test system consists of 3 generators at buses 1, 2 and 3. Bus 1 is considered as the slack bus. Buses 5, 6 and 8 are the load buses. HPFC is placed in the middle of a line by creating two new numbers, numbered as bus 10 and 11. As mentioned in earlier, \[ |V_{10}|, |V_{11}| \] and active power flow through the series branch \[ P_{10-11} \] are needed to be specified for the HPFC in its power flow model. Effect of HPFC is investigated by installing it in different lines e.g. line 4-5, 6-9 and 7-8 of WSCC 9-bus system one by one as shown in Table III. Here the lines are selected arbitrarily as the focus of this study is validation of the model and not the identification of suitable location of HPFC in the system.

Case I shows the bus voltages of the system without any FACTS device installed. Considering case 2, the active power flow in the line 4-5 is 0.409 pu for the uncompensated system. With HPFC the active power flow in that line is increased to 0.445 pu while maintaining \[ |V_{10}| \] and \[ |V_{11}| \] as 1.02 pu and 1.03 pu respectively. Following the changes, the bus voltages for the compensated system are shown. For Case 3, the active power flow in line 6-9 is -0.595 pu for uncompensated system, which is increased to -0.7 pu with installation of HPFC. Specifying \[ |V_{10}|, |V_{11}| \] and \[ P_{10-11} \] as 1.025 pu, 1.03 pu and -0.7 pu respectively, the changes in bus voltages are observed. There has been increase in bus voltages with the effect of HPFC. Similarly in Case 4, the uncompensated active power flow in line 7-8 is 0.764 pu. The HPFC compensated power flow becomes 0.82 pu with \[ |V_{10}| \] specified as 1.03 pu and \[ |V_{11}| \] as 1.025 pu. This results in increase in the bus voltages as shown in the Table III.

<table>
<thead>
<tr>
<th>( P_{\nu\nu}(\text{pu}) )</th>
<th>Bus No.</th>
<th>10</th>
<th>11</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without FACTS</td>
<td>- ( V(\text{pu}) )</td>
<td>-</td>
<td>-</td>
<td>1.0400</td>
<td>0.1025</td>
<td>1.0254</td>
<td>1.0259</td>
<td>0.9958</td>
<td>1.0129</td>
<td>1.0261</td>
<td>1.0162</td>
<td>1.0327</td>
</tr>
<tr>
<td>HPFC in line 4-5</td>
<td>( V(\text{pu}) )</td>
<td>1.0200</td>
<td>1.0300</td>
<td>1.0400</td>
<td>1.0253</td>
<td>1.0254</td>
<td>1.0308</td>
<td>1.0127</td>
<td>1.0165</td>
<td>1.0302</td>
<td>1.0193</td>
<td>1.0343</td>
</tr>
<tr>
<td>( \theta (\text{\degree}) )</td>
<td>-1.179</td>
<td>-1.745</td>
<td>0</td>
<td>10.186</td>
<td>5.253</td>
<td>-2.204</td>
<td>-2.683</td>
<td>-3.466</td>
<td>4.651</td>
<td>1.534</td>
<td>2.561</td>
<td></td>
</tr>
<tr>
<td>HPFC in line 6-9</td>
<td>( V(\text{pu}) )</td>
<td>1.0250</td>
<td>1.0300</td>
<td>1.0400</td>
<td>1.0253</td>
<td>1.0254</td>
<td>1.0269</td>
<td>0.9979</td>
<td>1.0149</td>
<td>1.0271</td>
<td>1.0181</td>
<td>1.0359</td>
</tr>
<tr>
<td>( \theta (\text{\degree}) )</td>
<td>-0.111</td>
<td>-3.749</td>
<td>0</td>
<td>7.845</td>
<td>2.250</td>
<td>-2.216</td>
<td>-4.459</td>
<td>-3.188</td>
<td>2.293</td>
<td>-1.100</td>
<td>-0.437</td>
<td></td>
</tr>
<tr>
<td>HPFC in line 7-8</td>
<td>( V(\text{pu}) )</td>
<td>1.0300</td>
<td>1.0250</td>
<td>1.0400</td>
<td>1.0253</td>
<td>1.0254</td>
<td>1.0270</td>
<td>0.9993</td>
<td>1.0136</td>
<td>1.0317</td>
<td>1.0197</td>
<td>1.0339</td>
</tr>
<tr>
<td>( \theta (\text{\degree}) )</td>
<td>1.204</td>
<td>3.491</td>
<td>0</td>
<td>8.337</td>
<td>5.504</td>
<td>-2.213</td>
<td>-4.261</td>
<td>-3.384</td>
<td>2.810</td>
<td>1.888</td>
<td>2.811</td>
<td></td>
</tr>
</tbody>
</table>

Table IV
B. Change of power flow through line 5-7 with HPFC

To investigate the effect on series injected voltage by changing the power flow through the line, HPFC is installed in line 5-7 and different specified values of $P_{10-11}$, $|V_{10}|$ and $|V_{11}|$ are considered. The changes in $V_c$, $V_s$, $V_t$ and $X_{sc}$ are shown in Table IV. Case 1 is the condition for the uncompensated system. The active power flow in the line 5-7 is -0.843 pu. Voltages at bus 5 and 7 are 0.9958∠-3.98pu and 1.0261∠3.71pu respectively.

Case 2 is the condition with HPFC compensation. The objective of HPFC is to increase $P_{10-11}$ to -0.975 pu while maintaining $|V_{10}|$ and $|V_{11}|$ as 1.0131 pu and 1.0139 pu respectively. This is achieved with $X_{sc}$ value of -0.0855 pu. The series injected voltage $V_s$ becomes 0.0822∠-89.23°pu. Bus 5 and 7 voltage magnitudes increase to 0.9983 pu and 1.0284 pu respectively.

In Case 3, the specified values of $|V_{10}|$ and $|V_{11}|$ are changed to 1.02 pu and 1.025 pu respectively while maintaining $P_{10-11}$ as earlier. After effects, $V_c$ and $V_s$ increase up to 1.003 pu and 1.0326 pu respectively with $V_t$ and $X_{sc}$ as earlier.

For Case 4, $P_{10-11}$ is increased to -1.0 pu while $|V_{10}|$ and $|V_{11}|$ are specified as in Case 3. For this condition the value of $X_{sc}$ becomes -0.1013 pu. The capacitive reactance is more than previous case; also $V_c$ is increased to 0.0993 pu.

For Case 5, $P_{10-11}$ is decreased to -0.967 pu and $|V_{10}|$ and $|V_{11}|$ are specified as in Case 3. The values of $X_{sc}$, $V_c$, $V_s$ and $V_t$ are shown in Table IV.

V. CONCLUSION

In this paper, the steady state performance of HPFC is studied. The paper demonstrates how the conventional power flow algorithm can be systematically modified to include HPFC and thus a power flow model of HPFC is developed. The power flow control capability of HPFC is shown by specifying different amount of active and reactive power flow through the line between two voltage sources. Similarly in case of multi-machine system, it has been shown that different specified values of active power flow and HPFC terminal voltages can be obtained by appropriate change in series injected voltage. The Newton Raphson power flow program can be easily modified to study the effect of HPFC on steady state of power system.

REFERENCES