LOAD FLOW STUDIES BY CB MODEL APPROACH USING UPFC

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Abstract: This paper deals with an alternative proposition for the steady state modeling of unified power flow controller (UPFC). Since current limitations are determinant to FACTS apparatus design, this paper is focused on the steady-state modeling of UPFC for the direct implementation of the device in the Newton-Raphson (NR) power flow algorithm based on CB (Current Based) model, this model due to reduce the complexities of the computer program codes, availability of controlling in active, reactive power and voltage simultaneously or individual, the model overcome on the problem when UPFC is only link between two sub networks, NR power flow based on CB model is considered fast where most Jacobian elements are constant and equal to the terms of the nodal admittance matrix. The proposed UPFC model load flow has been tested using IEEE data test and shows it effectiveness in solving large network containing single or multiple UPFC devices.

Keywords: CB model, FACTS, optimal power flow, Newton Raphson method, UPFC.

1. INTRODUCTION

With the development of power systems, especially the opening of electric markets, it becomes more and more important to control the power flow along the transmission line, thus to meet the needs of power transfer. Power flow studies and optimization techniques are essential tools for the safe and economic operation of large electrical systems. The UPFC is one of the most complete equipment of FACTS new technological family, allowing the regulation of active and reactive powers, substantially enlarging the operative flexibility of the system [1]–[2]. Steady state models of UPFC described in the literature employ the power balance equation, resulting in the equality of the series and shunt active power of converters \( P_s = P_a \) assuring no internal active power consumption or generation. One of the first proposed models [3] uses this condition, but only in particular cases, when power and voltage are admittedly known, is the implementation of the model in traditional power flow program viable. Voltage source models employed in [4]–[7] consist of series and shunt voltages presented in the equations as control variables. The model described in [7], known as power injection model (PIM), is quite spread in the literature, representing the effect of active elements by equivalent injected powers. In the existing models, the current is not explicitly treated in the equations. Since in the specification of FACTS converters one of the main restrictions lies on current limitation, it is convenient to have a model that uses the current as
a variable, which will be used explicitly in power mismatching of the line flows and will be the purpose of this paper.

Hence, in Section 2, the equations of a current based model (CBM) are presented. In Section 3, NR power flow based on CB model using UPFC is presented, seeking to analyze the behavior of UPFC in the IEEE 5, 14 & 30 bus systems to reduce transmission losses. In Section 4 simulation results are presented. Section 5 contains the conclusion.

2. MODELLING OF UPFC

The developed CB model represents the UPFC in steady state, introducing the current in the series converter as variable (see Fig 2.1).

$V_s$: Series voltage
$Z_c$: Series transformer impedance
$Z_e$: Transmission line impedance

Let us consider busbar and existent in the transmission line where the UPFC will be located, with impedance $Z_e'$. Fictitious busbars $j$ and $j'$ are created in order to include the UPFC in the system. The series impedance of UPFC coupling transformer $Z_s$ and the transmission line are added, resulting in the equivalent impedance $Z_e=Z_e'+Z_s$ connected to the internal node $j$ and node $j'$ is eliminated. This association is quite simple, even in case of two port lines represented by Π circuits.

The equivalent network is presented in Fig 2.2, with the series voltage inserted between busbars $i$ and $j$.

![Fig 2.1: UPFC and network](image1)

![Fig 2.2: Equivalent model of UPFC in the electric network.](image2)

2.1 Injected Power Due to Current

The power consumption of the system load at busbar $i$ is called $S_i^0$. Additional powers and $S_i^c$, due to current $I$, are easily calculated according to Fig 2.3. Current $I$ introduces two variables $I$, $\phi$, related to module and phase of the current.

We can write the new power terms due to current:

$S_i^c = V_i I^*$
$P_i^c = V_i I \cos (\phi - \theta_i)$
$Q_i^c = V_i I \sin (\phi - \theta_i)$

$S_j^c = -V_j I^*$
$P_j^c = -V_j I \cos (\phi - \theta_j)$
$Q_j^c = -V_j I \sin (\phi - \theta_j)$

![Fig 2.3: Injected power due to current in busbars $i$ and $j$.](image3)
2.2 Series Voltage Equations

The following treatment of the series voltages for the UPFC is general for FACTS devices that can employ this feature. The main example is the SSSC and, consequently, other equipment such as IPFC and GIPFC that use series voltage can be modeled as well. Writing the voltage equation between nodes \( i \) and \( j \) we obtain

\[ V_j - V_i = V_s \]  

We obtain the equations, relative to the real and imaginary parts, \( F_n=0 \) and \( G_n=0 \), respectively:

\[ F_n = AV_i \cos(\alpha + \theta_i) + V_j \cos \theta_j \]  

\[ G_n = AV_i \sin(\alpha + \theta_i) + V_j \sin \theta_j \]  

2.3 Power Balance Equations

In order to complete the UPFC model, it is necessary to introduce the power balance equation between series and shunt converters. The series power will be added to the shunt power of busbar \( i \), similar to Fig 2.4.

Let us calculate the power in the series converter:

\[ S_s = re^{j\delta} V_i I \]  

Splitting the previous expression in active and reactive powers:

\[ P_s = rV_i I \cos(\theta_i + \delta - \phi) \]  

\[ Q_s = rV_i I \sin(\theta_i + \delta - \phi) \]  

Active power \( P_s \) is included in node \( i \) (see Fig 2.5).

2.4 Current injection mismatches equations
Case (1): When Bus j is PQ type
Real and imaginary parts of current injection mismatches are expressed in terms of power mismatches and voltages at bus j:
\[ \Delta I_{ij} = \frac{V_{ij} \Delta P_j + V_{gij} \Delta Q_j}{V_j^2} \]  
(2.6)
\[ \Delta I_{iq} = \frac{V_{ij} \Delta P_j - V_{gij} \Delta Q_j}{V_j^2} \]  
(2.7)
The calculation of real and imaginary current mismatches is straightforward for PQ buses, because the associated real and reactive power mismatches are known. The current mismatches given in Equations (2.6) and (2.7) are computed to form the vector of mismatches.

Case (2): When Bus j is PV type
\[ \Delta I_{ij} = \frac{V_{ij} \Delta P_j}{V_j} \]  
(2.8)
\[ \Delta I_{iq} = \frac{V_{ij} \Delta Q_j}{V_j} \]  
(2.9)
\[ \Delta V_j^2 = V_{pj}^2 - V_{oj}^2 \]  
(2.10)

2.5 Complete Jacobian
Calling the Jacobian matrix, without UPFC power addition
\[ J_c = \begin{bmatrix} H^o & N^o \\ J^o & L^o \end{bmatrix} \]  
(2.11)
Let us add the injected power due to current in busbars i and j and the voltage equations \( F_n \) and \( G_n \). The additional correction of the Jacobian matrix, due to the power balance equation, is also included, complementing the formulation
\[ [J] = [J_c] + [J] + [J_S] \]  
(2.12)

3. OPTIMIZATION APPROACH

START

Read load flow Data

Formation of Admittance Matrix \( Y_{bus} \)

Assume \( \delta^0 \) for i=2,3,4…n
\( V^0 \) for i=2,3,…..m for PQ bus
Tol = 1e-12
Test for Convergence is DPQ < Tol ?

Yes

No

Update state variables of UPFC

Vse & Vsh

K = K + 1

Output load flow information (BusBar voltages, Generations, line flows and transmission losses)

Stop
4. SIMULATION RESULTS

The 5 bus test system [5], the IEEE 14 bus, and the IEEE 30 bus are used for validating the proposed CB model for the UPFC Newton-Raphson power-flow analysis.

Fig 4.1: 5-Bus system with UPFC and load flow results

4.1 IEEE 5-BUS SYSTEM TEST

The objective of this test is to validate the result obtained by using CB model with result obtained using standard NRM in [5]. The same test data is used here i.e., the 5-Test Bus system. The network is incorporated with UPFC between bus 3 and 4 as shown in Fig 4.1, together with the power flow results. The UPFC purpose on this network is to maintain active and reactive powers leaving UPFC towards bus 4 to 40 MW and 2 MVAR respectively and also to maintain voltage magnitude on bus 3 at 1.0 p.u. The result of voltage and phase angle of the UPFC sources is presented in Table 4.1. Whereas; the result of power flow on the network is presented in Fig 4.1. Further simulations are carried out to the 5 bus system are summarized in Table 4.2. The table shows the UPFC specifications at different specified values for the line power flow. The table exhibits the ability of the model to handle different operating conditions.

Table 4.1: Result of voltage magnitude and phase angle of the UPFC sources (5- bus system)

<table>
<thead>
<tr>
<th>Bus</th>
<th>Voltage mag (p.u)</th>
<th>Angle (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auxiliary bus (6)</td>
<td>0.9965</td>
<td>-2.5122</td>
</tr>
<tr>
<td>Series source</td>
<td>0.1013</td>
<td>-92.7315</td>
</tr>
<tr>
<td>Shunt source</td>
<td>1.0173</td>
<td>-6.005</td>
</tr>
</tbody>
</table>

Table 4.2: Results of the UPFC for various specified values of line power flow (5- bus system)

<table>
<thead>
<tr>
<th>Specified power flow in line 6-4 (MVA)</th>
<th>Voltage of Auxiliary bus</th>
<th>Vcr</th>
<th>φcr</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>del</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The effect of source impedances on the UPFC final parameters is shown in this Section. These studies were carried out using IEEE 14-bus system. The UPFC is inserted between bus 3 and 4 to maintain active and reactive powers leaving UPFC towards bus 4 at 38 MW and 2 MVAR respectively, and also to maintain voltage magnitude on bus 3 at 1.0 p.u. The UPFC parameters corresponding to different combinations of source impedances are presented in Table 4.3, the parameters of the series source are only affected by its impedance value and they are independent of the shunt source impedance value. The same statement applies to the shunt source parameters.

Table 4.3: Effect of UPFC impedances for IEEE 14-bus system

<table>
<thead>
<tr>
<th>Xcr</th>
<th>Xvr</th>
<th>Vcr</th>
<th>Vvr</th>
<th>( \alpha_c )</th>
<th>( \alpha_v )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.1</td>
<td>0.9716</td>
<td>-6.5874</td>
<td>0.056</td>
<td>-56.672</td>
</tr>
<tr>
<td>0.05</td>
<td>0.05</td>
<td>0.9929</td>
<td>-5.7975</td>
<td>-0.0166</td>
<td>-84.2607</td>
</tr>
<tr>
<td>0.02</td>
<td>0.02</td>
<td>0.9965</td>
<td>-2.5122</td>
<td>0.1013</td>
<td>-92.7315</td>
</tr>
<tr>
<td>0.02</td>
<td>0.02</td>
<td>0.9904</td>
<td>-2.3888</td>
<td>0.1041</td>
<td>-87.0739</td>
</tr>
<tr>
<td>0.01</td>
<td>0.01</td>
<td>1.0132</td>
<td>-1.7696</td>
<td>0.1363</td>
<td>-103.0478</td>
</tr>
<tr>
<td>0.05</td>
<td>0.02</td>
<td>1.0420</td>
<td>-2.3820</td>
<td>-0.1422</td>
<td>56.4946</td>
</tr>
<tr>
<td>0.02</td>
<td>0.05</td>
<td>1.0336</td>
<td>-4.1289</td>
<td>0.0841</td>
<td>-142.5178</td>
</tr>
</tbody>
</table>

Fig 4.2: IEEE 14 bus voltages and PQ losses

Fig 4.2 depicts the graph of final voltage magnitudes of IEEE 14 bus system and the total transmission loss of the system which is converged for 7 iterations in 0.1340 seconds.
4.3 IEEE 30-BUS SYSTEM TEST

Two UPFCs are inserted between bus 6 – 9 and 10 – 21 to maintain active and reactive powers leaving UPFC towards bus 9 and 21 at 40 MW and 2 MVAR respectively and also to maintain voltage magnitude on bus 6 and 10 at 1.0 p.u.

![Graph showing bus voltage magnitudes and PQ losses](image)

As in Fig 4.3, the graph shows the final voltage magnitudes of IEEE 30 bus system and the total transmission loss of the system which is converged for 7 iterations in 0.1570 seconds.

Table 4.4: The UPFC Model implemented in the IEEE 30 Bus Network with A Specified Values of a 40 Mw, 2 Mvar and Specified Voltage 1 P.U.

<table>
<thead>
<tr>
<th>UPFC</th>
<th>Send Bus</th>
<th>Receive Bus</th>
<th>Voltage of auxiliary Bus</th>
<th>Series source</th>
<th>Shunt source</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>V</td>
<td>Vdel</td>
<td>Vcr</td>
</tr>
<tr>
<td>1</td>
<td>6</td>
<td>9</td>
<td>6</td>
<td>1.0278</td>
<td>-3.3693</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>21</td>
<td>10</td>
<td>0.9988</td>
<td>-5.7324</td>
</tr>
</tbody>
</table>

Table 4.3 shows case study to test the UPFC model implemented in medium power system. The compensator voltage and angle is also included in the case study of Table 4.3. The case table exhibits the situation when the controlled line power is reversed and to show the IEEE 30 bus when more than one UPFC is implemented in the network. The results indicate that the proposed model is reliable handling multiple UPFC in the system.

5. CONCLUSION

This paper has described the direct implementation of a unified power flow controller (UPFC) steady-state model into NR power flow based on CB model, which is capable of solving medium power networks reliably. By using this direct UPFC, the problems associated with the selection of proper initial values of the UPFC control parameters and the
modifications of the Jacobian matrix are eliminated, UPFC model load flow has been tested using IEEE data test and show its effectiveness in solving network containing single or multiple UPFC devices.

The results test of CB model shows the ability of CB model to solve networks containing UPFC device. Although most of the cases in terms of iteration number, the UPFC model requires a few more iteration number compared to the uncontrolled case.

As the case study is carried out for the medium power networks, the effectiveness of reducing the total transmission losses and improvement in the power flows are seen from the test results. As the complication raises in the network the effectiveness of selecting and using multiple UPFCs in the large networks leads to almost accurate expected results.

REFERENCES


