DIGITAL SIMULATION OF IPFC FOR POWER FLOW USING PSPICE

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Abstract: Interline Power Flow Controller (IPFC) is a new concept of Flexible AC Transmission System (FACTS) controller with the unique capability for series compensation with the unique capability of power flow management among multi-line of a substation. The IPFC employs a number of Voltage Sourced Converters (VSCs) linked at the same DC terminal, each of which can provide series compensation for the selected line of the transmission system. Through common dc link, any inverters within the IPFC is able to transfer real power to any other and thereby facilitate real power transfer among the line. Interline Power Flow Controller (IPFC) can control the power flow in a multi-line system. Power imbalance between over-loaded and under-loaded lines was corrected. Single phase circuit model for uncompensated system was developed.

Key words: FACTS, SSSC, IPFC, PSPICE.

1. Introduction

An Interline Power Flow Controller (IPFC), shown in Fig.1, consists of two series VSCs, whose DC capacitors are coupled, allowing active power to circulate between different power lines. When operating below its rated capacity, the IPFC is in regulation mode, allowing the regulation of the P and Q flows on one line, and the Power flow on the other line. In addition, the net active power generation by the two coupled VSCs is zero, neglecting power losses. It can also be regarded as several SSSCs sharing a common DC link [1]. In this way, the power optimization of the overall system can be realized by appropriately transferring power through the common DC link from over-loaded lines to under-loaded lines [2, 3].

An elementary IPFC scheme consisting of two back-to-back dc to ac inverters is used as a tool to compensate a transmission line by series voltage injection. Two synchronous voltage sources, with phasors $V_{1pq}$ and $V_{2pq}$ in series with transmission line1 and 2 respectively, represent the two back-to-back dc to ac inverters as illustrated in Figure2. The IPFC is
designed with a combination of the series connected VSC which can inject a voltage with controllable magnitude and phase angle at the fundamental frequency while DC link voltage can be maintained at a desired level. The common dc link is represented by a bidirectional link \((P_{12} = P_{1pq} = -P_{2pq})\) for real power exchange between voltage sources.

Transmission line 1, represented by reactance \(X_1\), has a sending-end bus with voltage phasor \(V_{ls}\) and a receiving end voltage phasor \(V_{lr}\). The sending end voltage phasor of Line 2, represented by reactance \(X_2\), is \(V_{l2}\), and the receiving end voltage phasor is \(V_{lr}\). Simply, all the sending end and receiving end voltages are assumed to be constant with fixed amplitudes, \(V_{ls} = V_{l1} = V_{l2} = V_{lr} = 1\) p.u., and with fixed angles resulting in identical transmission angle \(\theta_1 = \theta_2\) for the two systems. The two line impedances, and the rating of the two compensating voltage sources, are also assumed to be identical. This means \(V_{1pqmax} = V_{2pqmax}\) and \(X_1 = X_2\). Although in practice system 1 and system 2 could be likely different due to different transmission lines, respectively. It can control total three power system quantities such as three independent power flows of two lines. Such an IPFC, which is shown in Fig 4 used to shown the basic operation principle for the sake of simplicity. The mathematical derivation is applicable to an IPFC with an arbitrary number of series converters [6].

The equivalent circuit of IPFC consisting two controllable series injected voltage sources is shown in Fig. 5. Real power can be exchanged between series converters via the common DC link. The sum of real power exchange should be zero [7].

According to the equivalent circuit of the IPFC shown in Fig 5. The power flow equations can be derived as follows

\[
P = V_1^2 R_1 + \sum V_n V_n (g_n \cos \theta_n + b_n \sin \theta_n)
\]

\[
Q = V_1^2 b_1 - \sum V_n V_n (g_n \sin \theta_n + b_n \cos \theta_n)
\]

\[
= \sum V_n V_n (g_n \cos \theta_n - b_n \sin \theta_n) + b_{1pq} \sin \theta_{1pq} + b_{2pq} \cos \theta_{2pq}
\]

\[
= V_{1ef}^2 b_{1ef} - \sum V_n V_n (g_n \sin \theta_n + b_n \cos \theta_n)
\]

\[
= \sum V_n V_n (g_n \cos \theta_n - b_n \sin \theta_n) + b_{1pq} \sin \theta_{1pq} + b_{2pq} \cos \theta_{2pq}
\]

\[
= V_1^2 b_1 - \sum V_n V_n (g_n \sin \theta_n + b_n \cos \theta_n)
\]

So line 1 can be compensated. The rotation with angle \(\theta_{1pq}\) modulates both the magnitude and the angle of phasor \(V_{1pq}\) and, therefore, both the transmitted real power, \(P_{1pq}\), and the reactive power, \(Q_{1pq}\), vary with \(\theta_{1pq}\). This process requires the voltage source representing Inverter 1 \((V_{1pq})\) to supply and absorb both reactive, \(Q_{1pq}\) and real, \(P_{1pq}\) power [4, 5].

2. Equivalent Circuit Analysis of IPFC

An IPFC with combining two or more series connected converters working together extends the concepts of voltage and power flow control beyond the hat is achievable with a known one-converter FACTS controller-SSSC. A simplest IPFC consists of two converters, which are connected in series with two transmission lines, respectively. It can control total three power system quantities such as three independent power flows of two lines. Such an IPFC, which is shown in Fig 4 used to shown the basic operation principle for the sake of simplicity. The mathematical derivation is applicable to an IPFC with an arbitrary number of series converters [6].

The equivalent circuit of IPFC consisting two controllable series injected voltage sources is shown in Fig. 5. Real power can be exchanged between series converters via the common DC link. The sum of real power exchange should be zero [7].
For uncompensated line

\[ V_R = V_S - V_X \]  

(7)

\[ I = V_S / (X + X_L + R_L) \]  

(8)

For compensated line

\[ V_R = V_S + V_{iq} \]  

(9)

4. Simulation Results

Line-1 and Line-2 are assumed to be operating at 11KV and 10KV respectively. Operating status of Line-1 is overloaded and Line-2 is under-loaded. Lines 1 & 2 are connected to identical loads. Both are identical lines. For uncompensated condition IPFC is disabled as the coupling transformers are disconnected from the lines.

3. Simulation of IPFC System

Upper and lower lines are referred to as Line-1 and Line-2 respectively. Line-1 and Line-2 are connected by coupling transformers at the sending end. Diode Bridge, capacitor and VSC form the link permitting the real power transfer between lines. The circuit model of uncompensated system is shown in Fig. 6. It is assumed that Line-1 is overloaded and Line-2 is under-loaded. During normal operating condition Line-1 and Line-2 are decoupled with the isolation of the coupling transformers.
The Uncompensated System is shown in Fig 4. The voltages $V_{1R}$ & $V_{2R}$ are shown in Fig 7a. The real power waveforms for $P_1$ & $P_2$ are shown in Fig 7b. The reactive power waveforms for $Q_1$ & $Q_2$ are shown in Fig 7c. The circuit model of the compensated system is shown in Fig 8. The wave forms with $\rho = -90^\circ$ are shown in Fig 8a to 8f. The wave forms with $\rho = -180^\circ$ are shown in Fig 9a to 9e.

Compensated condition of IPFC is enabled by connecting the coupling transformers to the lines to form the dc link between Lines 1 & 2. Simulation results for $\rho = -90^\circ$ and $-180^\circ$, $-270^\circ$ and $0^\circ$ are presented in Table 1.
Fig. 8c. $V_{IR}$, $V_{2R}$

Fig. 8d. $V_{IR}$, $V_{2R}$

Fig. 8e. $P_1, P_2$

Fig. 9a. $V_{2S}, V_{2pq}, V_{2Seff}, V_{2R}$

Fig. 9b. $I_2, V_{2pq}$

Fig. 9c. $V_{IR}$, $V_{2R}$

Fig. 9d. $P_1, P_2$

Fig. 9e. $Q_1, Q_2$
When $\rho$ varies from 0° to -180° on Line-2, $P_2$ and $Q_2$ decreases and for $\rho'$ from -180° to 0° on Line-2, (under-loaded) $P_2$ & $Q_2$ increases. $P_2$ and $Q_2$ attains maximum value for $\rho$ between -270° and 0°.

The power transfer capability of Line-2 increases due to addition of IPFC.

### Table 1. Summary of voltages & powers

<table>
<thead>
<tr>
<th>Compensation</th>
<th>$V_{1S}$</th>
<th>$V_{2S}$</th>
<th>$V_{1R}$</th>
<th>$V_{2R}$</th>
<th>$P_1$</th>
<th>$P_2$</th>
<th>$Q_1$</th>
<th>$Q_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without</td>
<td>11</td>
<td>10</td>
<td>8.5</td>
<td>7.5</td>
<td>1.1</td>
<td>0.9</td>
<td>420</td>
<td>420</td>
</tr>
<tr>
<td>$\rho$=90°</td>
<td>11</td>
<td>10</td>
<td>8.5</td>
<td>6.5</td>
<td>1.1</td>
<td>0.6</td>
<td>400</td>
<td>200</td>
</tr>
<tr>
<td>$\rho$=180°</td>
<td>11</td>
<td>10</td>
<td>8.5</td>
<td>9.0</td>
<td>1.1</td>
<td>0.9</td>
<td>420</td>
<td>500</td>
</tr>
<tr>
<td>$\rho$=0°</td>
<td>11</td>
<td>10</td>
<td>8.5</td>
<td>9.0</td>
<td>1.0</td>
<td>1.2</td>
<td>350</td>
<td>400</td>
</tr>
</tbody>
</table>

### 5. Conclusion

Interline Power Flow Controller (IPFC) is a VSC based series compensation type FACTS controller. IPFC is used to balance the power in two or more lines originating from a sub-station. In this paper IPFC capable of balancing the power in a overloaded line and a under-loaded line is simulated. Simulated results demonstrate the power transfer capability of IPFC between two lines through dc link. IPFC system is successfully simulated for different angles of injection. The simulation results agree with the analytical results.

### 6. References


