ANALYSIS OF INTERLINE POWER FLOW CONTROLLERS (IPFC) FOR DIFFERENT CONVERTER CONFIGURATIONS FOR IMPROVED REACTIVE POWER INJECTIONS SUPPORTED BY FILTER CONFIGURATIONS FOR QUALITY IMPROVEMENT (THD)

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Abstract

Of the different FACTS devices available now a days, IPFC is more advanced and easily controllable to manage effective transfer of power among inter connected lines and inter connected power system networks. An IPFC is a VSC-based FACTS controller which uses Series compensation
technique for the unique power injection from one line to another. This paper elucidates on the analysis of Improvement in Power Transfer Capabilities with effective reduction in distortions of the AC output (lower THDs) of an IPFC by incorporating certain advanced converter configurations and including application specific designed Filter Configurations. All the simulations are carried out in MATLAB SIMULINK.

**Key Words:** FACTS, IPFC, VSC, THD

## 1 INTRODUCTION

**INTERLINE POWER FLOW CONTROLLER (IPFC)**

The rapid development of self-commutated semiconductor devices, have made it potential to design power electronic materials called flexible AC transmission controller (FACT) devices.[1] Flexible ac transmission system (FACTS) controllers have the potential to increase the capacity of existing transmission networks through functional adaptability and control flexibility. FACTS controllers have the capability of direct control of transmission line flows by changing the main transmission constraints such as magnitude voltage, power angle of transmission lines voltages and currents, and impedance of the lines.

The IPFC is a series-series type of FACTS device that is used to exchange reactive powers in between two or more transmission lines those are connected to the same bus. This element consists of two (or more) series voltage source converter-based devices (SSSCs) installed in two (or more) lines and connected at their DC terminals[1,2]. Thus, in addition to serially compensate the reactive power, each SSSC can provide real power to the common DC link from its own line. This capability allows the IPFC to provide both reactive and real power compensation for some of the lines and thereby optimize the utilization of the overall transmission systems. The main objective of an IPFC is to optimize both real and reactive power flow among multiline, and transfer power from overloaded to under loaded lines. The model of the IPFC is developed using MATLAB and the simulation results are presented. **Basic structure of Interline Power Flow Controller (IPFC)**
Structure of interline power controller (IPFC) is consists of a set of converters that are connected in series with different transmission lines. The converters are connected through a common DC link to exchange active power. Each series converter can supply independent reactive compensation of own transmission line. **Working principle of interline power flow controller (IPFC)**

The IPFC structure makes it possible to transfer reactive power, as well as to exchange real power with the line. This active power can be obtained through power exchange through DC connection between the SSSCs in different lines. On the other hand, the transmitted powers in each line is a function of the voltage amplitude of sending and receiving buses, phase shift of sending and receiving buses and series impedance of the line. The interline power flow controller works with a number of direct current to alternative current converters each providing series compensation for a different transmission line[3]. Let use two back-to-back voltage-source converters (VSCs), based on the use of insulated gate bipolar transistors (IGBT). The voltage source converters (VSC) produce voltages that vary in magnitude and phase angle. These voltages are inserted in series with the managed transmission lines using series transformers as shown in figure below.

![Fig.1. Schematic diagram of two converters IPFC](image-url)

The real power exchanged at the ac terminal is converted by the corresponding VSC into dc power which appears at the dc link as a negative or a positive demand. Consequently, the real power negotiated by each VSC must be equal to the real power negotiated
by the other VSC through the dc lines. As result interline power flow controller (IPFC) can maintain the flow of active and reactive power in multiple line system even when a failure occur IPFC can switch off failure line and by bass to the set line. **Power Injection Model of IPFC:**

This model is useful to study the impact of the IPFC on the power system network. Usually, in the steady state analysis of power systems, the VSC may be represented as a synchronous voltage source injecting an almost sinusoidal voltage with controllable magnitude and angle. Based on this, the equivalent circuit of IPFC is shown in Figure3. In Figure3, $V_i, V_j$ and $V_k$ are the complex bus voltages at the buses i, j and k respectively, defined as $V_m = V_m \angle \theta (m=i, j$ and k ). $V_{sein}$ is the complex controllable series injected voltage source, defined as $V_{sein} = V_{sein} \angle \theta sein (n = j, k)$ and $Z_{sein} (n = j, k)$ is the series coupling transformer impedance. The injection model is obtained by replacing the voltage

![Fig 2. Power injecting model of IPFC](image)

Source ($V_{sein}$) as current source ($I_{sein}$) in parallel with the transmission line. For the sake of simplicity, the resistance of the transmission lines and the series coupling transformers are neglected. Therefore, the current source can be expressed as

$$I_{sein} = -j b_{se} V_{sein}$$

(1)
Now, the current source \((I_{\text{sein}})\) can be modelled as injection powers at the buses i, j and k. The complex power injected at ith bus is

\[
S_{\text{inj},i} = j, k \sum V_i(-I_{\text{sein}})^* \tag{2}
\]

Substitute (1) in (2). Then

\[
S_{\text{inj},i} = j, k \sum V_i(j b_{\text{sein}} V_{\text{sein}})^* \tag{3}
\]

Then the active power and reactive power injections at \(i^{th}\) bus are

\[
P_{\text{inj},i} = \text{Re}(S_{\text{inj},i}) = j, k \sum (V_i V_{\text{isin}} b_{\text{sein}} \sin(\theta_i - \theta_{\text{sein}})) \tag{4}
\]

\[
Q_{\text{inj},i} = \text{Im}(S_{\text{inj},i}) = j, k \sum (V_i V_{\text{isin}} b_{\text{sein}} \cos(\theta_i - \theta_{\text{sein}})) \tag{5}
\]

The complex power injected at \(n^{th}\) bus (n=j,k)

\[
S_{\text{inj},n} = V_n(I_{\text{sein}})^* \tag{6}
\]

Substitute (1) in (6). Then

\[
S_{\text{inj},n} = V_n(-j b_{\text{sein}} V_{\text{sein}})^* \tag{7}
\]

After simplification, the active power and reactive power injections at nth bus are

\[
P_{\text{inj},n} = \text{Re}(S_{\text{inj},n}) = -V_n V_{\text{sein}} b_{\text{sein}} \sin(\theta_n - \theta_{\text{sein}}) \tag{8}
\]

\[
Q_{\text{inj},n} = \text{Im}(S_{\text{inj},n}) = V_n V_{\text{sein}} b_{\text{sein}} \cos(\theta_n - \theta_{\text{sein}}) \tag{9}
\]

Based on (4), (5), (8), and (9), power injection model of IPFC can be seen as three dependent power injections at buses i, j and k as shown in Figure. As IPFC neither absorbs nor injects active power with respect to the ac system, the active power exchange between the converters via the dc link is zero, i.e.

\[
\text{Re}(V_{\text{sein}} I_{ji}^* + V_{\text{sein}} I_{ki}^*) = 0 \tag{10}
\]

Where the superscript * denotes the conjugate of a complex number. If the resistances of series transformers are neglected, (10) can be written as

\[
\sum_{m=i,j,k} P_{\text{inj},m} = 0 \tag{11}
\]
Advantageous of IPFC

The Interline Power Flow Controller (IPFC) is one of the Voltage Source Converter (VSC) based facts controllers which can effectively manage the power flow via multi-line transmission system. IPFC has different applications[7]

- Balancing reactive and real power flows through compensated transmission lines, transmitting power from burdened load lines to other lines that not heavily loaded
- Compensation of voltage drops on resistance through lines and improving the performance of the compensated system when dynamic disturbances occur
- Increasing the Rotor angle Stability by this interconnected synchronous machine of a power to remain in synchronous stage during disturbance and normal operating condition
- Damping Low Frequency Oscillations
- Increase transient stability of power system
- Power flow stability

DIFFERENT CONVERTER CONFIGURATIONS USED IN THE PROPOSED IPFC

The Back-to-back connected dc transmission links have played a significant role in interconnecting two or more asynchronous networks. The back-to-back voltage sourced converters undertake the same duty but with the added advantage of having the capability of independently controlling ac voltage on the connecting bus on each side. This is because the reactive power generated on the ac side of each voltage sourced converter is relatively independent of the real power being transferred from one converter to the other(s). Another advantage of back-to-back voltage sourced converters is that ac voltage maintained during emergency reversal of power. Such a feature is advantageous if the link is being used to help stabilize frequency excursions in either network. There is also the possibility that when there is no requirement to transfer power, the converters can be separated at the dc capacitor by dividing it between
each, and the voltage sourced converters can revert to STATCOM operation in their respective systems.

2 SIX PULSE BACK TO BACK CONNECTED CONVERTER

![Six Pulse Converter Configuration](image)

Fig. 3. Six pulse converter configuration used in IPFC

The transmission of the power from one line to another line through rectifier to inverter. Power flow can be controlled by varying the dc voltage ($V_{dc}$), which can be changed by controlling the delay angles. In this 6 pulse back to back converter the rectifier delay angles varied from 0 to 180 degrees but inverter delay kept constant (90 degrees) with a DC Capacitor used in the IPFC.

3 TWELVE PULSE BACK TO BACK CONNECTED CONVERTER

12 pulse converter is a serial connection of two back to back six pulse converters, which are spaced by 30 electrical degrees. The phase difference effected to cancel out the 6-pulse harmonics on the Ac and Dc side.
Fig. 4. 12 pulse converter configuration of an HVDC link with a DC Capacitor used in the IPFC.

Fig. 5 Detailed model of the Two Area Network Interconnected with IPFC

OUTPUTS WITH A 6 PULSE CONVERTER

ReActive and Active Powers at the Load Terminals of Line 1 with IPFC with different Delay angles applied to the Rectifier Switches.
Fig. 6: ZERO DEGREES DELAY ANGLE WITH OUT FILTERS

Fig. 7: ZERO DEGREES DELAY ANGLE WITH FILTERS
Fig. 8 60 DEGREES DELAY ANGLE WITH FILTERS

Fig. 9 120 DEGREES DELAY ANGLE WITH FILTERS
ReActive and Active Powers at the Load Terminals of Line 1 with IPFC with different Delay angles applied to the Rectifier Switches.

Fig. 10 180 DEGREES DELAY ANGLE WITH FILTERS

OUTPUTS WITH A 12 PULSE CONVERTER

Fig. 11 OUTPUTS WITH A 12 PULSE CONVERTER
Fig. 12 ZERO DEGREES DELAY ANGLE WITH FILTERS

Fig. 13 SIXTY DEGREES DELAY ANGLE WITH FILTERS
Table-1 IPFC outputs by using 6-pulse converter
TABLE 2 IPFC outputs by using 12-pulse converter

From above simulation results of ipfc by using 6-pulse (table-1) and 12 pulse (table-2) back to back converter we can absorbed the reactive and active powers are injected from line-1 to line-2 THD (Total Harmonic Distortions)

In these multipulse converter circuits the converter bridges are operated at fundamental frequency switching losses substantially. Pulse
number increased in multiple of six, and an increase in every six pulse VSC reduces the harmonics in the system proportionally.

Fig.16 THD values of IPFC (6-pulse converter without filters and with delay of 180 degrees)

Fig.17. THD values of IPFC (6-pulse converter with filters and with delay of 180 degrees)
Fig. 18. THD values of IPFC (6-pulse converter with modified value of filter capacitance and with delay of 180 degrees)

Fig. 19. THD values of IPFC (12-pulse converter with filters and without delay of 180 degrees)
TABLE 3. The THD of IPFC OUTPUTS for 6-pluse VSC converters

<table>
<thead>
<tr>
<th>Delay angle</th>
<th>THD Without Filter</th>
<th>THD With Filter</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>63.95</td>
<td>7.99</td>
</tr>
<tr>
<td>60</td>
<td>63.95</td>
<td>7.80</td>
</tr>
<tr>
<td>120</td>
<td>89.40</td>
<td>6.94</td>
</tr>
<tr>
<td>180</td>
<td>147.7</td>
<td>1.21</td>
</tr>
</tbody>
</table>

TABLE 4. The THD of IPFC OUTPUTS for 12-pluse VSC converters

...
4 CONCLUSION

Usage of 6-pulse converters in the IPFC allows for flexible transfer of power between the networks (Between Two lines of a same network and Between Lines of Two Different Networks. And incorporation of 12-pulse converter configurations in the IPFC allows for Improved levels of Power Transfer. The power transfer between the Networks was shown to be improved and controlled easily by varying the delay angle. By introducing the filters in these configurations we can reduce the harmonics.

From figures and tables presented it can be observed that the THD values at the output terminals of the IPFC are reduced by changing the converter configuration from 6 pulse to 12 pulse (i.e 63.95 value reduced to 13.90) for different firing /delay angles. And by appropriate introduction of filters, the value of THD can further be reduced in 6-pulse as well as in 12-pulse converters. The best value of THD obtained for a 6-pulse converter configuration of IPFC is 7.47. And the best value of THD obtained for a 12-pulse converter configuration of IPFC is 0.19. This remarkable improvement in the Power Transfer Capabilities and Lower THD values of the IPFC is an added advantage for enhancing the controllability of the Network and in exchange of Quality Power between the networks.

<table>
<thead>
<tr>
<th>Delay angle</th>
<th>Without filter</th>
<th>With improved value of filter capacitance</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>13.90</td>
<td>0.19</td>
</tr>
<tr>
<td>60</td>
<td>6.96</td>
<td>0.19</td>
</tr>
<tr>
<td>120</td>
<td>5.76</td>
<td>0.17</td>
</tr>
<tr>
<td>180</td>
<td>5.76</td>
<td>0.17</td>
</tr>
</tbody>
</table>
APPENDIX

NETWORK 1 (LINE 1) CONFIGURATIONS Generator

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<table>
<thead>
<tr>
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<tbody>
<tr>
<td>1</td>
<td>Rated Voltage</td>
</tr>
<tr>
<td>2</td>
<td>Frequency</td>
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</tbody>
</table>

Transmission Line

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<tbody>
<tr>
<td>3</td>
<td>Length</td>
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</table>

Transformers

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<tbody>
<tr>
<td>4</td>
<td>Voltage Ratings</td>
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<tr>
<td>5</td>
<td>Power Rating</td>
</tr>
</tbody>
</table>

Load

6. Load with Y grounded configuration

7. Voltage Rating | 25kV |
8. Active Power | 10MW |
9. Reactive Power | 10KW |

NETWORK 2 (LINE 2) CONFIGURATIONS Generator

<p>| | |</p>
<table>
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<tbody>
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<td>1</td>
<td>Rated Voltage</td>
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<tr>
<td>2</td>
<td>Frequency</td>
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Transmission Line

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Transformers

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<tbody>
<tr>
<td>4</td>
<td>Voltage Ratings</td>
</tr>
<tr>
<td>5</td>
<td>Power Rating</td>
</tr>
</tbody>
</table>

Load

6. Load with Y grounded configuration

7. Voltage Rating | 50kV |
8. Active Power | 10MW |

Note: Power transferred from Network 2 to Network 1
References

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