CHAPTER 5

INTERLINE POWER FLOW CONTROLLER SYSTEM

5.1 GENERAL

In the IPFC structure, a number of inverters are linked together at their DC terminals. Each inverter can provide a series reactive compensation, as an SSSC, for its own line. However, the inverters can transfer real power between them via their common DC terminal. 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 multilines, and transfer power from overloaded to under loaded lines. The model of the closed loop controlled IPFC is developed using MATLAB and the simulation results are presented. The closed loop control of the IPFC is obtained using the PI controller.

5.2 MODEL OF THE IPFC USING MATLAB

An elementary IPFC, composed of voltage source converters 1 and 2 with a common DC link, provides the series compensation for lines 1 and 2. Controlling the real power flow is achieved by approximately adjusting the angle of the IPFC in lines 1 and 2. The reactive power flow is achieved by adjusting the input voltage of lines 1 and 2. The model of the IPFC is developed and simulated using MATLAB simulink.
5.2.1 Model of a Basic Transmission Line using MATLAB

The transmission line is designed with the resistance of the line and the reactance. The transmission line is simulated for AC sources of 110kV and 120 kV. The circuits of the primary and secondary lines are shown in Figures 5.1 and 5.2 respectively. The voltage at the sending and receiving ends is observed. The power across the load resistor and load inductor is also taken for an uncompensated line. The primary transmission line consists of the voltage source $V_1$ and the source impedance is represented as $Z_1$. The impedance of the transmission lines is represented as $Z_2$ and $Z_3$. The load in the primary transmission line is represented using $Z_{L1}$.

![Figure 5.1 Model of the primary transmission line](image)

The secondary transmission line consists of the voltage source $V_2$ and the source impedance is represented as $Z_1$. The impedance of the transmission lines is represented as $Z_2$ and $Z_3$. The load in the secondary transmission line is represented using $Z_{L2}$. 
Figure 5.2 Model of the secondary transmission line

From the values of the Power Engineer’s hand book, appropriate values are calculated for the real time application, and such values are used as impedance of primary and secondary transmission lines. From the impedance values, the loads of the primary and secondary transmission lines are calculated.

Source voltage $V=110$ kV

$Z_T = (118 + j 217)$ ohm

$Z_L = (432 + j 324)$ ohm

$I = (V/Z_T) = 165.5, \angle -45.77^\circ$ A.

$V_R = I*Z_L = 714161.245, \angle -8.94^\circ$ V

$P = V_R*I*cos \Phi = (714161.245, \angle -8.94^\circ) * (165.5, \angle -45.77^\circ) * (0.8)$

$|P| = 9.46146$ MW

$Q = V_R*I*sin \Phi = (714161.245, \angle -8.94^\circ) * (165.5, \angle -45.77^\circ) * (0.6)$

$|Q| = 7.096$ MVAR

The Schematic of the transmission line models for 120kV and 110kV are shown in Figures 5.3 and 5.4 respectively.
The reactive power in the load for 120kV and 110kV basic transmission lines is shown in Figures 5.5 and 5.6 respectively. This power was obtained without using any interlink. By introducing the IPFC controller the power is improved.
The reactive power in the 120kV and 110kV transmission lines is 7.825 MVAR and 7.086 MVAR respectively. This transmission line values coincide with the theoretical value of 7.096 MVAR.

5.2.2 Model of the Closed Loop Controlled IPFC

The circuit model of the closed loop IPFC system with primary and secondary loads is shown in Figure 5.7. The load voltage is sensed and it is rectified. It is then compared with a reference signal. The multiple PWM technique is used. The output of the pulse generator is used to drive the switches of the inverter. Subsystem 1 represents the pulse generation module, which is shown in Figure 5.8. Subsystem 2 senses the voltage across the
primary load, and subsystem 3 senses the voltage across the secondary load. Subsystems 2 and 3 are shown in Figures 5.9 and 5.10 respectively. Subsystem 4 represents the circuit of the PI controller.

Figure 5.7 Circuit of the closed loop controlled IPFC
Figure 5.8 Subsystem 1 of the closed loop IPFC

Figure 5.9 Subsystem 2 of the closed loop IPFC
Simulation is done with the primary line input as 120kV and the secondary line input as 110kV. The reactive power output of the secondary load is 7.108MVAR. The reactive power output of the closed loop IPFC system with unequal voltages is shown in Figure 5.11.

The model of the closed loop IPFC system is shown in Figure 5.7. Simulation is done with equal voltages on the input sides [primary and secondary line inputs as 110kV]. The reactive power output of the secondary load is 7.109MVAR. The reactive power output of the closed loop IPFC system with equal voltages is shown in Figure 5.12.
The model of the closed loop IPFC system is shown in Figure 5.7. Simulation is done with equal voltages on the input sides and different phase angles [primary line input source voltage at 110kV with phase angle 15° and secondary line source voltage at 110kV with 30° phase angle]. Due to the difference in the phase angle, there is an increase in the real power of the secondary load when compared to the primary load.

The real power of the primary load is 8.8 MW and that of the secondary load is 9.51 MW with the primary line operating at 110 \(\angle 15^\circ\) kV and secondary line operating at 110 \(\angle 30^\circ\) kV as shown in Figure 5.13. By controlling the phase angle, the flow of real power between lines having equal input voltages can be controlled.
Figure 5.13 Real power of the primary load and the secondary load
a. Real power of the primary load
b. Real power of the secondary load

5.2.3 Model of the IPFC in a Four-Bus Test System

In this section, we illustrate the proposed IPFC dispatch strategy for maximizing the voltage stability limited power transfer in a four-bus test system. Perhaps the most common approach in the voltage stability analysis is to increase the system loading \( P_{\text{load}} \) and observe the resulting voltage variation \( V \) on the critical buses. The analysis is frequently presented in the form of Power Voltage (PV) curves, which are now being used in many power control centers.

To generate consistent PV curves, we modify the IPFC control strategy slightly by enforcing the desired circulating power \( P_c \) at all operating conditions, regardless of whether the VSCs are at their rated capacities or not. That is, if both VSCs are below their rated capacities, then, besides requesting
a specific power circulation level, the series VSCs will regulate the line active power flows. The reactive power flow is no longer enforced.

The four-bus test system shown in Figure 5.14 has two equivalent generators and two equal amounts of loads at bus2 and bus4.

![The four-bus test system](image)

**Figure 5.14 The four-bus test system**

From the reference Xuan Wei et al (2004), there are two transmission paths with line 3-4 weaker than line 1-2 (stronger line 1-2 and weaker line 3-4). An IPFC is sited at bus 1 with each VSC on one of the parallel lines on the two transmission paths. It is noted that by closing the switches A and B, the IPFC is bypassed, which is referred to as the uncompensated system. The IPFC is in service if switches A and B are opened.

By increasing the loads $P_{\text{load1}}$ at bus 2, $P_{\text{load2}}$ at bus 4 and the necessary amount of generation at bus 1 and bus 3, we can investigate the variation of voltage $V_2$ at bus 2 and $V_4$ at bus 4, with and without the IPFC. Note that a positive $P_c$ denoted that power is circulating from VSC$_2$ on line 3-4 to VSC$_1$ on line 1-2.
5.2.3.1 Model of the closed loop IPFC with variations in the firing angle of VSC1

The single-phase four bus closed loop IPFC system has been simulated in MATLAB Simulink, using the power system toolbox as shown in Figure 5.15. Switches A and B are opened for the time period of 0.3 sec to 0.6 sec. Then the IPFC is in service during the above mentioned time period, which is referred to as the compensated system. Switches A and B are closed for the remaining time period; the IPFC is bypassed, which is referred to as the uncompensated system. By increasing the loads at bus 2 and bus 4, we can investigate the variation of the output voltage and real power at bus 4, with and without the IPFC.

The electrical data of the system used in the present work is as below:

Generator 1 & 2 : 15.7kV
Transformer : 15.7/ 400 kV, 1000MVA, \( r=0.0059 \) p.u., \( l = 0.127 \) p.u.
Series transformer : 3/ 45 kV, 160 MVA, \( r = 0.005 \) p.u., \( l = 0.06 \) p.u.
Transmission line : \( r = 3.2 \Omega / 100 \text{km}, l = 103 \text{ mH/100km}, c = 1.1 \text{ F/100km} \)
Figure 5.15 Circuit model of the closed loop IPFC system with changes in the firing angle of VSC$_1$. 
Without the IPFC, the output of the stronger line is $2.1 \times 10^8$ W and $2.8 \times 10^8$ VAR and the output of the weaker line is $2.0289 \times 10^8$ W and $2.7098 \times 10^8$ VAR, which are shown in Figures 5.16 and 5.17 respectively.

**Figure 5.16 Real power and reactive power of the stronger line**

a. Real power of the stronger line.

b. Reactive power of the stronger line.

**Figure 5.17 Real power and reactive power of the weaker line**

a. Real power of the weaker line.

b. Reactive power of the weaker line
The subsystem of the closed loop controlled IPFC system with firing angle changes in VSC₁ is shown in Figure 5.18. A reference signal is compared with a ramp signal, and its output is given as pulse to switches of the converter. The firing angle of the pulse generators in VSC₁ is varied, and the corresponding variations in real power and output voltage are observed for different loads. As referred from the reference [43], Xuan Wei (2004), the power was exchanged from VSC₁ to VSC₂ or vice versa.

By increasing the power circulation from VSC₁ to VSC₂ for the load considered in the range of 600 MW to 800 MW, reactive power is taken from the stronger line 1-2 and injected into the weaker line 3-4, allowing a higher voltage at bus 4. Conversely, the load is considered in the range of 800 MW to 950 MW, by increasing the power circulation from VSC₂ to VSC₁, bus 4 voltage is decreased and bus 2 voltage is raised.
Figure 5.18  Subsystem of the closed loop IPFC with changes in the firing angle of VSC₁

For the load considered in the range of 600 MW to 800 MW, the real power flows from VSC₁ to VSC₂ and the output power variations in the weaker line 3-4 are as shown in Figure 5.19. For the load considered in the range of 800 MW to 950 MW, the real power flows from VSC₂ to VSC₁ is as shown in Figure 5.20.
Figure 5.19 Real power in the weaker line for 650 MW load

Figure 5.20 Real power in the weaker line for 900 MW load

The change in real power for various loads from 600MW to 950MW with the change in power \((P_c)\) is shown in Figure 5.21. The change in the output voltage for various loads from 600MW to 950MW is shown as power voltage curve in Figure 5.22.
5.2.3.2 **Model of the closed loop IPFC with variations in the firing angle of VSC\(_2\) with reference to the sending end voltage**

The model of the closed loop controlled IPFC system with firing angle variations in VSC\(_2\) taking sending end voltage as reference is shown in Figure 5.17, and the subsystem is shown in Figure 5.23. A reference signal is compared with a ramp signal, and its output is given as pulses to the switches of the converter. The firing angle of the pulse generators in VSC\(_2\) is varied.
and the corresponding variations in the reactive power & output voltage of the weaker line are observed for different loads.

![Subsystem of the closed loop IPFC with changes in the firing angle of VSC2 taking the sending end voltage as reference](image)

Figure 5.23  Subsystem of the closed loop IPFC with changes in the firing angle of VSC$_2$ taking the sending end voltage as reference

The reactive power variation in the weaker line 3-4 with a load in the range of 600 MW to 750 MW is shown in Figure 5.24. It is observed that
the reactive power increases from $1.6858 \times 10^8$ VAR to $1.8934 \times 10^8$ VAR, and voltage increases from $1.631 \times 10^4$ V to $1.73 \times 10^4$ V. Thus, there is a reactive power flow from VSC$_1$ to VSC$_2$.

Figure 5.24 Reactive power in the weaker line for 650 MW load

For the load considered in the range of 800MW to 950 MW, the reactive power variation in the weaker line is shown in Figure 5.25. It is observed that the power decreases from $1.92 \times 10^8$ VAR to $1.89 \times 10^8$ VAR and voltage decreases from $1.87 \times 10^4$ V to $1.73 \times 10^4$ V. Thus, there is a reactive power flow from VSC$_2$ to VSC$_1$.

Figure 5.25 Reactive power in the weaker line for 900 MW load
The change in the output voltage for the loads considered in the range of 600MW to 950MW, with the change in reactive power ($Q_c$) for bus 4 is shown in Figure 5.26.

![Figure 5.26 Change in the reactive power of the weaker line](image-url)

5.2.3.3 Model of the closed loop IPFC with variations in the firing angle of VSC$_2$ with reference to the receiving end voltage

The model of the closed loop controlled IPFC system with firing angle changes in VSC$_2$, taking the receiving end voltage as reference is shown in Figure 5.17, and the subsystem is shown in Figure 5.27. A reference signal is compared with a ramp signal and its output is given as pulse to the switches of the converter. The firing angle of the pulse generators in VSC$_2$ is varied, and the corresponding variations in the reactive power and output voltage of the weaker line are observed for different loads.
Figure 5.27 Subsystem of the IPFC with changes in the firing angle of VSC\textsubscript{2} taking the receiving end voltage as reference

For a load of 650 MW, the reactive power output in the weaker line is shown in Figure 5.28. It is observed that the power increases from 1.97*(10^8) VAR to 1.99*(10^8) VAR, and the voltage increases from 1.7*(10^4)V to 1.73*(10^4) V. Thus, there is a flow of reactive power from VSC\textsubscript{1} to VSC\textsubscript{2}.

Figure 5.28 Reactive power in the weaker line for 650 MW load
5.3 CONCLUSION

The IPFC is simulated for the compensation and power flow management of the multiline transmission system. In the IPFC structure, the converters are linked together at their DC terminals. Each inverter can provide a series reactive compensation, as an SSSC, for its own line. However, the converters can transfer real power between them through their common DC terminal. This capability allows the IPFC to provide both real and reactive compensation for some of the lines and thereby optimize the utilization of the overall transmission system. In particular, the IPFC can equalize both real and reactive power flow in the lines, relieve the overloaded lines from the burden of the reactive power flow, compensate against resistive as well as reactive voltage drops, and provide a concerted multiline counter measure during dynamic disturbances.

A new dispatch strategy for an IPFC operating at the rated capacity is proposed. When the IPFC operates at its rated capacity, it can no longer regulate the line active power flow set point or the reactive power flow set point or both. In such cases, the dispatch strategy switches to a power circulation set point control to co-optimize both series VSCs, without exceeding one or both rated capacities. The dispatch results show that the IPFC can improve the power transfer in the system. The power circulation between the two VSCs can be used to adjust bus voltages to improve the voltage stability limit transfer. The simulation results are in line with the predictions. The IPFC is capable of balancing the power through the lines. The power quality is improved since the IPFC permits additional power. The circuit models for the IPFC system are developed using MATLAB. These models are used for simulating a four bus system. The simulation results using MATLAB are presented. The IPFC increases the real power transfer and improves the voltage profile.