

Multi-Line Power Flow Control using Interline Power Flow Controller (IPFC) in Power Transmission Systems

A.V.Naresh Babu, S.Sivanagaraju, Ch.Padmanabharaju and T.Ramana

Abstract—The interline power flow controller (IPFC) is one of the latest generation flexible AC transmission systems (FACTS) controller used to control power flows of multiple transmission lines. This paper presents a mathematical model of IPFC, termed as power injection model (PIM). This model is incorporated in Newton-Raphson (NR) power flow algorithm to study the power flow control in transmission lines in which IPFC is placed. A program in MATLAB has been written in order to extend conventional NR algorithm based on this model. Numerical results are carried out on a standard 2 machine 5 bus system. The results without and with IPFC are compared in terms of voltages, active and reactive power flows to demonstrate the performance of the IPFC model.

Keywords—flexible AC transmission systems (FACTS), interline power flow controller (IPFC), power injection model (PIM), power flow control.

I. INTRODUCTION

THE most powerful and versatile FACTS devices are unified power flow controller (UPFC) and interline power flow controller (IPFC). It is found that, in the past, much effort has been made in the modeling of the UPFC for power flow analysis [1]-[5]. However, UPFC aims to compensate a single transmission line, whereas the IPFC is conceived for the compensation and power flow management of multi-line transmission system. Interline power flow controller (IPFC) is a new member of FACTS controllers. Like the STATCOM, SSSC and UPFC, the IPFC also employs the voltage sourced converter as a basic building block [6].

A simple model of IPFC with optimal power flow control method to solve overload problem and the power flow balance for the minimum cost has been proposed [7]. A multiconrol functional model of static synchronous series compensator (SSSC) used for steady state control of power system parameters with current and voltage operating constraints has been presented [8]. The injection model for congestion management and total active power loss minimization in

electric power system has been developed [9].

Mathematical models of generalized unified power flow controller (GUPFC) and IPFC and their implementation in Newton power flow are reported to demonstrate the performance of GUPFC and IPFC [10]. Based on the review above, this paper presents a power injection model of IPFC and its implementation in NR method to study the effect of IPFC parameters on bus voltages, active and reactive power flows in the lines. Further, the complex impedance of the series coupling transformer and the line charging susceptance are included in this model.

This paper is organized as follows: section II describes the operating principle and mathematical model of IPFC. Section III outlines the incorporation of IPFC model in NR method. In section IV, numerical results are presented to illustrate the feasibility of IPFC model and finally, conclusions are drawn in section V.

II. INTERLINE POWER FLOW CONTROLLER

A. Operating Principle of IPFC

In its general form the inter line power flow controller employs a number of dc-to-ac converters each providing series compensation for a different line. In other words, the IPFC comprises a number of Static Synchronous Series Compensators (SSSC). The simplest IPFC consist of two back-to-back dc-to-ac converters, which are connected in series with two transmission lines through series coupling transformers and the dc terminals of the converters are connected together via a common dc link as shown in Fig.1. With this IPFC, in addition to providing series reactive compensation, any converter can be controlled to supply real power to the common dc link from its own transmission line [11].

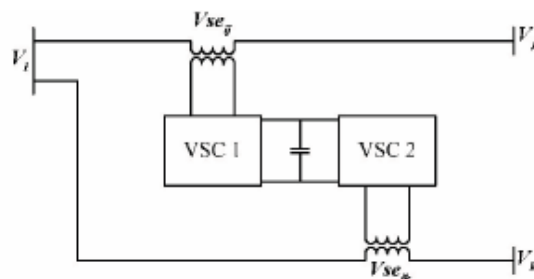


Fig.1 Schematic diagram of two converter IPFC

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B. Mathematical Model of IPFC

In this section, a mathematical model for IPFC which will be referred to as power injection model is derived. This model is helpful in understanding the impact of the IPFC on the power system in the steady state. Furthermore, the IPFC model can easily be incorporated in the power flow model. 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 Fig.2.

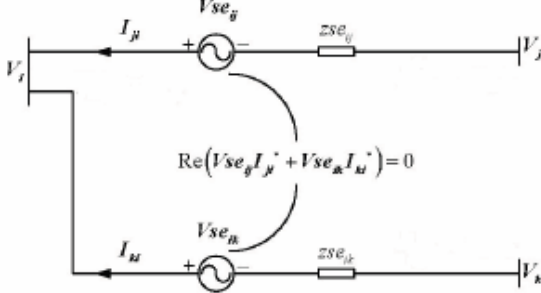


Fig.2 Equivalent circuit of two converter IPFC

In Fig.2, V_i, V_j and V_k are the complex bus voltages at the buses i, j and k respectively, defined as $V_x = V_x \angle \theta_x$ ($x=i, j$ and k). Vse_{in} is the complex controllable series injected voltage source, defined as $Vse_{in} = Vse_{in} \angle \theta se_{in}$ ($n=j, k$) and Zse_{in} ($n=j, k$) is the series coupling transformer impedance. The active and reactive power injections at each bus can be easily calculated by representing IPFC as current source. For the sake of simplicity, the resistance of the transmission lines and the series coupling transformers are neglected. The power injections at buses are summarized as

$$P_{inj,i} = \sum_{n=j,k} V_i Vse_{in} b_{in} \sin(\theta_i - \theta se_{in}) \quad (1)$$

$$Q_{inj,i} = - \sum_{n=j,k} V_i Vse_{in} b_{in} \cos(\theta_i - \theta se_{in}) \quad (2)$$

$$P_{inj,n} = -V_n Vse_{in} b_{in} \sin(\theta_n - \theta se_{in}) \quad (3)$$

$$Q_{inj,n} = V_n Vse_{in} b_{in} \cos(\theta_n - \theta se_{in}) \quad (4)$$

Where $n=j, k$.

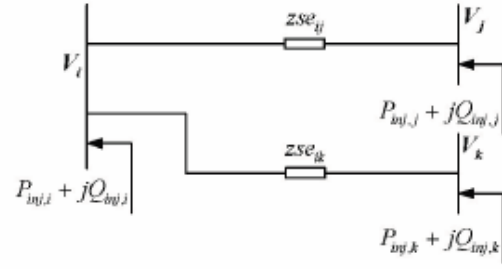


Fig.3 Power injection model of two converter IPFC

The equivalent power injection model of an IPFC is shown in Fig.3. 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.

$$\text{Re}(Vse_{ij}I_{ji}^* + Vse_{ik}I_{ki}^*) = 0 \quad (5)$$

Where the superscript * denotes the conjugate of a complex number. If the resistances of series transformers are neglected, (5) can be written as

$$\sum_{m=i,j,k} P_{inj,m} = 0 \quad (6)$$

Normally in the steady state operation, the IPFC is used to control the active and reactive power flows in the transmission lines in which it is placed. The active and reactive power flow control constraints are

$$P_{ni} - P_{ni}^{spec} = 0 \quad (7)$$

$$Q_{ni} - Q_{ni}^{spec} = 0 \quad (8)$$

Where $n=j, k$; $P_{ni}^{spec}, Q_{ni}^{spec}$ are the specified active and reactive power flow control references respectively, and

$$P_{ni} = \text{Re}(V_n I_{ni}^*) \quad (9)$$

$$Q_{ni} = \text{Im}(V_n I_{ni}^*) \quad (10)$$

Thus, the power balance equations are as follows

$$P_{gm} + P_{inj,m} - P_{lm} - P_{line,m} = 0 \quad (11)$$

$$Q_{gm} + Q_{inj,m} - Q_{lm} - Q_{line,m} = 0 \quad (12)$$

Where P_{gm} and Q_{gm} are generation active and reactive powers, P_{lm} and Q_{lm} are load active and reactive powers. $P_{line,m}$ and $Q_{line,m}$ are conventional transmitted active and reactive powers at the bus $m=i, j$ and k .

III. SOLUTION METHODOLOGY

The overall solution procedure for Newton-Raphson method with IPFC model can be summarized as follows.

- 1) Read the load flow data and IPFC data.
- 2) Assume flat voltage profile and set iteration count $K=0$
- 3) Compute active and reactive power mismatch. Also, the Jacobian matrix using NR method equations [12].
- 4) Modify power mismatch and jacobian using IPFC mathematical model (1) - (12).
- 5) If the maximal absolute mismatch is less than a given tolerance, it results in output. Otherwise, go to step 6
- 6) Solve the NR equations; obtain the voltage angle and magnitude correction vector dx .
- 7) Update the NR solution by $x=x+dx$.
- 8) Set $K=K+1$, go to step 3.

IV. CASE STUDY AND RESULTS

In this section, numerical results are carried out on a standard 2-machine 5-bus system [13] to show the robust performance and capabilities of IPFC model. The test system with IPFC is shown in Fig.4. Bus 1 is considered as slack bus, while bus 2 as generator bus and other buses are load buses. For all the cases, the convergence tolerance is $1e-5$ p.u. System base MVA is 100.

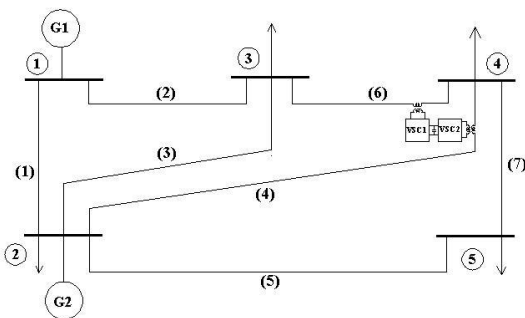


Fig.4 2-machine 5-bus system with IPFC

The two converters of IPFC are embedded in lines 4 and 6 respectively and bus 4 is selected as common bus for the two

converters. The complex bus voltages, active and reactive power flows of the test system without and with IPFC are summarized in Table I and II respectively.

TABLE I
BUS VOLTAGES WITH OUT AND WITH IPFC

Bus No.	Mag. of Voltages (p.u)		Angle of Voltage(degree)	
	Without IPFC	With IPFC	Without IPFC	With IPFC
1	1.060	1.060	0.000	0.000
2	1.000	1.000	-2.061	-2.004
3	0.987	0.986	-4.637	-4.787
4	0.984	0.995	-4.957	-3.799
5	0.972	0.976	-5.765	-5.328

TABLE II
LINE FLOWS WITH OUT AND WITH IPFC

Line No.	Active Power Flow(MW)		Reactive Power Flow(MVAR)	
	Without IPFC	With IPFC	Without IPFC	With IPFC
1	89.331	87.714	73.995	74.471
2	41.791	42.945	16.820	16.982
3	24.473	26.435	-2.518	-2.508
4	27.713	29.867	-1.724	-1.435
5	54.660	48.964	5.558	3.950
6	19.386	22.369	2.865	2.625
7	6.598	12.140	0.518	1.579

From Table I, it can be seen that the voltages at slack bus and generator bus are same without and with IPFC and there is a change in load bus voltages. Especially, the voltage at bus 4 increases from 0.984 to 0.995 p.u to which IPFC converters are connected. Also, from Table II, it is clear that the active power flow in line 4 increases from 27.713 MW to 29.867 MW and reactive power flow decreases from 1.724 MVAR to 1.435 MVAR. Similarly, the active power flow in line 6 increases from 19.386 MW to 22.369 MW and reactive power flow decreases from 2.865 MVAR to 2.625 MVAR.

Further, a detailed analysis is carried out to study the effect of IPFC parameters on active and reactive power flows in lines 4 and 6. The inductive reactance of the coupling transformers are taken to be 0.01 p.u. The series injected voltage magnitudes and angles vary in the range 0.01 to 0.2 p.u and $-\pi$ to $+\pi$ respectively. The variation of active and reactive power flows in line 4 with respect to IPFC parameters is shown in Fig.5 and Fig.6 respectively. Similarly, the variation of active and reactive power flows in line 6 with respect to IPFC parameters is shown in Fig.7 and Fig.8 respectively.

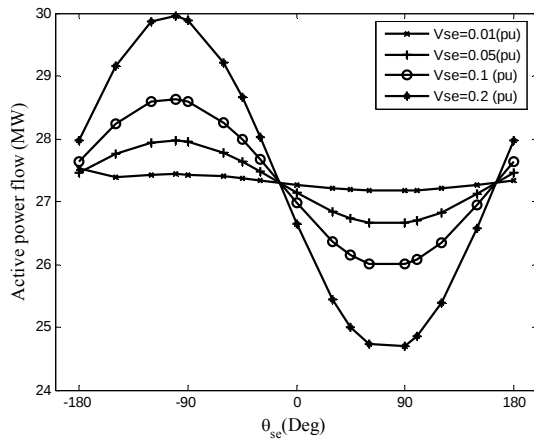


Fig.5 Effect of IPFC parameters on active power flow in line 4

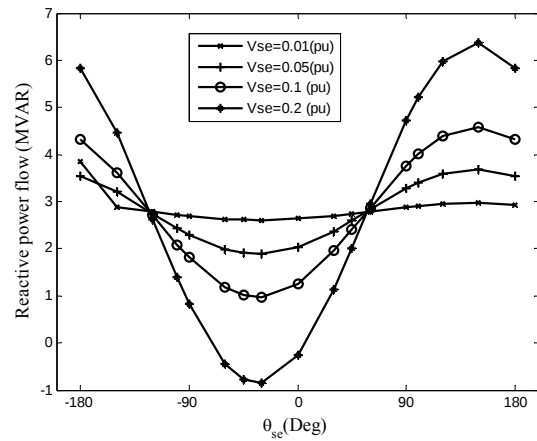


Fig.8 Effect of IPFC parameters on reactive power flow in line 6

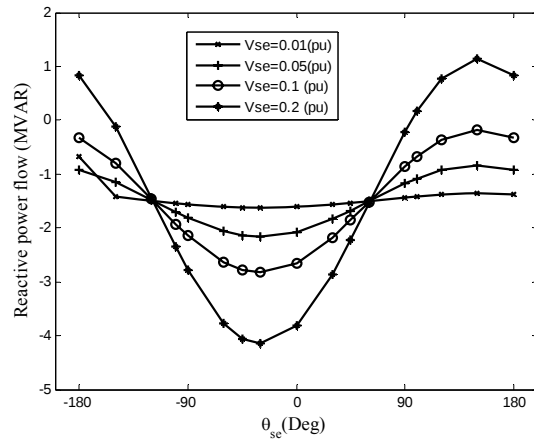


Fig.6 Effect of IPFC parameters on reactive power flow in line 4

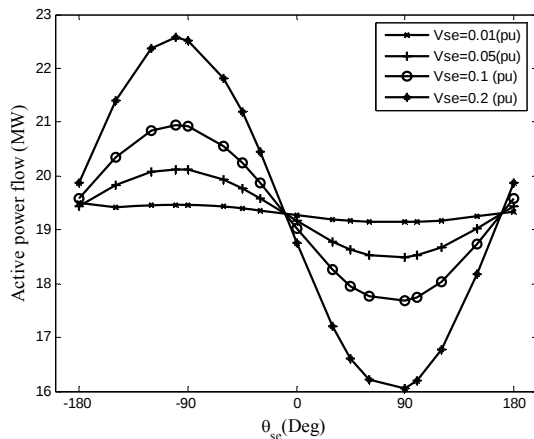


Fig.7 Effect of IPFC parameters on active power flow in line 6

From the graphical results, it can be seen that the active and reactive power flow in both the lines 4 and 6 can be controlled using IPFC parameters (V_{se} and θ_{sc}). As the V_{se} increases for different values of θ_{sc} , the active power flow in both the lines increases and reactive power flow decreases.

V.CONCLUSION

A power injection model of the inter line power flow controller (IPFC) and its implementation in Newton-Raphson power flow method has been presented. In this model, the complex impedance of the series coupling transformer and the line charging susceptance are included. Numerical results on the test system have shown the convergence and the effectiveness of the IPFC model. It shows that the incoming of IPFC can increase the bus voltage to which IPFC converters are connected and there is a significant change in the system voltage profile at the neighboring buses, increase in active power flow and decrease in reactive power flow through the lines. Also, the effect of IPFC parameters on active and reactive power flows through the lines in which IPFC is placed has been investigated.

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