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Multi-Line power Flow Control Using Interline Power Flow Controller (IPFC) in Power Transmission system

Devesh Raj Saxena

Department of Electrical engineering , B.V.D.U.C.O.E pune

Email-devesh_saxena86@hotmail.com

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. This paper also calculate the L-index and the maximum loading condition , and the critical bus system , which helps in determining the limit of stability of the system.

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 modelling 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 multicontrol 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 calculation of L-index and critical bus system. 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

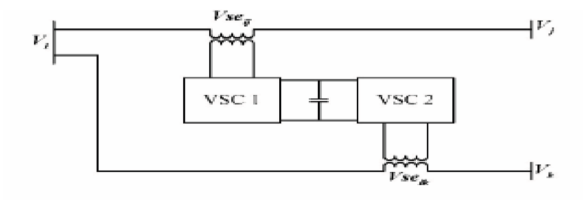


Fig.1 Schematic diagram of two converter IPFC

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.

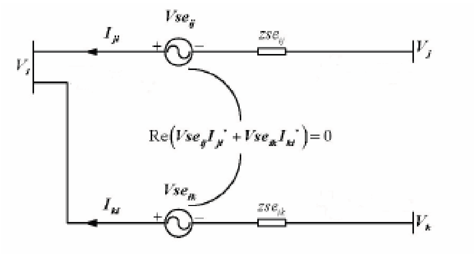


Fig.2 Equivalent circuit of two converter IPFC

In Fig.2, *i V*, *j V* and *k V* are the complex bus voltages at the buses *i*, *j* and *k* respectively, defined as *xV* = *V* ∠θ (*x*=*i*, *j* and *k*) . *In Vse it* is the complex controllable series injected voltage source, defined as *in Vse* = *Vse* ∠θ*se* (*n*=*j*,*k*) and *in Zse* (*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

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

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

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

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

Where n=j,k

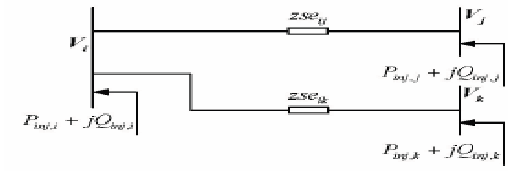


Fig.3 Power injection model of two converter IPFC

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.

$$\mathrm{Re}\left(Vse_{ij} I_{ji}^{*} + Vse_{ik} I_{ki}^{*}\right) = 0 \qquad (5)$$

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

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

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

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

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

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

$$P_{ni} = \mathrm{Re}(V_n I_{ni}^{*}) \qquad (9)$$

$$Q_{ni} = \mathrm{Im}(V_n I_{ni}^{*}) \qquad (10)$$

Thus, the power balance equations are as follows

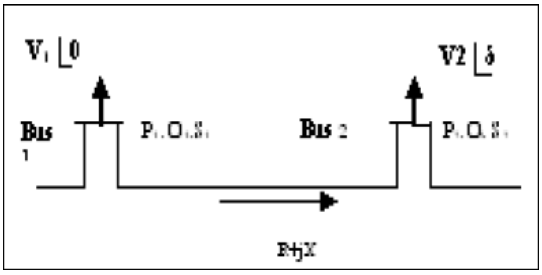
$$P_{gm} + P_{inj,m} - P_{lm} - P_{line,m} = 0 \qquad (11)$$

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

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*.

C) Loading Index formulation

The Voltage Stability Index abbreviated by Lij and referred to a line is formulated in this study as the measuring unit in predicting the voltage stability condition in the system. The mathematical formulation to speed up the computation is very simple. The Lij is derived from the voltage quadratic equation at the receiving bus on a two bus system [7]. The general two-bus representation is illustrated in



From the figure above, the voltage quadratic equation at the receiving bus is written as

$$\left[V_2^2 - \left(\frac{R}{X}sin\delta + cos\delta\right)V_1V_2 + \left(X + \frac{R^2}{X}\right)Q_2 = 0\right]$$

Setting the discriminate of the equation to be greater than or equal to zero:

$$\left[\left(\frac{R}{X}\sin\delta + \cos\delta\right)V_1\right]^2 - 4\left(X + \frac{R^2}{X}\right)Q_2 \geq 0$$

Equation A

Rearranging Eq.A, we obtain

$$L_{ij} = \frac{4Z^2 Q_j X}{V_i^2 (R sin\delta + X cos\delta)^2}$$

Where:

Z = line impedance

X = line reactance,

Qj = reactive power at the receiving end

Vi = sending end voltage

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 30-bus system [13] to show the robust performance and capabilities of IPFC model.

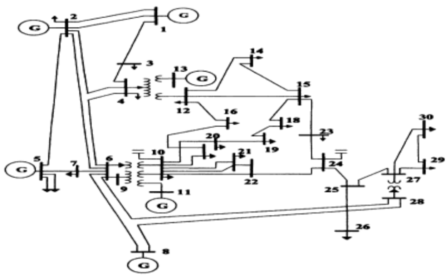


Fig.4 30-bus system with IPFC

Figure 4. 30 –Bus system

Critical lines	Critical buses	voltage magnitude without IPFC	Voltage magnitude withIPFC
39	30	0.536	0.896
37	26	0.600	0.954
34	25	0.687	0.914
33	27	0.711	0.881
35	27	0.711	0.881
36	27	0.711	0.860
39	29	0.747	0.831
25	20	0.764	0.971
08	07	0.961	0.875
13	09	0.899	0.911

Table .1 Critical bus ranking and line outages

Line no.	Q without IPFC in MVAR	Q with IPFC in MVAR	P without IPFC in MW	P with IPFC in MW
39	3.351	2.155	10.895	10.198
38	25.070	20.145	10.908	10.102
40	44.207	30.214	1.170	-0.358
37	9.645	2.369	19.419	17.323
34	7.527	2.344	10.331	10.109
33	4.422	1.123	1.643	-7.1211
35	-3.429	-1.123	-8.7771	-17.410
36	49.128	41.218	50.966	55.197
32	6.600	2.193	6.906	3.904
27	33.341	31.613	46.444	41.445
25	11.705	10.729	25.129	25.290
07	29.444	47.444	61.555	115.468

Table 2:- Active and Reactive Power flow with IPFC

λ (scalar multiplier)	BUS-7	BUS-21	BUS-24	BUS-25	BUS-26	BUS-27	BUS-29	BUS-30
0	1.003	1.032	1.022	1.019	1.001	1.026	1.006	0.995
10	0.9	1.0	1.0	1.0	0.9	1.0	0.9	0.9

ƛ	bus-1	bus-2	bus-5	bus-8	bus-11	bus-13
0	-17.021	48.822	35.975	30.826	16.119	10.423
10	-1.569	39.666	31.126	52.598	19.079	14.678
20	17.533	42.24	32.16	49.471	25.041	21.413
30	35.748	36.077	41.326	58.93	30.544	24.589
40	33.14	50.807	50.275	72.17	33.336	24.402
50	53.615	46.484	71.666	67.234	40.004	28.051
60	71.579	34.154	88.191	88.156	44.09	29.09
70	68.94	51.055	96.832	94.341	40.479	31.195
80	70.403	73.464	108.556	116.348	48.036	32.546
90	71.579	91.288	119.179	131.601	52.846	38.882
100	72.654	113.144	130.33	147.215	55.918	43.61
150	96.972	254.427	194.78	242.508	75.473	73.827
160	106.66	292.033	210.118	267.274	80.808	82.06
170	172.709	523.027	336.918	347.7	95.095	104.2
150	115.125	450.711	312.082	248.504	78.719	90.351

	91	23	11	08	89	16	94	82
20	0.971	1.007	0.993	0.988	0.966	0.996	0.971	0.957
30	0.959	0.99	0.975	0.97	0.946	0.979	0.951	0.935
40	0.956	0.98	0.962	0.959	0.932	0.97	0.94	0.922
50	0.945	0.961	0.942	0.936	0.907	0.948	0.914	0.895
60	0.94	0.947	0.924	0.919	0.887	0.932	0.894	0.87
70	0.938	0.94	0.913	0.91	0.87	0.924	0.88	0.861
80	0.933	0.936	0.907	0.903	0.866	0.918	0.875	0.851
90	0.93	0.915	0.887	0.885	0.845	0.903	0.856	0.83
100	0.926	0.904	0.874	0.871	0.829	0.891	0.841	0.812
150	0.904	0.835	0.791	0.784	0.723	0.811	0.735	0.691
160	0.899	0.816	0.768	0.758	0.691	0.785	0.701	0.652
170	0.875	0.772	0.712	0.687	0.608	0.711	0.6	0.536
150	0.705	0.603	0.658	0.589	0.508	0.598	0.505	0.4

Table 3:- PV- CURVE DATA FOR CRITICAL BUSES

Table 4:-Variation in generator Reactive Power with Loading

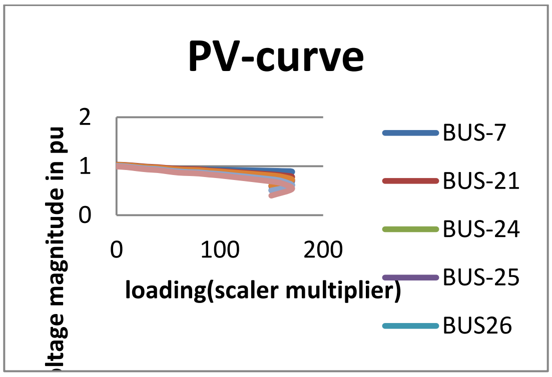
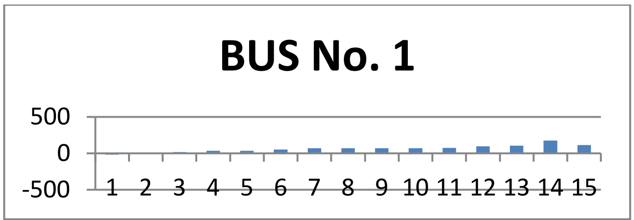
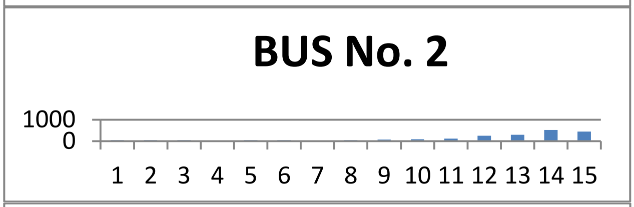
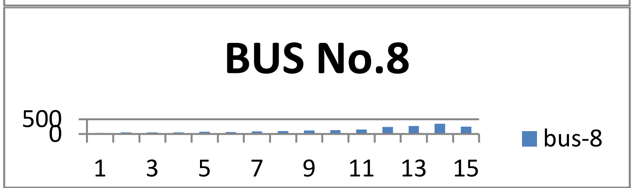
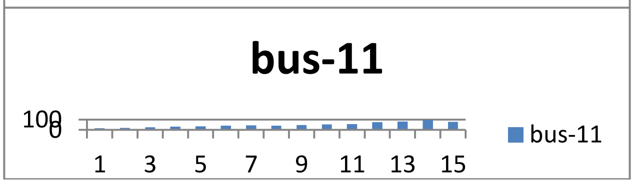


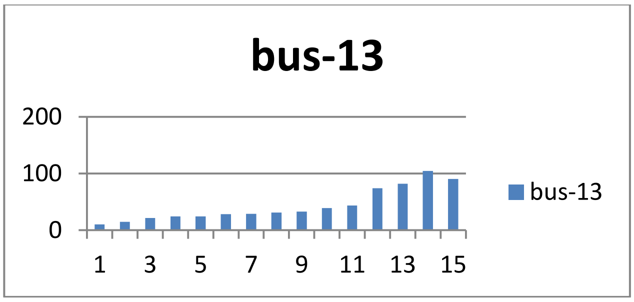
Figure 6.1 PV curve











V. Results

a) From Critical bus ranking

The bus 30 is identified as weakest bus due to overloading, this is the bus which can leads to system collapse which further may leads to the outage of line 39 connected to this bus. The MWM is calculated for without line outage and with line outage conditions. Table.1 shows congestion ranking of line without outage and line with outage condition. It is observed that outages of lines 40, 37, 36, 26, 25, 13, and 2 are considered as critical lines and have the higher ranks.. Hence outages of these lines results in sudden voltage drop and leads to voltage collapse.

b) From P-V curve

The graph is obtained in power-flow simulation by monitoring a voltage at a bus of interest and varying the power in small increments until power-flow divergence is encountered. Each equilibrium point shown represents a steady-state operating condition. This means that the generation real-power dispatch and all voltage support equipment have been established such that the system meets the reliability criteria for each operating point on the graph up to and including the operating limit point indicated on the graph. Beyond the operating limit, further increase in power may result in a breach of one or more of the line outage.

By analyzing the result obtained from load flow solutions of congested system, it is found that system collapses at 270% loading when the bus voltage of 30^{th} bus fall below 0.536 pu.

c) Results obtained from Incorporation of IPFC

The selection of buses and line for incorporation of IPFC is done according to the critical bus ranking and line outages as shown in table (1). According to this bus no. 30 is the most critical bus also further loading of this bus leads to system collapse. Bus no 29 is the stable bus, So master converter, whose parameters has to be controlled is connected to bus 30 and slave converter with support of which master converter's parameters will be controlled, is connected to bus 29. With the buses 27, 29, 30 line no 35, 36, 37, 38, 39 are connected so the power flow through these line will be assisted. The enhanced voltage magnitude for critical buses and power flow for the lines are shown in table 1 and 2.

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