POWER FLOW ANALYSIS OF A POWER SYSTEM IN THE PRESENCE OF INTERLINE POWER FLOW CONTROLLER (IPFC)

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ABSTRACT

One of the latest generation flexible AC transmission systems (FACTS) controllers is interline power flow controller (IPFC). In general, it is connected in multiple transmission lines of a power system network. This paper presents power injection model (PIM) of IPFC. This model is incorporated in Newton-Raphson (NR) power flow algorithm to study the effect of IPFC parameters in power flow analysis. 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 to demonstrate the performance of the IPFC model.

Keywords: power flow analysis, FACTS, IPFC, newton-raphson method.

1. INTRODUCTION

The interline power flow controller (IPFC) is a new member of FACTS controllers. Like the static synchronous compensator (STATCOM), static synchronous series compensator (SSSC) and unified power flow controller (UPFC), the IPFC also employs the voltage sourced converter as a basic building block. The UPFC and IPFC consists at least two converters. 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.

The basic theory and operating characteristics of the IPFC with phasor diagrams, P-Q plots and simulated wave forms has been explained [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 multi control 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-2 describes the operating principle of IPFC. Section-3 presents power injection model of IPFC. In section-4, numerical results are presented to illustrate the feasibility of IPFC model and finally, conclusions are drawn in section-5.

2. 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 consists 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 Figure-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].

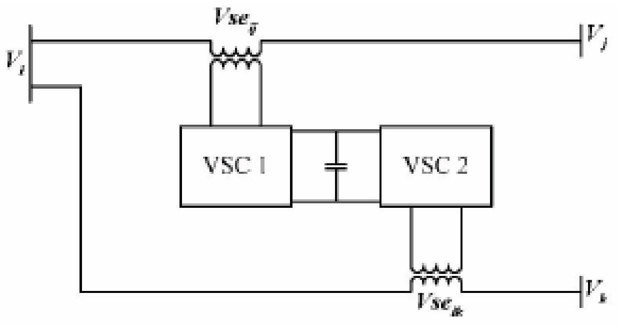

Figure-1. Schematic diagram of two converter IPFC.

3. POWER INJECTION 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 Figure-2.

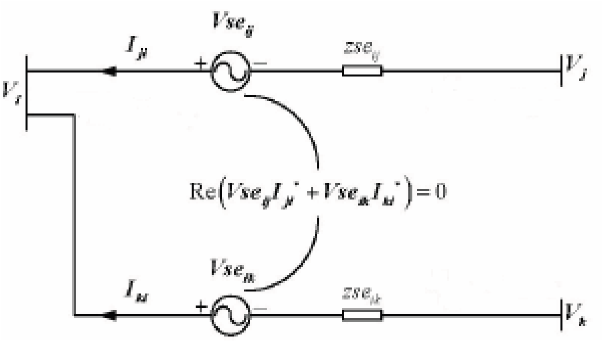

Figure-2. Equivalent circuit of two converter IPFC.

In Figure-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

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

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

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

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

Where *n=j, k.* The equivalent power injection model of an IPFC is shown in Figure-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

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

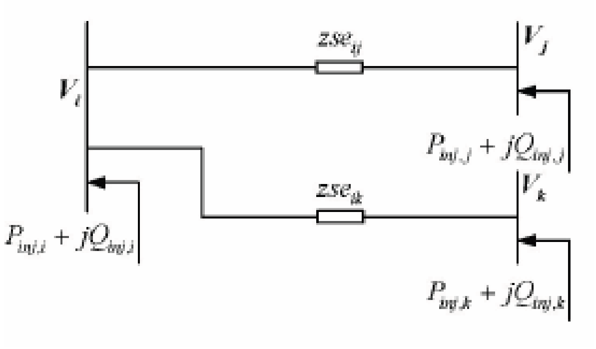

Figure-3. Power injection model of two converter IPFC.

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

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

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

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.*

4. RESULTS AND DISCUSSIONS

Numerical results are carried out on a standard 2-machine 5-bus system [12] to show the robust performance and capabilities of IPFC model. The test system with IPFC is shown in Figure-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 1x10^{-5} p.u. System base MVA is 100.

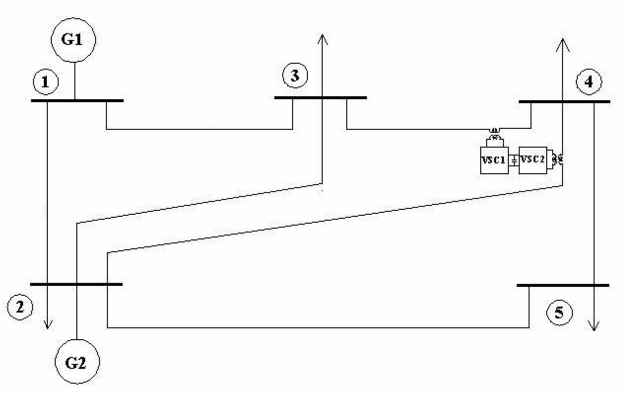

Figure-4. 2-machine 5-bus system with IPFC.

First of all without any compensation, the electrical system is studied in order to determine the power flow in each of the transmission line and the bus voltages. The power flow results without IPFC are given in Table-1 as case-I. Then, the two converters of IPFC are embedded in lines between buses 2-4 and 3-4 respectively, close to bus 4.

Table-1. Power flow results for case-I.

From bus-To bus i - j	**Line flows** (p.u)
1-2	0.8933 + j 0.7400
1-3	0.4179 + j 0.1682
2-3	0.2447 - j 0.0252
2-4	0.2771 - j 0.0172
2-5	0.5466 + j 0.0556
3-4	0.1939 + j 0.0287
4-5	0.0660 + j 0.0052

A detailed analysis is carried out to study the effect of IPFC parameters on line flows and bus voltages but, only few results are given for demonstration purpose. The power flow results for IPFC parameters Vse=0.1 p.u and θse= -150^0 are given in Table-2 as case-II. Similarly, the power flow results for another set of IPFC parameters Vse=0.15 p.u and θse= -100^0 are given in Table-3 as case-III. Also, the voltage profile of the test system for case-I, case-II and case-III is shown in Figure-5.

Table-2. Power flow results for case-II.

From bus-To bus i - j	**Line flows** (p.u)
1-2	0. 8849 + j 0.7424
1-3	0. 4212 + j 0.1727
2-3	0.2517 - j 0.0204
2-4	0.2824 - j 0.0081
2-5	0.5262 + j 0.0335
3-4	0. 2035 + j 0.0362
4-5	0. 0858 + j 0.0247

Table-3. Power flow results for case-III.

From bus-To bus i – j	**Line flows** (p.u)
1-2	0.8838 + j 0.7428
1-3	0.4276 + j 0.1651
2-3	0.2597 - j 0.0304
2-4	0. 2930 - j 0.0214
2-5	0. 5065 + j 0.0596
3-4	0.2175 + j 0.0174
4-5	0. 1050 - j 0.0024

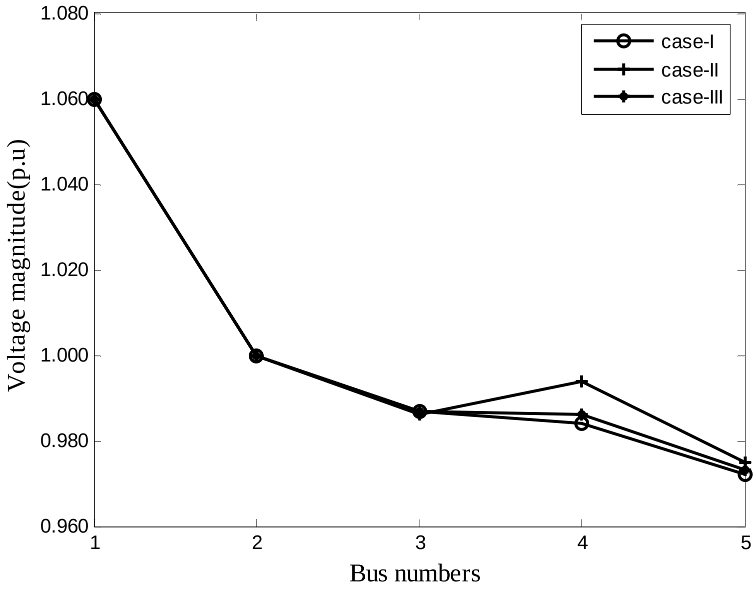

Figure-5. Effect of IPFC parameters on voltage profile of the test system.

Table-4. Iteration count and mismatch for the test system.

Case	Number of iterations	Maximum mismatch
I	4	$9.821\text{x}10^{-10}$
II	7	$8.495\ \text{x}10^{-06}$
III	9	$1.963\ \text{x}10^{-06}$

Comparing the power flow results from Table-1, Table-2 and Table-3, it is clear that the transmitted active and reactive power flow of all the lines has remarkably changed. Especially, there is an increase in active power flow in the lines in which IPFC is placed. This indicates multi line power flow control capability of IPFC. From Figure-5, it can be seen that voltage at slack bus and generator bus is same without and with IPFC and there is a change in load bus voltages. Especially, the voltage at bus 4 to which IPFC converters are connected increases significantly. Also, Table-4 shows number of iterations and maximum mismatch for the three cases. The Newton-Raphson power flow algorithm with IPFC requires more number of iterations in case-II and case-III than in case-I for converged solution. But, still it maintains quadratic convergence characteristics. The number of iterations is more because of additional power flow control constraints of IPFC.

5. CONCLUSIONS

A power injection model of the inter line power flow controller (IPFC) has been presented. This model is incorporated in Newton-Raphson power flow algorithm to demonstrate the performance of IPFC. Numerical results on the test system show that, the active power flow through the lines in which IPFC is placed increases. Also, there is a significant change in the system voltage profile at the neighboring buses and increase in the voltage at a bus to which IPFC converters are connected .This shows that multi control capability of IPFC which plays an important role in power systems and still the Newton-Raphson power flow algorithm with IPFC maintains quadratic convergence characteristics.

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