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Assessment of Available Transfer Capability for Power System Network with Multi-Line FACTS Device

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Abstract

This paper presents the use of an advanced and versatile member of flexible alternating current transmission systems (FACTS) device which is interline power flow controller (IPFC) to improve the available transfer capability (ATC). In general, IPFC is used in multiple transmission lines of a power system network. A mathematical model of IPFC, termed as power injection model (PIM) is derived. A program in MATLAB has been written in order to extend repeated power flow (RPF) method based on this model for ATC enhancement. Numerical results are carried out on IEEE-14 bus system for different cases to illustrate the effectiveness of IPFC for improvement of ATC.

Keywords: Flexible alternating current transmission systems device, interline power flow controller, power injection model, available transfer capability.

Introduction

The latest generations of 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].

Ref.[7] focuses on the evaluation of the impact of FACTS control on available transfer capability enhancement. An optimal power flow based ATC enhancement model is formulated to achieve the maximum power transfer of the specified interface with FACTS control. Ref.[8] presents the application of one type of FACTS device, the unified power flow controller(UPFC) to improve the transfer capability of a power system. Probabilistic assessment of available transfer capability based on Monte Carlo method with sequential simulation has been reported [9]. An approach to determine the optimum location and optimum capacity of TCSC in order to improve ATC as well as voltage profile has been presented. Further, real genetic algorithm (RGA) associated with analytical hierarchy process and fuzzy sets are implemented as a hybrid heuristic technique to optimize a complicated problem [10]**.**

Ref.[11] presents hybrid approach, combining a structure preserving and a time domain simulation method to compute the dynamic ATC in presence of two types of FACTS controllers like static synchronous compensator (STATCOM) and unified power flow controller(UPFC). A probabilistic modeling based approach for total transfer capability enhancement using FACTS devices has been reported [12]. Careful study of the former literature reveals that ATC analysis has been performed with single line FACTS device. But, a multi-line FACTS device which is IPFC has been used in this paper for ATC analysis. The feasibility of the IPFC is demonstrated on a standard IEEE-14 bus system for different cases. The obtained results are compared without and with IPFC. The results reveal that best solution obtained with IPFC is quite encouraging and useful for system planners.

Multi-Line FACTS Device: Interline Power Flow Controller (IPFC)

Operating Principle of IPFC

In its general form the interline 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 Fig.1 [13]-[14].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

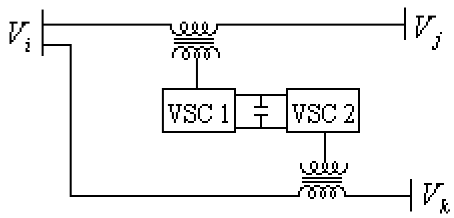

Figure 1: Schematic diagram of two converter IPFC

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 useful to study the impact of the IPFC on the power system network and can easily be incorporated in the power flow algorithm. 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.

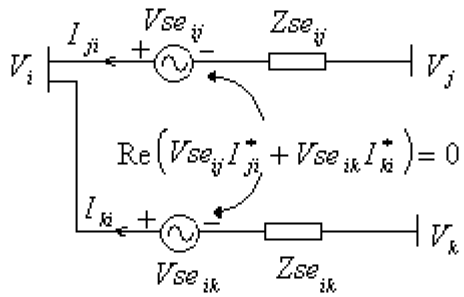

Figure 2: Equivalent circuit of two converter IPFC

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 $V_m = V_m \angle \theta_m$ (*m=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 injection model is obtained by replacing the voltage source (Vse_{in}) as current source (Ise_{in}) 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

$$Ise_{in} = -jbse_{in}Vse_{in} \tag{1}$$

Now, the current source (Ise_{in}) can be modeled as injection powers at the buses *i, j* and *k.* The complex power injected at i^{th} bus is

$$S_{inj,i} = \sum_{n=j,k} V_i \left(-Ise_{in}\right)^* \tag{2}$$

Substitute (1) in (2)

$$S_{inj,i} = \sum_{n=j,k} V_i \left(jbse_{in}Vse_{in}\right)^* \tag{3}$$

After simplification, the active power and reactive power injections at i^{th} bus are

$$P_{inj,i} = \mathrm{Re}(S_{inj,i}) = \sum_{n=j,k} \left(V_i Vse_{in} bse_{in} \sin(\theta_i - \theta se_{in}\right) \tag{4}$$

$$Q_{inj,i} = \text{Im}(S_{inj,i}) = -\sum_{n=j,k}\left(V_i Vse_{in} bse_{in} \cos(\theta_i - \theta se_{in}\right) \quad (5)$$

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

$$S_{inj,n} = V_n \left(Ise_{in}\right)^* \quad (6)$$

Substitute (1) in (6)

$$S_{inj,n} = V_n \left(-\ jbse_{in} Vse_{in}\right)^* \quad (7)$$

After simplification, the active power and reactive power injections at n^{th} bus are

$$P_{inj,n} = \text{Re}(S_{inj,n}) = -V_n Vse_{in} bse_{in} \sin(\theta_n - \theta se_{in}) \quad (8)$$

$$Q_{inj,n} = \text{Im}(S_{inj,n}) = V_n Vse_{in} bse_{in} \cos(\theta_n - \theta se_{in}) \quad (9)$$

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 Fig.3.

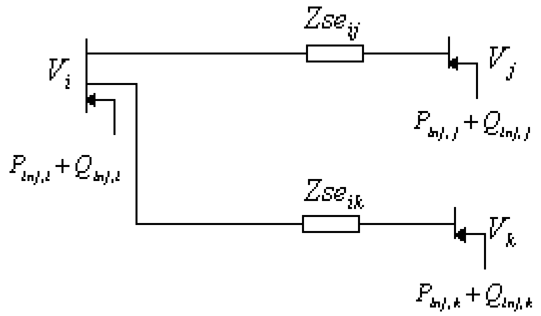

Figure 3: Power injection model of two converter IPFC

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.

$$\text{Re}\left(Vse_{ij} I_{ji}^* + Vse_{ik} I_{ki}^*\right) = 0 \quad (10)$$

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

$$\sum_{m=i,j,k} P_{inj,m} = 0 \quad (11)$$

Solution Methodology for ATC Calculation with IPFC

The overall solution procedure for ATC calculation with IPFC can be summarized as follows:

Step 1: Read the system data, source bus, sink bus and IPFC data.
Step 2: Form the bus admittance matrix by direct inspection method.
Step 3: Assume a step increase in power transfer at source bus and sink bus.
Step 4: Solve the power flow problem using Newton-Raphson method and check whether any limit is violated.
Step 5: If no limit is violated, go to step 3.
Step 6: If limit is violated, calculate ATC.
Step 7: Repeat the procedure with IPFC.
Step 8: Repeat the procedure for line outage with out and with IPFC.

Results and Discussions

In this section, a standard IEEE 14-bus system [15] has been considered to demonstrate the effectiveness of IPFC for ATC analysis. ATC is calculated using RPF method for test system with the following 4 cases:
Case 1: Base case.
Case 2: Base case with IPFC.
Case 3: Line outage.
Case 4: Line outage with IPFC.

Table 1: ATC results of IEEE 14 bus system for case-1

Transaction	Source bus	Sink bus	ATC (MW)	Violated constraints OLL/VVB
1	14	4	100	9 -14
2	9	7	72	7- 8
3	13	11	40	6 -11
4	7	1	100	7- 9
5	12	7	59	7- 8

Table 2: ATC results of IEEE 14 bus system for case-2

Transaction	Source bus	Sink bus	ATC(MW)	
			Without IPFC	With IPFC
1	14	4	100	124
2	9	7	72	85
3	13	11	40	50
4	7	1	100	109
5	12	7	59	66

In 14-bus test system, bus 1 is considered as slack bus, while bus 2, 3, 6, and 8 are taken as generator buses and other buses are load buses. The one converter of IPFC is embedded in a line between the buses 9-14 which is considered as 1st line and the other converter of IPFC is placed in a line between the buses 13-14 which is considered as 2nd line and bus 14 is selected as common bus for two converters. The line connected between the buses 2-3 is considered as outage line for the analysis. ATC results for five transactions of test system with different cases are given in table 1, 2, 3 and 4 respectively along with violated constraints either over loaded line (OLL) or voltage violation bus (VVB). By comparing case-1 results with case-2 results, it can find that the ATC value for all transactions is enhanced with IPFC. Similarly, by comparing case-3 results with case-4 results, it can also find that the ATC value for all transactions is enhanced with IPFC even under line outage. Further, it is observed that the transmission line outage causes decrease in ATC value compared to the base case.

Table 3: ATC results of IEEE 14 bus system for case-3

Transaction	Source bus	Sink bus	ATC (MW)	Violated constraints
				OLL/VVB
1	14	4	82	9 -14
2	9	7	59	7- 8
3	13	11	21	6 -11
4	7	1	87	7- 9
5	12	7	34	7- 8

Table 4: ATC results of IEEE 14 bus system for case-4

Transaction	Source bus	Sink bus	ATC(MW)	
			Without IPFC	With IPFC
1	14	4	82	90
2	9	7	59	67
3	13	11	21	34
4	7	1	87	94
5	12	7	34	50

Conclusion

In this paper, a multi-line FACTS device which is IPFC has been used to examine the impact of IPFC on ATC enhancement. ATC is calculated using RPF method for different cases of test system. The results demonstrate the effectiveness and robustness of IPFC. The results obtained for test system without and with IPFC are compared and observations reveal that ATC is significantly improved with IPFC under base case as well as line outage case.

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