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Research paper

Approaches for effective using of interline power flow controller steady state model

Nabil A. Hussein [1] *, Ayamn A. Eisa [2], Hassan M. Mahmoud [3], Safy A. Shehata [1], El-Saeed A. Othman [4]

[1] Nuclear Research Center, Egypt Atomic Energy Authority (EAEA), Egypt
[2] National Center for Radiation Research and Technology, EAEA, Egypt
[3] Ministry of Electricity and Renewable Energy (MOEE) , Egypt
[4] Dept. of electrical engineering, Faculty of Engineering, Al-Azhar University, Egypt
**Corresponding author E-mail: Nabil_Ahmed.eaea@yahoo.com*

Abstract

Interline power flow controller (IPFC) is the latest proposed flexible alternating current transmission systems (FACTS) device. Although IPFC was proposed in 1998, its performance studying stills good research area. It cannot be denied that, the first step for performance analysis is developing an effective simulation model. This paper is tackling; the steady state modeling for a power system equipped with IPFC device, approaches for applying this model and the idea behind each approach. 5-Bus, 14-Bus and 30-Bus systems have been chosen as case studies to support the comparison between the three approaches.

Keywords: *FACTS; IPFC Modeling; Newton Raphson; Power Flow; SLFE..*

1. Introduction

FACTS concept was first mentioned in the electric power research institute (EPRI) Journal in 1986 [1]. It was proposed to increase existing power system capabilities for mitigating the problems induced by the earlier technology. FACTS devices was developed into generations based on configuration, connection and function [2]. IPFC device is more attractive than its peers of universal power line conditioners, mainly unified power flow controller (UPFC) and unified power quality conditioners (UPQC) [3]. One IPFC device is only needed for power flow controlling in more than one line as shown in figure 1.

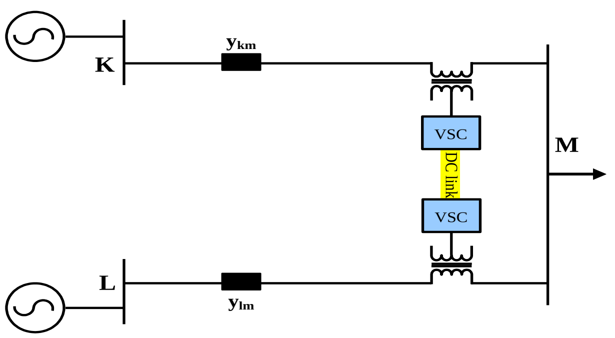


Fig. 1: IPFC Arrangements in Two Transmission Lines [2]

2. Literature review

In 2006, Yan Zhang and Chen proposed power injected model (PIM) of IPFC for power flow incorporated in Newton-Raphson method. Numerical results based on the IEEE 57-Bus and IEEE 300-Bus systems have shown the convergence and efficiency of the proposed model. The authors reported that the proposed model is a useful tool for power system planning and operation control of large-scale power system [4].

In June 2007, S. Sankar, and S. Ramareddy described interline Power flow controller in power system as a VSC-based FACTS controller for series compensation with the unique capability of power management among multi-lines of a substation [5].

A.V.Naresh Babu et al (2010) applied the PIM proposed in [4] to study the power flow control in transmission lines in which IPFC is placed. Numerical results were carried out on a standard 2-machine 5-Bus system. The results without and with IPFC were compared in terms of voltages, active and reactive power flows to demonstrate the performance of the IPFC model [6].

R. Strzelecki, and G. Benysek (2010) presented IPFC system to be utilized to control active and reactive power flow in given number of systems. They reported that the advantage of IPFC system over classical UPFC, one DC element common for inverters, lets it proper to avoid problem of power flow control in one system resulting synchronous deterioration of power in other systems [3].

In April 2011, Sunil Kumar Jilledi presented comparison paper of multi-line power flow control using UPFC and IPFC in power transmission systems. The author concluded that the IPFC is very effective FACTS device in the modern power system network [7].

Natália M. R. Santos et al (2011) applied the PIM proposed in reference [6] on the same power system (IEEE 5-bus system) but with IPFC different location [8].

Nabil A. Hussein et al (2012) presented an analysis for the steady state performance of IPFC device in IEEE 5-bus and 14-bus systems. They concluded that IPFC affect over all system voltage profile, lines power flow, lines power losses, and total power losses in the system. The authors also expected that the research in this area would tackle the dynamic behavior, studying the effect of each control parameter on the system, proposing an intelligent technique of controlling IPFC and determination of the optimum position of IPFC in the power system [2].

In 2013, [9] presented a development of the IPFC model, such development was not attractive and it added nothing effective.

In July 2014, NEHA JAIN presented an interactive functional toolkit related to interline power flow controller. He reported that the IPFC like alternative FACTS controller contribute to the best system operation by reducing the ability loss and raising the voltage profile [10].

In 2014, [11] discussed the impact of changing inter-line power flow controller parameters on IEEE 5-bus system. The authors classified the IPFC device parameters in two types. They also studied the impact of changing each parameter at fixing the others. They reported that this study is important for designers before installing the IPFC device in any power system.

Yogesh Kumar, Bipul Kunj and Navita (June 2015) presented valuable thesis on using IPFC equipped with fuzzy logic controller to control the Transmission Line Power Flow. They compared the open loop and closed loop models output and they concluded that the IPFC device improves the power quality and managed power flow in the transmission line [12].

In 2015, Abdelkader Benslimane and Chelleli Benachiba discussed the power quality enhancement using the interline power flow controller. The results without and with IPFC were compared in terms of voltage and active power flows to demonstrate the performance of the IPFC model [13].

In December 2015, [14] discussed the contingency management of power system with IPFC using real power performance index and line stability index. The authors concluded that the load flow control using multifaceted IPFC device could maintain a reliable system operation even in the event of contingencies. The reported also that the proper placement and tuning of the costly device is necessary for its effective utilization.

In March 2016, K. RAVISHANKER and P. NARASIMHA REDDY analyzed the performance of interline power flow controller for practical power system. They conclude that the interline power flow controller increase the power transfer capability and the practical utility system with IPFC is able to maintain voltage profile within the allowable limit [15].

The IPFC performance in the power systems have been presented by the authors in 2018, two IEEE test power systems have been chosen to provide overall scenarios for the IPFC behavior [16].

3. Mathematical model of IPFC system

As its name stands for, IPFC devices are used to control the power flow within power system. Therefore, the mathematical modeling of a power system without/with IPFC device is mainly based on power flow study. Load flow study is based on a model of the components of the network (generators, transmission lines, transformers, etc) and on the hypotheses of active and reactive power injection at the different nodes of the network.

Assuming the power system is operating in a balanced steady state condition. The problem is to determine the magnitude and phase angle of voltages at every node and the power flow for each line.

A single-phase model is used for analysis (due to balanced conditions). The per-unit system is usually used. Four quantities are associated with each bus. These are voltage magnitude V, and phase angle δ, real power P, and reactive power Q [17]. These quantities can be obtained by solving the power flow equations, which named also the static load flow equations (SLFE). SLFE is the expression of the net complex bus power in terms of network voltages and admittances. This equation is usually solved by Newton Raphson (NR) iterative method because of its quadratic convergence. The mathematical model of the power system will be presented without and with the IPFC.

3.1. System without the IPFC

The Consider a power system network having N buses and NG is the number of generators, one of these generators is to be a swing bus. Thus, there are NG-1 PV-Bus type, and N-NG PQ-Bus type. Assuming that the swing bus is numbered as bus 1, the PV-Buses are numbered 2, 3… NG and the PQ-Buses are numbered NG+1, NG+2… N.

- The input data to solve the power system problem are:
- The admittances of all series and shunt elements (implying that Y-matrix can be obtained),
- The voltage magnitudes (Vi, i=1, 2,…, NG) at swing and PV-Bus types,
- The real power of all buses except the swing bus (Pi, i=2, 3,…,N)
- The reactive power of PQ-Bus type (Qi, i=NG+1, NG+2, …, N)

Considering the NR method then

$$\begin{bmatrix} f_P \\ f_Q \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V} \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} \quad (1)$$

Where

$$P_i = \sum_{j=1}^{N} V_i V_j Y_{ij} \cos(\theta_{ij} + \delta_j - \delta_i)$$

$$Q_i = -\sum_{j=1}^{N} V_i V_j Y_{ij} \sin(\theta_{ij} + \delta_j - \delta_i)$$

The Jacobian matrix J can be given as:

$$J = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \quad (2)$$

Where

$$J_1 = \frac{\partial P}{\partial \delta}, J_2 = \frac{\partial P}{\partial V}, J_3 = \frac{\partial Q}{\partial \delta}, J_4 = \frac{\partial Q}{\partial V}$$

The following equations represent the general form for J elements as follow:

For J1:

These equations applied for all buses except the slake bus because the voltage magnitude and angle are known at this bus:

$$\frac{\partial P_i}{\partial \delta_i} = \sum_{\substack{j=1 \\ j\neq i}}^{N} V_i V_j Y_{ij} \sin(\theta_{ij} + \delta_j - \delta_i) \quad (3)$$

$$\frac{\partial P_i}{\partial \delta_j} = -V_i V_j Y_{ij} \sin(\theta_{ij} + \delta_j - \delta_i) \quad (4)$$

For J2:

These equations applied for all buses except the slake bus:

$$\frac{\partial P_i}{\partial V_i} = 2V_i Y_{ii} \cos(\theta_{ii}) + \sum_{\substack{j=1 \\ j\neq i}}^{N} V_j Y_{ij} \cos(\theta_{ij} + \delta_j - \delta_i) \quad (5)$$

$$\frac{\partial P_i}{\partial V_j} = V_i Y_{ij} \cos(\theta_{ij} + \delta_j - \delta_i) \quad (6)$$

For J3:

These equations applied for only the load busses at which the voltage magnitude and angle are unknown:

$$\frac{\partial Q_i}{\partial \delta_i} = \sum_{\substack{j=1 \\ j\neq i}}^{N} V_i V_j Y_{ij} \cos(\theta_{ij} + \delta_j - \delta_i) \quad (7)$$

$$\frac{\partial Q_i}{\partial \delta_j} = -V_i V_j Y_{ij} \cos(\theta_{ij} + \delta_j - \delta_i) \quad (8)$$

For J4:

These equations applied for only the load busses:

$$\frac{\partial Q_i}{\partial V_i} = -2V_i Y_{ii} \sin(\theta_{ii}) - \sum_{\substack{j=1 \\ j\neq i}}^{N} V_i V_j Y_{ij} \sin(\theta_{ij} + \delta_j - \delta_i) \quad (9)$$

$$\frac{\partial Q_i}{\partial V_j} = -V_i Y_{ij} \sin(\theta_{ij} + \delta_j - \delta_i) \quad (10)$$

3.2. System with the IPFC

All Considering the power system proposed in previous section, equipped with an IPFC device located between lines K-M and L-M where K, L and M are busses in the system as shown in figure 2 [7].

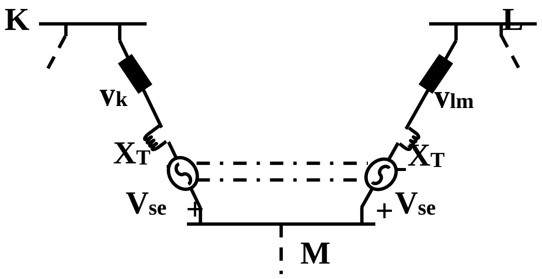


Fig. 2: Single Line Diagram of a System with IPFC.

IPFC data has to be added to input data required for system without IPFC in order to solve the power system problem.
Considering the NR method then:

$$\begin{bmatrix} f_P \\ f_Q \\ f_{ipfc} \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V} & \frac{\partial P}{\partial ipfc} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V} & \frac{\partial Q}{\partial ipfc} \\ \frac{\partial f_{ipfc}}{\partial \delta} & \frac{\partial f_{ipfc}}{\partial V} & \frac{\partial f_{ipfc}}{\partial ipfc} \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta V \\ \Delta ipfc \end{bmatrix} \quad (11)$$

The Jacobian matrix J can be formed as:

$$J = \begin{bmatrix} J_1 & J_2 & \\ J_3 & J_4 & J_5 \\ J_6 & J_7 & J_8 \end{bmatrix} \quad (12)$$

Where:

$J_1 = \frac{\partial P}{\partial \delta}$, $J_2 = \frac{\partial P}{\partial V}$, $J_3 = \frac{\partial Q}{\partial \delta}$, $J_4 = \frac{\partial Q}{\partial V}$, $J_5 = \begin{bmatrix} \frac{\partial P}{\partial ipfc} \\ \frac{\partial Q}{\partial ipfc} \end{bmatrix}$, $J_6 = \frac{\partial f_{ipfc}}{\partial \delta}$, $J_7 = \frac{\partial f_{ipfc}}{\partial V}$, $J_8 = \frac{\partial f_{ipfc}}{\partial ipfc}$

As insertion of the IPFC changes the active and reactive power function at the related busses (K, L and M) according to the relations discussed before ($P_{inew} = P_i + P_{inj_i}, Q_{inew} = Q_i + Q_{inj_i}$), this change affects the main Jacobian matrix as follow
For J1:

$$\frac{\partial P_{inew}}{\partial \delta_i} = \frac{\partial P_i}{\partial \delta_i} + \frac{\partial P_{inj_i}}{\partial \delta_i} \quad (13)$$

$$\frac{\partial P_{inj_i}}{\partial \delta_i} = -V_i V_{se_i} Y_{im} \sin(\theta_{im} + \delta_{se_i} - \delta_i) \ , i = k, l \quad (14)$$

$$\frac{\partial P_{inj_m}}{\partial \delta_m} = \sum_{i=k,l} V_m V_{se_i} Y_{im} \sin(\theta_{im} + \delta_{se_i} - \delta_m) \quad (15)$$

$$\frac{\partial P_{inew}}{\partial V_i} = \frac{\partial P_i}{\partial V_i} + \frac{\partial P_{inj_i}}{\partial V_i} \quad (16)$$

$$\frac{\partial P_{inj_i}}{\partial V_i} = -V_{se_i} Y_{im} \cos(\theta_{im} + \delta_{se_i} - \delta_i) \ , i = k, l \quad (17)$$

$$\frac{\partial P_{inj_m}}{\partial V_m} = \sum_{i=k,l} V_{se_i} Y_{im} \cos(\theta_{im} + \delta_{se_i} - \delta_m) \quad (18)$$

For J2:
For J3:

$$\frac{\partial Q_{inew}}{\partial \delta_i} = \frac{\partial Q_i}{\partial \delta_i} + \frac{\partial Q_{inj_i}}{\partial \delta_i} \quad (19)$$

$$\frac{\partial Q_{inj_i}}{\partial \delta_i} = -V_i V_{se_i} Y_{im} \cos(\theta_{im} + \delta_{se_i} - \delta_i) \ , i = k, l \quad (20)$$

$$\frac{\partial Q_{inj_m}}{\partial \delta_m} = \sum_{i=k,l} V_m V_{se_i} Y_{im} \cos(\theta_{im} + \delta_{se_i} - \delta_m) \quad (21)$$

$$\frac{\partial Q_{inew}}{\partial V_i} = \frac{\partial Q_i}{\partial V_i} + \frac{\partial Q_{inj_i}}{\partial V_i} \quad (22)$$

$$\frac{\partial Q_{inj_i}}{\partial V_i} = V_{se_i} Y_{im} \sin(\theta_{im} + \delta_{se_i} - \delta_i) \ , i = k, l \quad (23)$$

$$\frac{\partial Q_{inj_m}}{\partial V_m} = -\sum_{i=k,l} V_{se_i} Y_{im} \sin(\theta_{im} + \delta_{se_i} - \delta_m) \quad (24)$$

For J4:
The added elements in the Jacobian matrix due to presence of the IPFC device expressed as J5, J6, J7 and J8
Regarding f_{ipfc} *and* $\Delta ipfc$, three approaches are used to assign its form; these approaches are the main subject of this paper. The main criterion which is common between the three approaches is the active power invariance of IPFC device, i.e. the summation of the series active injected power $P_{se_{net}}$ equals zero, and the other three criteria could differ according to the applied approach as follow:

3.2.1. The first approach

No In this approach, IPFC device looks to be open loop controlled as the series injected voltages in magnitude and angle are predefined values (V_{se_k}, V_{se_l} *and* δ_{se_k}). δ_{se_l} value is kept unknown to verify the first criterion so that:

$$f_{ipfc} = [P_{se_{net}}], \Delta ipfc = [\Delta\delta_{se_l}]$$

For J5:

The equation $J_5 = \begin{bmatrix} \frac{\partial P}{\partial \delta_{se_l}} \\ \frac{\partial Q}{\partial \delta_{se_l}} \end{bmatrix}$ consists of the following elements:

$$\frac{\partial P_l}{\partial \delta_{se_l}} = V_l V_{se_l} Y_{lm} \sin(\theta_{lm} + \delta_{se_l} - \delta_l) \quad (25)$$

$$\frac{\partial P_m}{\partial \delta_{se_l}} = -V_m V_{se_l} Y_{lm} \sin(\theta_{lm} + \delta_{se_l} - \delta_m) \quad (26)$$

$$\frac{\partial Q_l}{\partial \delta_{se_l}} = V_l V_{se_l} Y_{lm} \cos(\theta_{lm} + \delta_{se_l} - \delta_l) \quad (27)$$

$$\frac{\partial Q_m}{\partial \delta_{se_l}} = -V_m V_{se_l} Y_{im} \cos(\theta_{lm} + \delta_{se_l} - \delta_m) \quad (28)$$

For J6:
The equation $J_6 = \frac{\partial P_{se_{net}}}{\partial \delta}$ consists of the following elements:

$$\frac{\partial P_{se_{net}}}{\partial \delta_i} = -V_i V_{se_i} Y_{im} \sin(\theta_{im} + \delta_{se_i} - \delta_i) \ , i = k, l \quad (29)$$

$$\frac{\partial P_{se_{net}}}{\partial \delta_m} = \sum_{i=k,l} V_m V_{se_i} Y_{im} \sin(\theta_{im} + \delta_{se_i} - \delta_m) \quad (30)$$

For J7:
The equation $J_7 = \frac{\partial P_{se_{net}}}{\partial V}$ consists of the following elements:

$$\frac{\partial P_{se_{net}}}{\partial V_i} = -V_{se_i} Y_{im} \cos(\theta_{im} + \delta_{se_i} - \delta_i) \ , i = k, l \quad (31)$$

$$\frac{\partial P_{se_{net}}}{\partial V_m} = \sum_{i=k,l} V_{se_i} Y_{im} \cos(\theta_{im} + \delta_{se_i} - \delta_m) \quad (32)$$

For J8:
The equation $J_8 = \frac{\partial P_{se_{net}}}{\partial \delta_{se_l}}$ consists of the following elements:

$$\frac{\partial P_{se_{net}}}{\partial \delta_{se_l}} = V_l V_{se_l} Y_{lm} sin(\theta_{lm} + \delta_{se_l} - \delta_l) - V_m V_{se_l} Y_{lm} sin(\theta_{lm} + \delta_{se_l} - \delta_m) \quad (33)$$

3.2.2. The second approach

This approach is the most commonly derived approach in research papers. IPFC device looks to be a transmission line power limiter. The transferred power values through the device connected lines (master and slave) are predefined (P_{d1}, P_{d2} *and* Q_{d1}). These three criteria in addition to the above mentioned criterion are the control criteria. $V_{se_k}, V_{se_l}, \delta_{se_k}$ *and* δ_{se_l} values are kept unknown so that:

$$f_{ipfc} = \begin{bmatrix} P_{d1} \\ P_{se_{net}} \\ Q_{d1} \\ P_{d2} \end{bmatrix}, \Delta ipfc = \begin{bmatrix} \Delta\delta_{se_k} \\ \Delta\delta_{se_l} \\ \Delta V_{se_k} \\ \Delta V_{se_l} \end{bmatrix}$$

For J5:
The equation $J_5 = \begin{bmatrix} \frac{\partial P}{\partial ipfc} \\ \frac{\partial Q}{\partial ipfc} \end{bmatrix}$ consists of the following elements:

$$\frac{\partial P_i}{\partial \delta_{se_i}} = V_i V_{se_i} Y_{im} sin(\theta_{im} + \delta_{se_i} - \delta_i) \ , i = k, l \quad (33)$$

$$\frac{\partial P_m}{\partial \delta_{se_i}} = -V_m V_{se_i} Y_{im} sin(\theta_{im} + \delta_{se_i} - \delta_m), i = k, l \quad (34)$$

$$\frac{\partial P_i}{\partial V_{se_i}} = -V_i Y_{im} cos(\theta_{im} + \delta_{se_i} - \delta_i) \ , i = k, l \quad (35)$$

$$\frac{\partial P_m}{\partial V_{se_i}} = V_m Y_{im} cos(\theta_{im} + \delta_{se_i} - \delta_m), i = k, l \quad (36)$$

$$\frac{\partial Q_i}{\partial \delta_{se_i}} = V_i V_{se_i} Y_{im} cos(\theta_{im} + \delta_{se_i} - \delta_i) \ , i = k, l \quad (37)$$

$$\frac{\partial Q_m}{\partial \delta_{se_i}} = -V_m V_{se_i} Y_{im} cos(\theta_{im} + \delta_{se_i} - \delta_m), i = k, l \quad (38)$$

$$\frac{\partial Q_i}{\partial V_{se_i}} = V_i Y_{im} sin(\theta_{im} + \delta_{se_i} - \delta_i) \ , i = k, l \quad (39)$$

$$\frac{\partial Q_m}{\partial V_{se_i}} = -V_m Y_{im} sin(\theta_{im} + \delta_{se_i} - \delta_m), i = k, l \quad (40)$$

For J6:
The equation $J_6 = \frac{\partial f_{ipfc}}{\partial \delta}$ consists of the following elements:

$$\frac{\partial P_{d1}}{\partial \delta_k} = V_k V_m Y_{km} sin(\theta_{km} + \delta_m - \delta_k) - V_k V_{se_k} Y_{km} sin(\theta_{km} + \delta_{se_k} - \delta_k) \quad (41)$$

$$\frac{\partial P_{d1}}{\partial \delta_m} = -V_k V_m Y_{km} sin(\theta_{km} + \delta_m - \delta_k) \quad (42)$$

$$\frac{\partial P_{se_{net}}}{\partial \delta_i} = -V_i V_{se_i} Y_{im} sin(\theta_{im} + \delta_{se_i} - \delta_i) \ , i = k, l \quad (43)$$

$$\frac{\partial P_{se_{net}}}{\partial \delta_m} = \sum_{i=k,l} V_m V_{se_i} Y_{im} sin(\theta_{im} + \delta_{se_i} - \delta_m) \quad (44)$$

$$\frac{\partial Q_{d1}}{\partial \delta_k} = V_k V_m Y_{km} cos(\theta_{km} + \delta_m - \delta_k) - V_k V_{se_k} Y_{km} cos(\theta_{km} + \delta_{se_k} - \delta_k) \quad (45)$$

$$\frac{\partial Q_{d1}}{\partial \delta_m} = -V_k V_m Y_{km} cos(\theta_{km} + \delta_m - \delta_k) \quad (46)$$

$$\frac{\partial P_{d2}}{\partial \delta_l} = V_l V_m Y_{lm} sin(\theta_{lm} + \delta_m - \delta_l) - V_l V_{se_l} Y_{lm} sin(\theta_{lm} + \delta_{se_l} - \delta_l) \quad (47)$$

$$\frac{\partial P_{d2}}{\partial \delta_m} = -V_l V_m Y_{lm} sin(\theta_{lm} + \delta_m - \delta_l) \quad (48)$$

For J7:
The equation $J_7 = \frac{\partial f_{ipfc}}{\partial V}$ consists of the following elements:

$$\frac{\partial P_{d1}}{\partial V_k} = -2V_k Y_{km} cos(\theta_{km}) + V_m Y_{km} cos(\theta_{km} + \delta_m - \delta_k) - V_{se_k} Y_{km} cos(\theta_{km} + \delta_{se_k} - \delta_k) \quad (49)$$

$$\frac{\partial P_{d1}}{\partial V_m} = V_k Y_{km} cos(\theta_{km} + \delta_m - \delta_k) \quad (50)$$

$$\frac{\partial P_{se_{net}}}{\partial V_i} = -V_{se_i} Y_{im} cos(\theta_{im} + \delta_{se_i} - \delta_i) \ , i = k, l \quad (51)$$

$$\frac{\partial Q_{d1}}{\partial V_k} = 2V_k Y_{km} sin(\theta_{km}) - V_m Y_{km} sin(\theta_{km} + \delta_m - \delta_k) + V_{se_k} Y_{km} sin(\theta_{km} + \delta_{se_k} - \delta_k) \quad (52)$$

$$\frac{\partial Q_{d1}}{\partial V_m} = -V_k Y_{km} sin(\theta_{km} + \delta_m - \delta_k) \quad (53)$$

$$\frac{\partial P_{d2}}{\partial V_l} = -2V_l Y_{lm} cos(\theta_{lm}) + V_m Y_{lm} cos(\theta_{lm} + \delta_m - \delta_l) - V_{se_l} Y_{lm} cos(\theta_{lm} + \delta_{se_l} - \delta_l) \quad (54)$$

$$\frac{\partial P_{d2}}{\partial V_m} = V_l Y_{lm} cos(\theta_{lm} + \delta_m - \delta_l) \quad (55)$$

For J8:
The equation $J_8 = \frac{\partial f_{ipfc}}{\partial ipfc}$ consists of the following elements:

$$\frac{\partial P_{d1}}{\partial \delta_{se_k}} = V_k V_{se_k} Y_{km} sin(\theta_{km} + \delta_{se_k} - \delta_k) \quad (56)$$

$$\frac{\partial P_{se_{net}}}{\partial \delta_{se_i}} = V_i V_{se_i} Y_{im} sin(\theta_{im} + \delta_{se_i} - \delta_i) - V_m V_{se_i} Y_{im} sin(\theta_{im} + \delta_{se_i} - \delta_m), i = k, l \quad (57)$$

$$\frac{\partial Q_{d1}}{\partial \delta_{se_k}} = V_k V_{se_k} Y_{km} cos(\theta_{km} + \delta_{se_k} - \delta_k) \quad (58)$$

$$\frac{\partial P_{d2}}{\partial \delta_{se_l}} = V_l V_{se_l} Y_{lm} sin(\theta_{lm} + \delta_{se_l} - \delta_l) \quad (59)$$

$$\frac{\partial P_{d1}}{\partial V_{se_k}} = -V_k Y_{km} cos(\theta_{km} + \delta_{se_k} - \delta_k) \quad (60)$$

$$+V_m Y_{im} sin(\theta_{im} + \delta_{se_i} - \delta_m), i = k, l \quad (61)$$

$$\frac{\partial Q_{d1}}{\partial V_{se_k}} = V_k Y_{km} sin(\theta_{km} + \delta_{se_k} - \delta_k) \quad (62)$$

$$\frac{\partial P_{d2}}{\partial V_{se_l}} = -V_l Y_{lm} cos(\theta_{lm} + \delta_{se_l} - \delta_l) \quad (63)$$

3.2.3. The third approach

The second approach could be modified to comply the IPFC definition. IPFC is defined as "combination of two or more static synchronous series compensators (SSSCs) which are coupled via a common dc link to facilitate bi-directional flow of real power between the ac terminals of the SSSCs and are controlled to provide independent reactive compensation for the adjustment of real power flow in each line and maintain the desired distribution of reactive power flow among the lines" [17-19].

This definition and the IPFC principle of operation show that the IPFC function is to:-

- Control the 1st line active power flow Pd1
- Control reactive power flows in both lines Qd1 , Qd2
- Maintain the total injected power to be zero based on the idea of maintaining constant common DC link and no active power source $P_{se_{net}} = 0$

The suggested modification considers the control parameter Qd2 to replace Pd2 control parameter considered in the conventional second approach. Then the equations related to Pd2 will be replaced with its corresponding relations of Qd2 as follows:-

$$f_{ipfc} = \begin{bmatrix} P_{d1} \\ P_{se_{net}} \\ Q_{d1} \\ Q_{d2} \end{bmatrix}, \Delta ipfc = \begin{bmatrix} \Delta\delta_{se_k} \\ \Delta\delta_{se_l} \\ \Delta V_{se_k} \\ \Delta V_{se_l} \end{bmatrix} \quad (64)$$

For J6:

$$\frac{\partial Q_{d2}}{\partial \delta_l} = V_l V_m Y_{lm} \cos(\theta_{lm} + \delta_m - \delta_l) - V_l V_{se_l} Y_{lm} \cos(\theta_{lm} + \delta_{se_l} - \delta_l) \quad (65)$$

$$\frac{\partial Q_{d2}}{\partial \delta_m} = -V_l V_m Y_{lm} \cos(\theta_{lm} + \delta_m - \delta_l) \quad (66)$$

For J7:

$$\frac{\partial Q_{d2}}{\partial V_l} = 2V_l Y_{lm} \cos(\theta_{lm} + \delta_m - \delta_l) - V_m Y_{lm} \cos(\theta_{lm} + \delta_m - \delta_l) + V_{se_l} Y_{lm} \cos(\theta_{lm} + \delta_{se_l} - \delta_l) \quad (67)$$

$$\frac{\partial Q_{d2}}{\partial V_m} = -V_l Y_{lm} \sin(\theta_{lm} + \delta_m - \delta_l) \quad (68)$$

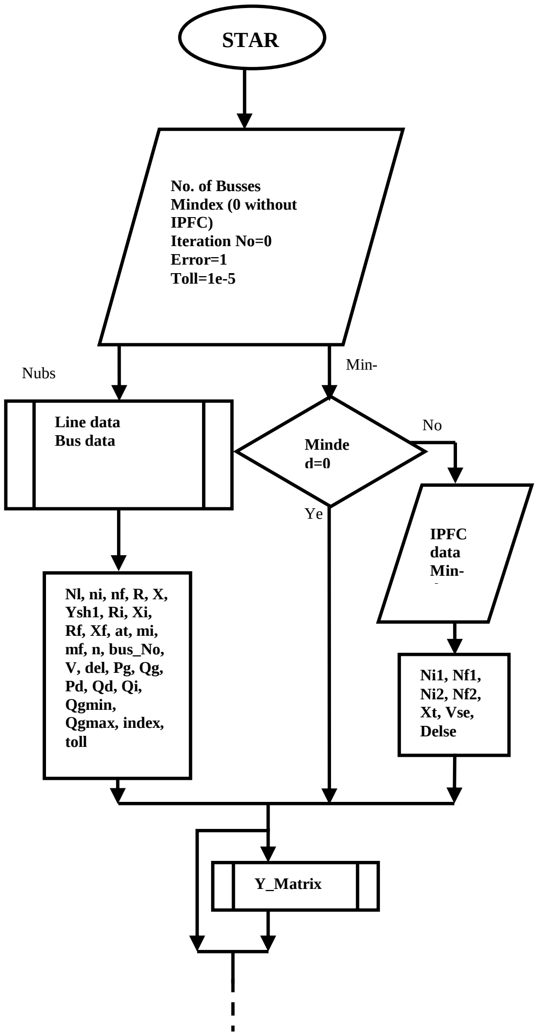
For J8:

$$\frac{\partial Q_{d2}}{\partial \delta_{se_l}} = V_l V_{se_l} Y_{lm} \cos(\theta_{lm} + \delta_{se_l} - \delta_l) \quad (69)$$

$$\frac{\partial Q_{d2}}{\partial V_{se_l}} = V_l Y_{lm} \sin(\theta_{lm} + \delta_{se_l} - \delta_l) \quad (70)$$

4. Simulation model and verification

Simulation model must have the same performance of the actual system to guarantee that all of the results are true. The accuracy is very important in simulation process. Flow chart, given in figure 3, shows the flow of idea in the main program of the simulation model. M-File MATLAB program is the tool presented to simulate the mathematical model of the power system with and without IPFC.



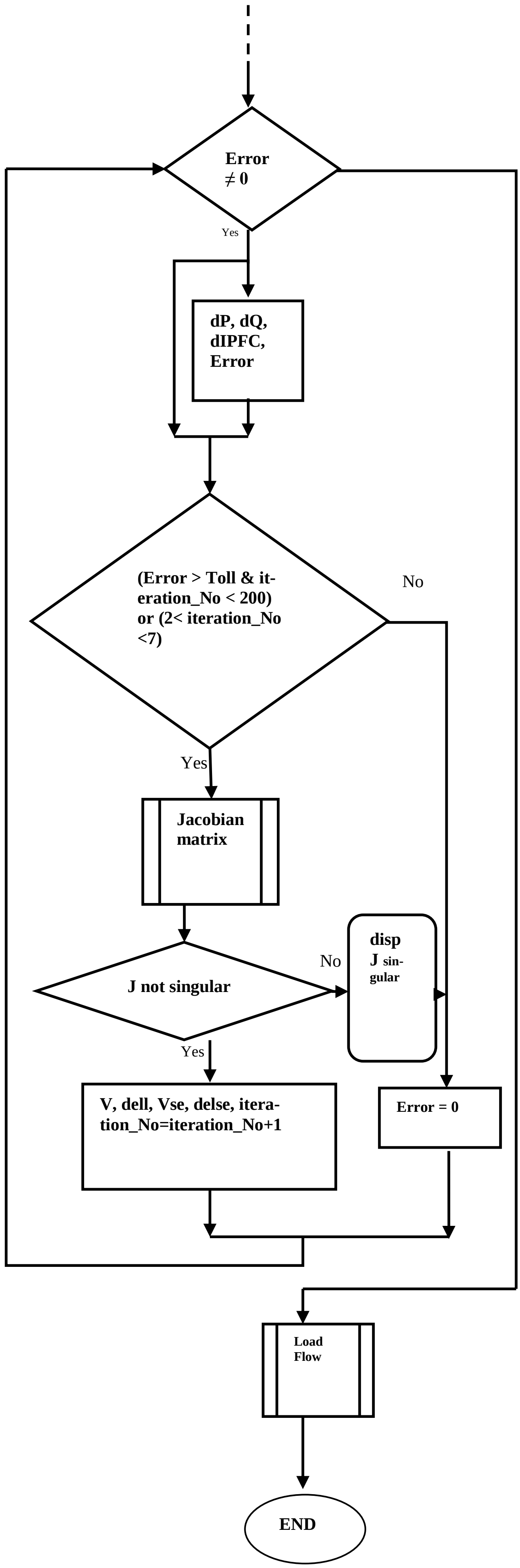


Fig. 3: Main Program Flow Chart.

Verification is very important step after building the simulation model. In this part, verification is performed in two steps; the first one is for the system without IPFC and the second step is for the system with IPFC installed.

4.1. Model verification for the system without IPFC

The standard IEEE 5-Bus test system is shown in Figure 4. Bus 1 is considered as slack bus, while bus 2 as generator bus and other buses are load buses. System base MVA is 100 [7].

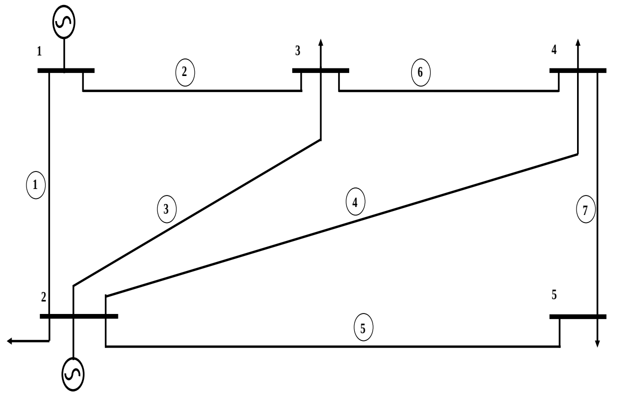


Fig. 4: Standard IEEE 5-Bus System.

Applying the standard IEEE 5-Bus test system data to the main program, the output of the program compared to the results mentioned in [6] for the system without IPFC is shown in the following table:-

Table 1: Main Program Verification for the System without IPFC

Bus No.	Program output		[6]	
	V in pu	δ º	V in pu	δ º
1	1.06	0	1.06	0
2	1	-2.0612	1	-2.06
3	0.9872	-4.6367	0.987	-4.64
4	0.9841	-4.957	0.984	-4.96
5	0.9717	-5.7649	0.972	-5.77

The program output and the results presented in [6] are identical. To verify the load flow function the active power flow data from the program and from [6] is shown below.

Table 2: Load Flow Function Verification for the System without IPFC

Line No.	Program o/p	[6]
	Active Power Flow (MW)	Active Power Flow (MW)
1	89.331	89.331
2	41.791	41.791
3	24.473	24.473
4	27.713	27.713
5	54.66	54.66
6	19.386	19.386
7	6.598	6.598

The function output and the results presented in [6] are identical.

4.2. Model verification for the system with IPFC

Reference [6] presented the standard IEEE 5-Bus system with IPFC installed between lines 4 and 6 as shown in the following figure:-

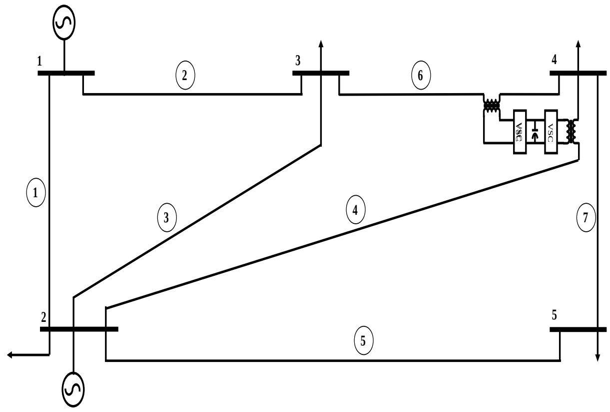


Fig. 5: Standard IEEE 5-Bus System with IPFC.

Applying the same case presented in [6] to the simulation main program, the output of the program compared to the results mentioned in [6] for the system without IPFC is as follow:-

Table 3: Main Program Verification for the System with IPFC

Bus No.	Program o/p		[6]	
	V in pu	δ º	V in pu	δ º
1	1.06	0	1.06	0
2	1	-2.0046	1	-2.004
3	0.9842	-4.7586	0.986	-4.787
4	0.9943	-3.7937	0.995	-3.799
5	0.9754	-5.3277	0.976	-5.328

The program output and the results presented in [6] are very close. To verify the load flow function the active power flow data from the program and from [6] is shown below.
For table 4, the function output and the results presented in [6] are very close. Then the derived model is verified to be applicable with power systems equipped or not equipped with IPFC.

Table 4: Load Flow Function Verification for the System with IPFC

Line No.	Program o/p	[6]
	Active Power Flow (MW)	Active Power Flow (MW)
1	87.741	87.714
2	42.944	42.945
3	26.462	26.435
4	29.86	29.867
5	48.971	48.964
6	22.368	22.369
7	12.133	12.14

5. Case study and results

In this section, numerical results are carried out on standard power systems to give a comparison between the three approaches in terms of network bus voltage (magnitude and angle), series injected voltage (magnitude and angle), No. of iterations and the error.
Three standard IEEE test networks are tested to support the comparison between the three approaches. IEEE 5, 14 and 30-Bus systems equipped with IPFC device are studied and the results are given in tables 5, 6 and 7.

Table 5: Three Approaches Results for 5-Bus Systems

V			Del		
1st approach	2nd approach	3rd approach	1st approach	2nd approach	3rd approach
1.06	1.06	1.06	0	0	0
1	1	1	-2.0423	-2.0421	-2.0421
0.9854	0.9854	0.9854	-4.6621	-4.6623	-4.6623
0.9883	0.9883	0.9883	-4.6487	-4.626	-4.626
0.9732	0.9732	0.9732	-5.6451	-5.6374	-5.6374
Vse			Delse		
0.0094	0.0094	0.0094	70.9732	70.9732	70.9718
0.0106	0.0106	0.0106	44.0423	43.9498	43.9493
Iteration No.			Error		
8	8	10	1.20E-14	5.79E-09	5.77E-06

Table 6: Three Approaches Results for 14-Bus Systems

V			Del		
1st approach	2nd approach	3rd approach	1st approach	2nd approach	3rd approach
1.06	1.06	1.06	0	0	0
1.045	1.045	1.045	-4.9856	-4.9856	-4.9856
1.01	1.01	1.01	-12.7389	-12.7389	-12.7389
1.0157	1.0157	1.0157	-10.2879	-10.2879	-10.2879
1.0183	1.0183	1.0183	-8.7606	-8.7607	-8.7607
1.07	1.07	1.07	-14.2238	-14.2242	-14.2242
1.0595	1.0595	1.0595	-13.3431	-13.3428	-13.3428
1.09	1.09	1.09	-13.3431	-13.3428	-13.3428
1.0528	1.0528	1.0528	-14.9281	-14.9277	-14.9277
1.0483	1.0483	1.0483	-15.0886	-15.0884	-15.0884
1.0555	1.0556	1.0556	-14.7859	-14.786	-14.786
1.0536	1.0536	1.0536	-15.2203	-15.2207	-15.2207
1.0511	1.0511	1.0511	-15.0701	-15.071	-15.071
1.0327	1.0327	1.0327	-16.0656	-16.0642	-16.0642
Vse			Delse		
0.0084	0.0084	0.0084	37.8188	37.8188	37.8195
0.0032	0.0032	0.0032	20.1971	20.2186	20.2189
Iteration No.			Error		
8	8	8	3.57E-15	6.03E-07	5.22E-07

Table 7: Three Approaches Results for 30-Bus Systems

V			Del		
1st approach	2nd approach	3rd approach	1st approach	2nd approach	3rd approach
1.06	1.06	1.06	0	0	0
1.043	1.043	1.043	-5.3468	-5.3468	-5.3468
1.0216	1.0216	1.0216	-7.5457	-7.5457	-7.5457
1.0129	1.0129	1.0129	-9.3001	-9.3001	-9.3001
1.01	1.01	1.01	-14.1522	-14.1522	-14.1522
1.0121	1.0121	1.0121	-11.0846	-11.0846	-11.0846
1.0035	1.0035	1.0035	-12.8705	-12.8705	-12.8705
1.01	1.01	1.01	-11.7993	-11.7993	-11.7993
1.051	1.051	1.051	-14.1299	-14.1299	-14.1299
1.0443	1.0443	1.0443	-15.7253	-15.7253	-15.7253
1.082	1.082	1.082	-14.1299	-14.1299	-14.1299
1.0574	1.0574	1.0574	-14.977	-14.977	-14.977
1.071	1.071	1.071	-14.977	-14.977	-14.977
1.0419	1.0419	1.0419	-15.9211	-15.9211	-15.9211
1.0379	1.0379	1.0379	-15.9367	-15.9367	-15.9368
1.0446	1.0446	1.0446	-15.5661	-15.5661	-15.5661
1.0391	1.0391	1.0391	-15.8848	-15.8848	-15.8848
1.028	1.028	1.028	-16.5999	-16.5999	-16.5998
1.0253	1.0253	1.0253	-16.7633	-16.7633	-16.7633
1.0293	1.0293	1.0293	-16.5611	-16.5611	-16.561
1.032	1.032	1.032	-16.1737	-16.1737	-16.1737
1.0326	1.0326	1.0326	-16.1611	-16.1611	-16.1611
1.0272	1.0272	1.0272	-16.3482	-16.3482	-16.3482
1.0213	1.0213	1.0213	-16.5531	-16.5531	-16.5531
1.0179	1.0179	1.0179	-16.2229	-16.2229	-16.2229
1.0003	1.0003	1.0003	-16.6421	-16.6421	-16.6421
1.0244	1.0244	1.0244	-15.7587	-15.7587	-15.7587
1.0108	1.0108	1.0108	-11.7324	-11.7324	-11.7324
1.0046	1.0046	1.0046	-16.9858	-16.9858	-16.9858
0.9931	0.9931	0.9931	-17.8665	-17.8665	-17.8665
Vse			Delse		
0.0028	0.0028	0.0028	37.2731	37.2731	37.2845
0.0006	0.0006	0.0006	79.8267	79.7924	80.262
Iteration No.			Error		
8	9	8	1.42E-14	3.9575E-07	9.5167E-07

The following points are shown from the results

- The desired bus voltages could be reached by any of the three approaches because they implemented the same mathematical model and solution technique
- The first approach is the most converged approach (small No. of iterations with very small error) as it works like an open loop controlled device
- As large was the power system as most converged the third approach unlike the second approach

Table 8: Gives A Concluded Comparison Between the Three Approaches

Item	1st approach	2nd approach	3rd approach
Characteristics	Looks like an open loop controlled device	• Commonly used • Gives a degree of closed loop control • Apply dependant control parameters	• Proposed by the authors • Comply the IPFC definition • Gives a degree of closed loop control • Apply independent parameters
Convergence	Highly converged	Decrease with system complexity	Increase with system complexity
Function	Used to define the device power ratings	• Used as power flow limiter • Used to study the device behavior in power systems	• Used as power flow limiter • Used to study the device behavior in power systems

6. Conclusion

The paper has tackled three approaches for power system equipped with IPFC device steady state modeling. The third approach is firstly proposed in this paper, this proposed model have the same mathematical model and solution technique of the second approach, it also complies the IPFC devise definition. First approach is the most converged one. First approach and at least one of the other two approaches are used to choose the compatible IPFC device in power systems.

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