APPLICATION OF AN INTERLINE POWER FLOW CONTROLLER AS AGC

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ABSTRACT

In recent years, power demand has increased substantially while the expansion of power generation and transmission. It has been severely limited due to limited resources and environmental limitations. As an outcome, some transmission lines are heavily loaded and the system stability becomes a power transfer-limiting factor. Flexible AC Transmission Systems (FACTS) controllers have been mainly used for solving various power system steady state control problems. Interline Power Flow Controller is a versatile device can be used to control power flows of a multi-line system or sub-networks. It can be anticipated that the IPFC may be used to solve the complex transmission network congestion management problems that transmission companies are now facing in the transmission open-access environment. A controller was proposed in the generation side of the power system. In order to obtain this objective, the Power Injection Model (PIM) is implemented into the modified IEEE 30-bus test system. The power optimization of the overall system can be obtained in the form of appropriate power transfer between the lines using the IPFC scheme, a new form of IPFC's utilization, that is, as an AGC actuator based on generation scheduling. The IPFC's model taking into account its practical constraints is implemented into the IEEE 30-bus test power system and programmed using the modified Newton-Rapson algorithm with MATLAB and the results are provided which indicates that IPFC can be used as an AGC.

Keywords: *AGC-Automatic Generation Controller, IPFC – Interline Power Flow Controller, VSC-Voltage Source Converter*

1. INTRODUCTION

As the consequence of fast growing demands on active and reactive power control and the rapid development of power electronic technology, power electronic based equipments, under the generic name of the Flexible Ac Transmission Systems (FACTS) devices, are being developed in the field of modern power systems. Most FACTS devices have demonstrated their ability to significantly increase the transmission capabilities of the network and considerably enhance the security of the system, because they can control most parameters related to the operation of transmission systems with a quick response. Now FACTS technology is regarded as one of emerging technologies for power system security improvement. Since power system stability is an important problem for secure system operation and transient instability has been the dominant stability problem with the majority systems, transient stability enhancement, which is one of the main applications of FACTS devices, has been attracting much interest of researchers, utilities and manufacturers. Among all the FACTS devices, the combined compensators such as the Unified Power Flow Controller (UPFC) and the Interline Power Flow Controller (IPFC) are regarded as the most powerful and versatile ones [1]. Both the UPFC and IPFC are based on the self commutated, voltage-sourced switching converters (VSCs) coupled via a common DC voltage link.

Unlike the UPFC, the IPFC employs at least two VSCs respectively connected in series with different lines, which can address the problem of compensating multiple transmission lines at a given substation. Compared with shunt compensators, series compensators are more effective in controlling the transmitted power, which is closely related to power system transient stability [5]. Thus, Static Series Compensators and combined compensators would be a better choice to improve transient stability and to damp the electromechanical oscillations. Various studies have been carried out on this topic, however, there is very few open literature on the application of

IPFC to the power system transient stability improvement.

2. FACTS TECHNOLOGY

The FACTS technology is not represented by a single high-power controlling device, but it is a collection of all the controllers, these individually or in coordination with the others give the possibility to fast control one or more of the interdependent parameters that influence the operation of transmission networks. These parameters include e.g. the line series impedance, the nodal voltage amplitude, the nodal voltage angular difference, then the shunt impedance and the line current. The design of the different schemes and configurations of FACTS devices is based on the combination of traditional power system components (such as transformers, reactors, switches, and capacitors) with power electronics elements (such as various types of transistors and Thyristors). The development of FACTS controllers is strictly related to the progress made by the power electronics. Over the last years, the current rating of thyristors has evolved into higher nominal values making power electronics capable of high power applications for the limit of tens, hundreds and thousands MW [13].

In general, FACTS devices can be traditionally classified according to their connection, as,

Shunt controllers:

The main devices of shunt controllers are the Static VAR Compensator (SVC) and the Static Synchronous Compensator (STATCOM).

Series controllers:

It includes the devices like the Thyristor Controlled Series Capacitor (TCSC) and the Static Synchronous Series Compensator (SSSC).

Combined controllers:

Elements such as the Thyristor Controlled Phase Shifting Transformer (TCPST), the Interline Power Flow Controller (IPFC), the Unified Power Flow Controller (UPFC) and the Dynamic Flow Controller (DFC) belong to this third category of FACTS.

FACTS devices are also classified according to the power electronics technology used for the converters as,

Thyristor-based controllers:

This includes the FACTS devices based on thyristors, namely the SVC, the TCSC, the TCPST and the DFC.

Voltage source-based controllers:

These devices are based on more advanced technology like Gate Turn-Off (GTO) Thyristors, Insulated Gate Commutated Thyristors (IGCT) and Insulated Gate Bipolar Transistors (IGBT). This group includes the STATCOM, the SSSC, the IPFC and the UPFC [11].

2.1 Need for Facts Device

Since the development of interconnection of large electric power systems, it has been the spontaneous system oscillations at very low frequencies in the range of 0.2–3.0 Hz. After starts, it would continue for a long period of time. In certain cases, it continues to develop causing system separation due to the lack of damping of the mechanical modes. In the past three decades, Power System Stabilizers (PSSs) have been extensively used to increase the system damping for low frequency oscillations. The power utility worldwide is currently implementing PSSs as effective excitation controllers to enhance the system stability. Yet, some problems are experienced with PSSs over the years of operation. Some of these were limited to the capability of PSS, due to damping in local modes and not in the inter-area modes of oscillations. In accumulation, it can cause huge variations in the voltage profile under severe disturbances and they may even result in leading power factor operation and losing system stability. It has necessitate a review of the traditional power system concepts and practices to achieve a larger stability margin, better operational flexibility, and better utilization of existing power systems. Flexible AC transmission systems (FACTS) have gained a great interest during the last few years, due to the recent techniques in power electronics. FACTS devices are mainly used for solving various power system steady state control problems such as voltage regulation, transfer capability enhancement and power flow control. As supplementary functions, damping the inter-area modes and enhancing power system stability using FACTS controllers have been extensively studied and investigate. Generally, it is not cost-effective to install FACTS devices for the sole purpose of power system stability enhancement.

3. INTERLINE POWER FLOW CONTROLLER

Recent developments of FACTS research have led to a new device: the Interline Power Flow Controller (IPFC). This element consists of two (or more) series voltage source converter-based devices (SSSCs) installed in two (or more) lines and connected at their DC terminals. Thus, in addition to serially compensate the reactive power, each SSSC can provide real power to the common DC link from its own line. The IPFC gives them the possibility to solve the problem of controlling different transmission lines at a determined substation. In fact, the under-utilized lines make available a surplus power which can be used by other lines for real power control. This capability makes it possible to equalize both real and reactive power flow between the lines, to transfer power demand from overloaded to under-loaded lines, to compensate against resistive line voltage drops and the corresponding reactive line power, and to increase the effectiveness of a compensating system for dynamic disturbances (transient stability and power oscillation damping). Therefore, the IPFC provides a highly effective scheme for power transmission at a multi-line substation. The IPFC is a multi-line FACTS device [11].
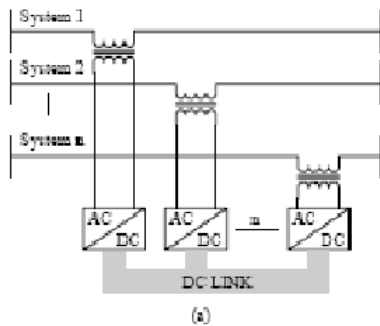

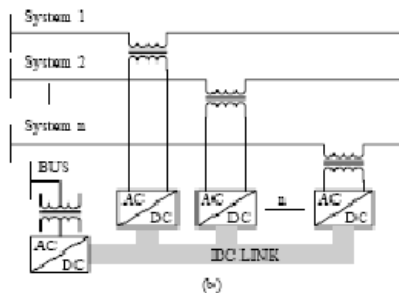*Figure 1: Schematic diagram of IPFC Without shunt converter*

Figure 2: Schematic diagram of IPFC With shunt converter

An Interline Power Flow Controller (IPFC) consists of a set of converters that are connected in series with different transmission lines. The schematic diagram of IPFC is illustrated in Figure.1. In addition to these series converters, it may also include a shunt converter which is connected between a transmission line and the ground. The converters are connected through a common DC link to exchange active power. Each series converter can provide independent reactive compensation of own transmission line. If a shunt converter is involved in the system, the series converters can also provide independent active compensation; otherwise not all the series converters can provide independent active compensation for their own line. Compared to the Unified Power Flow Controller (UPFC), the IPFC provides a relatively economical solution for multiple transmission line power flow control, since only one shunt converter is involved [9]. The IPFC also gains more control capability than the Static Synchronous Series Compensator (SSSC), which is like the IPFC but without a common DC link, because of the active compensation. From probabilistic point of view, the performance of the IPFC will be better when more series converter involves in to the IPFC system. However, because the converters are connected through the common DC link, the converters should be physically close to each other. The common DC link will become a location constrain for the IPFC and limits its commercial application in the future network. Therefore, a method which can eradicate the IPFC common DC link and provide the active power exchange between converters will be interesting.

3.1. 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 comprise a number of Static Synchronous Series Compensators (SSSC) [4].
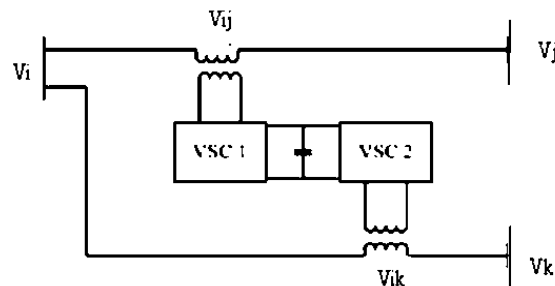

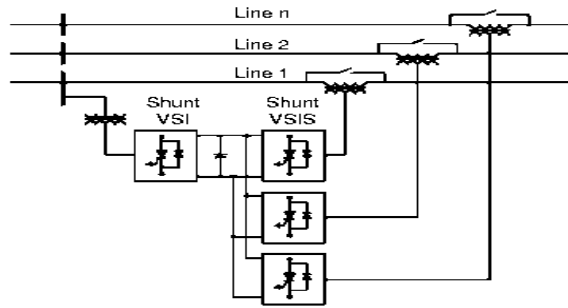*Figure 3: IPFC with back-to-back DC-to-AC converters*

Figure 4: Elementary of IPFC

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 3. With this IPFC, in addition to providing series reactive compensation, some converter can be controlled to supply real power to the common DC link from its own transmission line [13].
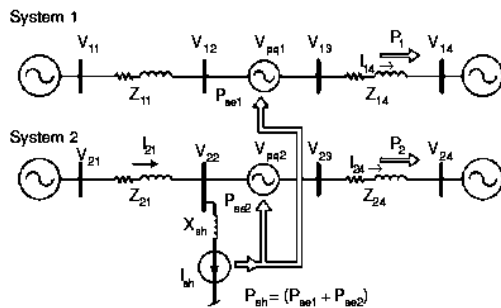

Figure 5: IPFC basic Configuration for Multi-Line Power Flow Control

3.2 IPFC and Power Network Model:

An Interline Power Flow Controller (IPFC Figure 4.) is a combination of two or more independent controllable Static Synchronous Series Compensators (SSSC) are solid-state voltage source converters which inject an almost sinusoidal voltage at variable magnitude and couples via a common DC link. After the effect of compensation by the mathematical equations the net reactive power is zero by the power balance method. The analysis developed here considers an IPFC connected to two balanced independent AC systems (Figure 5). If the buses V_{11} and V_{21} are merged having more than two compensated lines, the scheme would reflect the case of a multi-line substation from which power is dispatched to different receiving-ends. For analysis, the

equivalent sending and receiving end sources in both systems are regarded as stiff AC sources (infinite buses). It is also assumed that systems 1 and 2 have identical line parameters.

Under the IPFC configuration ($P_{sh} = 0$, $Q_{sh} = 0$), the system 2 will be termed as a secondary system, since it will have to provide the series real power demanded by the primary system. In the case of a conventional IPFC scheme, the real power exchange of converter 2 is pre-defined (i.e, there exists a constraint for line 2) and therefore, only its series reactive compensation controls the power flow in this line. Under the IPFC configuration system 1 will have two independently controlled variables (i.e., V_{pq1}, θ_{pq1}). Conversely, system 2, which will have to provide the series real power demanded by system 1, will only have one variable (V_{q2}) to be independently controlled [7].

The IPFC model developed here is based on the d-q orthogonal coordinates, which proved to be suitable for the steady-state analysis. Each converter in the analyzed system was regarded as a shunt or series source operating with fundamental frequency and characterized by ideal sinusoidal waveforms [10]. The steady-state power equality between the shunt and series inverters is applied to the model. Thus, it can be established that:

$$P_{sh} = \Sigma P_{sei} \qquad (1)$$

In equation (1), i stand for the total number of series converters. Here i = 2, therefore,

$$P_{sh} = V_{22} I_{shd} + V_{22} I_{shq} \qquad (2)$$
$$P_{se1} = V_{p1} I_{14d} + V_{q1} I_{shq} \qquad (3)$$

$$P_{se2} = V_{p21} I_{24d} + V_{q2} I_{shq} \qquad (4)$$

The reactive power injected (absorbed) by the shunt converter can be expressed as,
$$Q_{sh} = V_{22d} I_{shq} - V_{22q} I_{shd} \qquad (5)$$

From the circuit considered (Figure 3.4.), the following relation can also be established:
$$V_{22}(d,q) + V_{pq2} = Z_{24} I_{24}(d,q) + V_{24}(d,q) \qquad (6)$$

Similarly for system 1,
$$V_{12}(d,q) + V_{pq}1 = Z14 I_{14}(d,q) + V_{14}(d,q) \qquad (7)$$

The V_p component in equations (6) and (7) corresponds to the direct axis component of the series voltages. The shunt current can be defined as,

$$I_{sh} = \sqrt{(I_{shd}^2 + I_{shq}^2)} \qquad (8)$$

whose angle is given by,

$$\theta_{sh} = \tan^{-1}(I_{shd}/I_{shq}) \qquad (9)$$

Then, the equation (8) can be written at bus V_{22} as,

$$I_{sh}(d,q) = I_{21}(d,q) - I_{24}(d,q) \qquad (10)$$

To resolve the above expressions two more additional expressions are needed, thus,

$$V_{21}(d,q) - V_{24}(d,q) + V_{pq2} = Z_{21} I_{21}(d,q) + Z_{24} I_{24}(d,q) \qquad (11)$$

$$V_{11}(d,q) - V_{14}(d,q) + V_{pq1} = (Z_{11} + Z_{14}) I_{14}(d,q) \qquad (12)$$

Manipulating the above expressions, a set of 10 equations will be obtained (some of them non-linear) that can be solved using any iterative method. Once computed the unknown variables (i.e., the d-q components of the V_{12}, V_{22}, I_{sh}, I_{14}, I_{24}), the power flow in the receiving-end of systems 1 and 2, without or with the series and shunt compensation effect, can be calculated.

$$S_1 = (P_1 + jQ_1) = V_{14} I_{14}' \qquad (13)$$

$$S_2 = (P_2 + jQ_2) = V_{24} I_{24} \qquad (14)$$

As in this case, the shunt VSI will no longer be present in the secondary system, some of the variables in the above equations will have to be zeroed (i.e., $I_{shd} = 0$, $I_{shq} = 0$ and $Q_{sh} = 0$), thus, leaving only one variable (V_{q2}) in system 2 to be independently controlled.

4. POWER FLOW ANALYSIS OF IPFC

In this situation, assuming a loss free IPFC operation and neglecting the resistance in the voltage source impedances, IPFC and coupling transformers shown in Figure 6. can be modeled means of a load at buses i , j and k if the IPFC is connected at the lines i-f and i-h which j and k are the dummies buses to connect the IPFC [5]. This is shown in Figure 6.

The sending end, the first receiving end and the second receiving end of the IPFC are transformed into PQ buses. The active and the reactive power loads in the bus j and the active power load in the bus k are set to the values being controlled by the IPFC (i.e. P_{ji}, Q_{ji}, P_{ki}). Q_{ki} is calculated during the load flow. A usual load flow solution is carried out with the equivalent model given in Figure 7. After load flow convergence a

set of nonlinear equations is solved by iteration to compute the IPFC control variables (i.e. V_{ser1}, θ_{ser1}, V_{ser2}, θ_{ser2}).

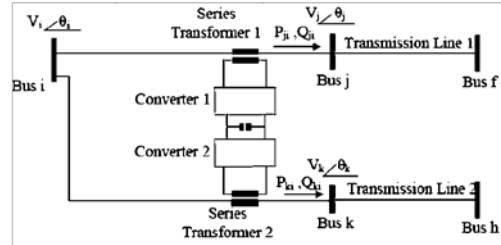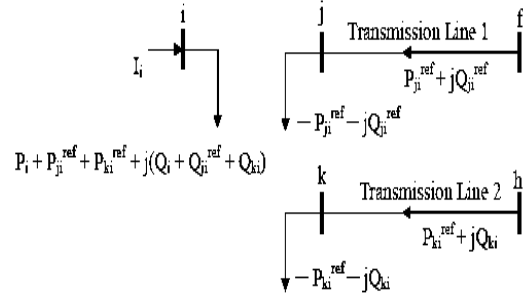*Figure 6: Basic Circuit Arrangement of IPFC*

Figure 7: IPFC Model in Power Injection

The sending end, the first receiving end and the second receiving end of the IPFC are transformed into PQ buses. The active and the reactive power loads in the bus j and the active power load in the bus k are set to the values being controlled by the IPFC (i.e. P_{ji}, Q_{ji}, P_{ki}). Q_{ki} is calculated during the load flow. A usual load flow solution is carried out with the equivalent model given in Figure 7. After load flow convergence a set of nonlinear equations is solved by iteration to compute the IPFC control variables (i.e. V_{ser1}, θ_{ser1}, V_{ser2}, θ_{ser2}).

4.1 Power Flow Solution of IPFC

Based on the equivalent circuit in Figure and neglecting the resistance in the voltage source impedances, the active and reactive power equations are:

At node i:

$$P_i = V_i V_j B_{ij} \sin(\theta_i - \theta_j) + V_i V_k B_{ik} \sin(\theta_i - \theta_k) + V_i V_{ser1} B_{ij} \sin(\theta_i - \theta_{ser1}) + V_i V_{ser2} B_{ik} \sin(\theta_i - \theta_{ser2}) \qquad (15)$$

$$Q_i = -V_i^2 B_{ii} - V_i V_j B_{ij} \sin(\theta_i - \theta_j) - V_i V_k B_{ik} \sin(\theta_i - \theta_k) - V_i V_{ser1} B_{ij} \sin(\theta_i - \theta_{ser1}) - V_i V_{ser2} B_{ik} \sin(\theta_i - \theta_{ser2}) \qquad (16)$$

At node j:

$P_j = V_iV_jB_{ij} \sin(\theta_j-\theta_i) + V_jV_{ser1}B_{jj} \sin(\theta_j-\theta_{ser1})$ (17)

$Q_j = -V_j^2B_{jj} - V_iV_jB_{ji}\sin(\theta_j-\theta_i) - V_jV_{ser1}B_{ji} \sin(\theta_j-\theta_{ser1})$

(18)

At node k:

$P_k = V_iV_kB_{ki} \sin(\theta_k-\theta_i) + V_kV_{ser1}B_{ki} \sin(\theta_k-\theta_{ser2})$

(19)

$Q_k = -V_k^2B_{kk} - V_iV_kB_{ki}\sin(\theta_k-\theta_i)$
$\qquad\qquad -V_kV_{ser2}B_{ki} \sin(\theta_k-\theta_{ser2})$

(20)

Series converter 1:

$P_{ser1} = V_iV_{ser1}B_{ij} \sin(\theta_{ser1}-\theta_i)$
$\qquad\qquad +V_jV_{ser1}B_{jj}\sin(\theta_{ser1}-\theta_j)$

(21)

$Q_{ser1} = -V_{ser1}^2B_{jj} - V_{ser1}V_jB_{ji}\sin(\theta_{ser1}-\theta_i)$
$\qquad\qquad - V_jV_{ser1}B_{jj} \sin(\theta_{ser1}-\theta_j)$ (22)

Series converter 2:

$P_{ser2} = V_iV_{ser2}B_{ik} \sin(\theta_{ser2}-\theta_i)$
$\qquad\qquad + V_kV_{ser2}B_{kk} \sin(\theta_{ser2}-\theta_k)$ (23)

$Q_{ser2} = -V_{ser2}^2B_{kk} - V_{ser2}V_kB_{ki}\sin(\theta_{ser2}-\theta_i)$
$\qquad\qquad - V_kV_{ser2}B_{kk} \sin(\theta_{ser2}-\theta_k)$

(24)

Where

$B_{ii} = -2X_{ser}^{-1}, \quad B_{jj} = B_{kk} = -X_{ser}^{-1}, \quad B_{ij} = B_{ji} = X_{ser}^{-1},$

$B_{ik} = B_{ki} = X_{ser}^{-1}.$

Equations (15) to (24) represent the set of nonlinear equations that are required to obtain the IPFC control variables after power flow solution. A set of nonlinear equations can be solved using the Newton - Raphson technique as follow [6]:

(Step-1) After the convergence of the power flow program, the voltage magnitudes and phase angles at buses I , j and k (i.e. V_i , θ_i , Vj , θ_j , V_k , θ_k) are obtained.

(Step-2) Assume suitable initial values for the IPFC control variables, V_{ser1}^0, θ_{ser1}^0, V_{ser2}^0 and θ_{ser2}^0.

(Step-3) Substitute in equations (1), (2), (3) and (5) to obtain $P_{i,\,cal}$, $Q_{i,\,cal}$, $P_{j,\,cal}$ and $P_{k,\,cal}$ respectively.

(Step-4) Solve the following linearized equation

$[f(x)] = [J] [\Delta X]$ (25)

Where, [f (x)] is the power mismatch and the superscript T indicates transposition.

[ΔX] is the solution vector and [J] is the Jacobian matrix.

$[f(x)] = [\ \Delta P_i\ \Delta P_j\ \Delta P_k\ \Delta Q_i\ ]^T$ (26)

$= [-\ P_{ref1} -\ P_{ref2}\ -\ P_{i,cal}\ P_{ref1}\ -P_{j,cal}\ P_{ref2}\ -P_{k,cal}$
$Q_{ref} -\ Q_{i,cal}\ ]^T$

$[\Delta X] = [\ \Delta V_{ser2}\ \Delta\theta_{ser1}\ \Delta\theta_{ser2}\ \Delta V_{ser1}\ ]^T$ (27)

$$J = \begin{bmatrix} \dfrac{\partial Pi}{\partial Vser2} & \dfrac{\partial Pi}{\partial\theta ser1} & \dfrac{\partial Pi}{\partial\theta ser2} & \dfrac{\partial Pi}{\partial Vser1} \\[2ex] \dfrac{\partial Pj}{\partial Vser2} & \dfrac{\partial Pj}{\partial\theta ser1} & \dfrac{\partial Pj}{\partial\theta ser2} & \dfrac{\partial Pj}{\partial Vser1} \\[2ex] \dfrac{\partial Pk}{\partial Vser2} & \dfrac{\partial Pk}{\partial\theta ser1} & \dfrac{\partial Pk}{\partial\theta ser2} & \dfrac{\partial Pk}{\partial Vser1} \\[2ex] \dfrac{\partial Qi}{\partial Vser2} & \dfrac{\partial Qi}{\partial\theta ser1} & \dfrac{\partial Qi}{\partial\theta ser2} & \dfrac{\partial Qi}{\partial Vser1} \end{bmatrix}$$ (28)

After solving equation (25), it is possible to update the values of the IPFC control variables using equation (26)

$X^1 = X^0 + \Delta X$ (29)

Where X represent any of the IPFC control variables (V_{ser1} , θ_{ser1} , θ_{ser2} , V_{ser2}).

(Step-6) Repeat steps 3 to 5 for several iterations, at each iteration make check on convergence that causes the required mismatch.

(Step-7) After the convergence, it is possible to determine the IPFC ratings using equations (7), (8), (9) and (10).

4.2 Test System

Numerical results are carried out on the IEEE 30-bus test system shown in Figure 8 and the system and line data are taken from reference [9].
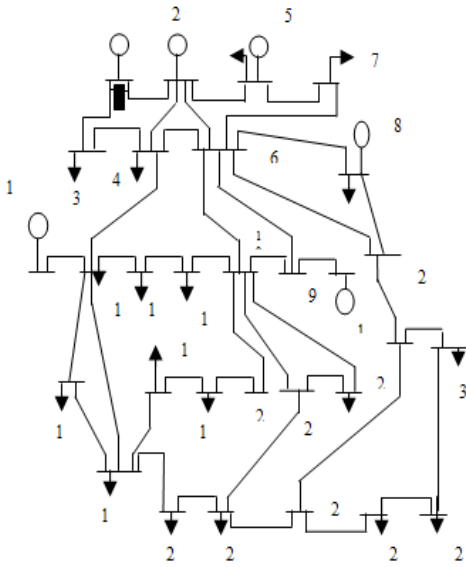
Figure 8: Single-line Circuit Diagram of the IEEE 30-Bus System

4.3 Modeling of IPFC for Power Flow Studies

In the following section, a model for IPFC which will be referred as IPFC injection model is derived. It is helpful in understanding the impact of the IPFC on the power system in steady state [11]. Furthermore, the IPFC injection model can easily be incorporated in steady state power flow model. Since the series voltage source converters do the main function of the IPFC.

4.3.1 IPFC Model Based on Two Voltage Source Representation

An IPFC can be represented in steady-state conditions by two voltage sources representing fundamental components of output voltage waveforms of the two converters and impedances being the leakage reactance of the two coupling transformers [6][7].
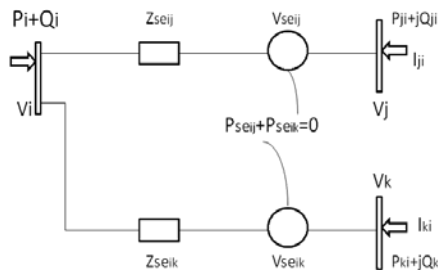

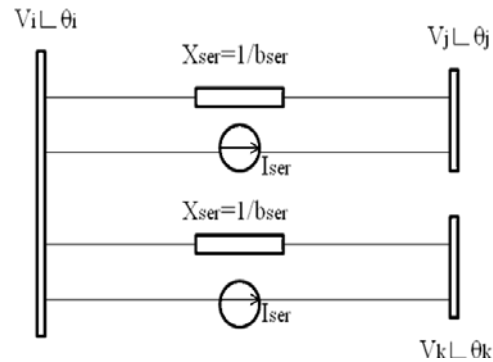*Figure 9: Representation of Two Series Connected Voltage Sources*

Figure 10: Replacement of Two Series Voltage Sources By Two Current Sources

Figure.10 depicts a two voltage-source model of an IPFC. The two voltage sources, V_{ser} are controllable in both magnitudes and phase angles. V_{ser} should be defined as:

$$V_{ser} = r \, V_i \, e^{j\gamma} \qquad (30)$$

The values of r and γ are defined within specified limits given by equations (31). The variables are represented certain percent of the voltage magnitude Vi at bus i.

$$0 \le r \le r_{max} \text{ and } 0 \le \gamma \le 2\pi \qquad (31)$$

The steady-state IPFC mathematical injection model is developed by replacing voltage source V_{ser} by a current source I_{ser} parallel with a susceptance $b_{ser} = 1/X_{ser}$. Therefore, the series current I_{ser} is defined by:

$$I_{ser} = -j \, b_{ser} \, V_{ser} \qquad (32)$$

The current source I_{ser} can be modeled by injected power at the three buses i , j and k which the IPFC is connected as shown in Figure 7.

The current sources I_{ser} corresponds to the injection powers S_{iser} , S_{jser} and S_{kser} where:

$$S_{iser} = 2V_i \, (-I_{ser})^* \qquad (33)$$

$$S_{jser} = V_j \, (I_{ser})^* \qquad (34)$$

$$S_{kser} = V_k \, (I_{ser})^* \qquad (35)$$

The injection powers S_{iser} , S_{jser} and S_{kser} are simplified to:

$$S_{iser} = 2 \, V_i \, [\, j \, b_{ser} \, r \, V_i \, e^{j\gamma}\,]^*$$
$$= -2 \, b_{ser} \, r \, V_i^2 \sin\gamma - j \, 2 \, b_{ser} \, r \, Vi^2 \cos\gamma \qquad (36)$$
$$P_{iser} = -2 \, b_{ser} \, r \, V_i^2 \sin\gamma \qquad (37)$$
$$Q_{iser} = -2 \, b_{ser} \, r \, V_i^2 \cos\gamma \qquad (38)$$

If we define $\theta_{ij} = \theta_i - \theta_j$ and $\theta_{ik} = \theta_i - \theta_k$ we have:

$S_{jser} = V_j \, [- j \, b_{ser} \, r \, V_i \, e^{j\gamma} \,]^* \qquad = b_{ser} \, r \, V_i \, V_j$

$\sin (\theta_{ij} + \gamma) + j \, b_{ser} \, r \, V_i \, V_j \, \cos (\theta_{ij} + \gamma)$

(39)

$$P_{jser} = b_{ser} \, r \, V_i \, V_j \, \sin (\theta_{ij} + \gamma) \qquad (40)$$

$$Q_{jser} = b_{ser} \, r \, V_i \, V_j \, \sin (\theta_{ij} + \gamma) \qquad (41)$$

$$S_{kser} = V_k \, [- j \, b_{ser} \, r \, V_i \, \theta_j \gamma \,]$$

$$= b_{ser} \, r \, V_i \, V_k \, \sin (\theta_{ik} + \gamma) + j \, b_{ser} \, r \, V_i \, V_k$$

$\cos (\theta_{ik} + \gamma)$ (42)

$$P_{kser} = b_{ser} \, r \, V_i \, V_k \, \sin (\theta_{ik} + \gamma) \qquad (43)$$

$$Q_{kser} = b_{ser} \, r \, V_i \, V_k \, \cos (\theta_{ik} + \gamma) \qquad (44)$$

Based on the justification above, the injection model of two series connected voltage sources can be seen as three dependent loads as shown in Figure 11.
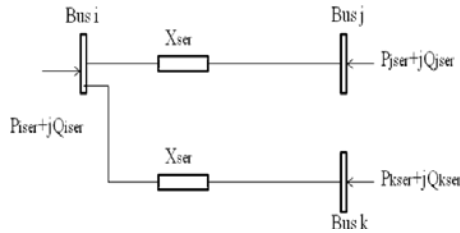

Figure 11: IPFC model

The apparent power supplied by the two series voltage sources are calculated from:

$$S_{ser1} = V_{ser} \, I_{ij}^* \; = r \, e^{j\gamma} \, V | \; (V_i' - V_j) \, / \, jX|_{ser}^{\;*} \qquad (45)$$

$$S_{ser2} = V_{ser} \, I_{ik}^* = r \, e^{j\gamma} \, V | \; (V_i' - V_j) \, / \, jX|_{ser}^{\;*} (46)$$

Active power and reactive power supplied by converters 1 and 2 are distinguished as:

$$P_{ser1} = r \, b_{ser} \, V_i \, V_j \, \sin (\theta_{ij} + \gamma) - r \, b_{ser} \, V_i^2 \, \sin \gamma$$

(47)

$$Q_{ser1} = - r \, b_{ser} \, V_i \, V_j \, \cos (\theta_{ij} + \gamma) + r \, b_{ser} \, V_i^2 \, \cos \gamma$$
$$+ \; r^2 \, b_{ser} \, V_i^2 \qquad (48)$$

$$Q_{ser2} = - r \, b_{ser} \, V_i \, V_k \, \cos (\theta_{ik} + \gamma) + r \, b_{ser} \, V_i^2 \, \cos \gamma$$
$$+ r^2 \, b_{ser} \, V_i^2 \qquad (49)$$

According to the operating principle of the IPFC, the operating constraint will represent the active power exchange among the converters via the common DC link is given by, the equality above is valid when the losses are not neglected.

$$P_{ser2} = - P_{ser1} \qquad (50)$$

Table 1: IPFC Input Parameters

From	To	P	Q	From	To	P	Q	Line Loss	
Bus	Bus	MW	MVar	Bus	Bus	MW	MVar	MW	MVar
1	2	173.143	-18.108	2	1	-167.964	33.617	5.179	15.509

5. RESULT AND DISCUSSION

The load flow equations are solved by the simultaneous method using the Newton-Raphson technique, which has good convergence characteristics. The results are presented for modified IEEE-30 bus test system. The table 5.1 shows the result of IEEE-30 bus test systems voltage(p.u),angle(deg),power injection, power Generation and load data using Newton-Raphson power flow programming.

IPFC Result

IPFC installed to control the active power flow of the line 1-2, the active power and the reactive power flow of the line 1-3. Table (5.3) and (5.4) show the IPFC control variables and its IPFC results respectively by IPFC model. Here we focus on the steady-state modeling of IPFC for the implementation of the device in the conventional power flow program using injection power flow IPFC model. The injected power flow IPFC model is based on the representation of IPFC in steady-state conditions by two voltage sources each are in series with a certain reactance [2]. A MATLAB conventional N-R power flow program has been modified in order to incorporate the injection power IPFC model in a power flow program [9].

Table 2: IPFC Control Variable

Table 3: IPFC Results in IEEE-30 Bus Test System

6. CONCLUSION

The IPFC can equalize both real and reactive power flow in lines, relieve the overloaded lines from the burden of reactive power flow, compensate against resistive as well as reactive voltage drops, and provide a concerted multi-line counter measure during dynamic disturbance. IPFC inserted into the modified IEEE-30 bus test system. Also, using the programming with MATLAB software, power flow of test system in presence of IPFC is carried out. The results are arranged in three tables. The results show the capability of IPFC utilization as an AGC actuator. In other words, from the tables, it observes that IPFC can maintain frequency at or close to the nominal value, control the power flow between some control areas and maintain each unit. 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..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.

V_{ser1} (p.u)	θ_{ser1}(deg)	V_{ser2} (p.u)	θ_{ser2}(deg)
0.0153	348.662	0.0206	185.239

P_{ser1} (MW)	Q_{ser1} (MVar)	P_{ser2} (MW)	Q_{ser2} (MVar)	Del_{ser1}	Del_{ser2}
-0.0191	-0.0642	0.0238	0.0013	348.65	185.239

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