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Power Flow Management Through Interline Power Flow Controller

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Abstract : *The problem of reactive power compensation and flow of power through the lines can be addressed with the help of new generation FACTS controllers. There are various FACTS controllers and can be classified on the basis of their connection in the circuit line such as series, shunt and series-shunt controllers. Some specific controllers are also used in conjunction with voltage source controllers, avoiding the need of bulky capacitor banks. UPFC is one such FACTS controller which finds need in transmission line where series converter of the UPFC injects via series transformer, an ac voltage with controllable magnitude and phase angle in series with the transmission line. The shunt converter supplies or absorbs the real power demanded by the series converter through the common dc link. Interline Power Flow Controller is another device, unique in the sense that it provides the balance of reactive and active power between two lines of the same substation through its voltage source converters connected in series with the two lines and a common DC Link. In this paper a model of IPFC using Newton power flow algorithm has been discussed.*

Keywords: *IPFC, FACTS, Power Flow, Reactive Power Control*

I. Introduction

Transmission Lines are characterized by four components namely series inductance, resistance, shunt-capacitance and conductance. The series inductance is responsible for the absorption of the reactive power whereas the shunt capacitance is responsible for the generation of reactive power [1]

Load compensation and voltage support are the two areas which need to be addressed here. Load compensation is practiced to increase the system power factor, to balance the real power drawn from the ac supply, compensate voltage regulation and to eliminate current harmonic components produced by large and fluctuating nonlinear industrial loads. Voltage support is required to reduce voltage fluctuation at a given terminal of a transmission line. Maximum transmittable active power can be enhanced by reactive power compensation. Series shunt and combination of series - shunt VAR compensation are used very often. Series compensation modifies the transmission or distribution system parameters, while shunt compensation changes the equivalent impedance of the load. It was common to use Traditional VAR Generators like fixed capacitors or mechanically switched capacitors and Synchronous Condensers The next advancement was Thyristorised VAR Compensators, Thyristor-Switched Capacitors, Thyristor-Controlled Reactor and Combined TSC and TCR providing the facility of stepped fine tuned and smooth switching. With the advent of self commutated Voltage source controlled (VSC) VAR compensators, bulky capacitor banks are avoided. Static Synchronous Compensator (STATCOM), Static Synchronous Series Compensator (SSSC), Dynamic Voltage Restorer (DVR), Unified Power Flow Controller (UPFC) and Superconducting Magnetic Energy Storage (SMES) are developed and put to application [2].

The all above devices are used to compensate reactive power in a transmission line. However an idea of Interline Power Flow Controller (IPFC) pertaining to the transmission system where two or more that two lines originating from the same substation could be linked to balance the load between overloaded and under loaded lines. A model of IPFC from the point of view of flow of Power is discussed and analyzed in this paper [3].

II. Facts Devices In Context Of Power Flow Control

Limitations of Conventional Compensators like lack of dynamic and transient performance, occurrence of severe overvoltage, very less frequency of operation and large switching period, increased losses and adverse effect in power system economy during light load conditions etc, provided further motivation for development of FACTS based devices [4].

'FACTS' is defined by the IEEE as "a power electronic based system and other static equipment that provide control of one or more AC transmission system parameters to enhance controllability and increase power transfer capability [5].

With the advent of high speed switching semiconductor devices like GTOs, the voltage source converters have find use in various FACTS devices for reactive power control and for stabilization of Electrical power system. FACTS devices exhibit characteristics such as Rapid dynamic response, Ability for frequent variations in output and smoothly adjustable output. FACTS are a family of devices, which can be inserted into power grids in series, in shunt, and in some cases, both in shunt and series. Important applications in power transmission and distribution involve devices such as SVC (Static VAR Compensators), Fixed Series Capacitors (SC) as well as Thyristor-Controlled Series Capacitors (TCSC) and STATCOM. FACTS mainly find applications in the areas of Power Transmission, Power Quality, Power Flow Control, Voltage Control, Reactive Power Compensation, Power Conditioning, Flicker Mitigation, Railway Grid Connection, Wind Power Grid Connection and Cable Systems. These first ones are Fixed or Mechanically Switched Capacitors, Synchronous Condensers, Thyristorised VAR Compensators, Thyristor-Switched Capacitors, Thyristor-Controlled Reactor, Combined TSC and TCR, Thyristor Controlled Series Compensation, Self-Commutated VAR Compensators [6].

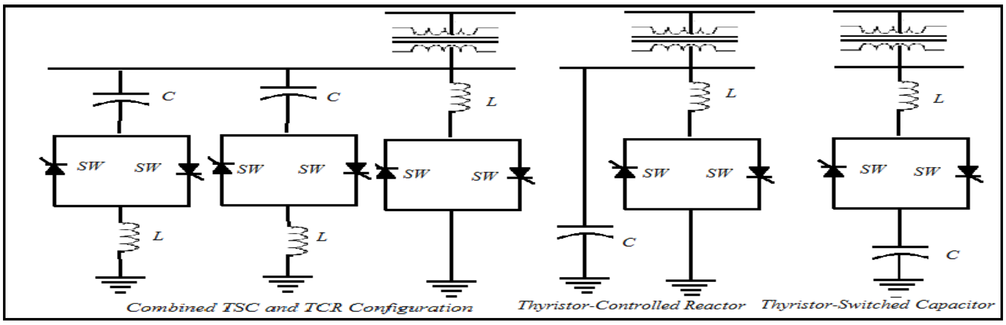


Fig.1 Conventional Thyristor controlled or switched Devices for reactive Power Compensation

The application of self-commutated converters as a means of compensating reactive power has demonstrated to be an effective solution. This technology has been used to implement more sophisticated compensator equipment such as static synchronous compensators, unified power flow controllers (UPFCs), IPFCs and dynamic voltage restorers (DVRs) [7].

III. Interline Power Flow Controller (Ipfc)

3.1 Principles of Operation of the IPFC Systems

Two Systems: 1 and 2 are assumed as shown in figure 2. . In this scheme IPFC consists of two back-to-back, series connected voltage source dc to ac inverters. Each of the series inverters controls power flow by injecting fully controllable voltages V_{c1} and V_{c2}. This can be shown functionally also in single line diagram, where two back-to-back dc to ac inverters are represented by voltage sources V_{c1} and V_{c2}. System 1 is represented by reactance X_1, has a sending-end bus with voltage phasor V_{11} and receiving-end bus with voltage V_{21}. Respectively System 2 is represented by reactance X_2 and voltage phasors V_{21} and V_{22}. Let's determine equation on power which series inverter (for example in System 1) cannot generate internally. For this purpose we have to define voltage phasors: [8]

$$V_{11} = V_{11}\cos\phi_{11} + jV_{11}\sin\phi_{11} \tag{1}$$

$$V_{21} = V_{21}\cos\phi_{21} - jV_{21}\sin\phi_{21} \tag{2}$$

$$V_{c1} = V_{c1}\cos\phi_{c1} + jV_{c1}\sin\phi_{c1} \tag{3}$$

On the base of those equations we can define active and reactive components of current:

$$I_{lp} = \frac{V_{11}\sin\varphi_{11} + V_{21}\sin\varphi_{21} + V_{Cq1}}{X_1} \tag{4}$$

$$I_{lp} = \frac{V_{21}\cos\varphi_{21} - V_{11}\cos\varphi_{11} - V_{Cp1}}{X_1} \tag{5}$$

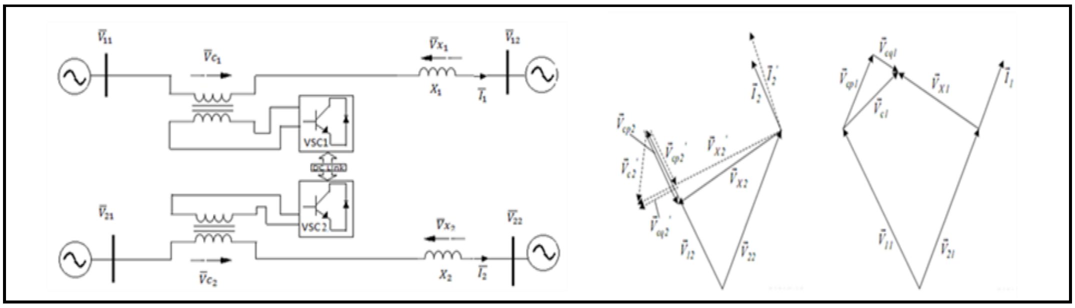


Fig. 2: IPFC Scheme (Two Systems 1 and 2 shown above) and Phasor

After simply transformations equations on active and reactive powers transmitted to the receiving-end bus are as follows: $P_{21} = \frac{V_{21}V_{11}}{X_1}(\cos\varphi_{21}\sin\varphi_{11} + \cos\varphi_{11}\sin\varphi_{21}) + \frac{V_{21}V_{cl}}{X_1}(\cos\varphi_{21}\sin\varphi_{cl}\} + \frac{V_{21}V_{cl}}{X_1}(\sin\varphi_{21}\cos\varphi_{cl})$

$$OR \quad P_{21} = \frac{V_{21}V_{11}}{X_1}\sin\delta_1 + V_{cql} + V_{cpl} \tag{6}$$

$$Q_{21} = \frac{V_{21}V_{11}}{X_1}(\cos\varphi_{21}\cos\varphi_{11} - \sin\varphi_{21}\sin\varphi_{11}) - \frac{V^2{}_{21}}{X_1} + \frac{V_{21}V_{c1}}{X_1}(\cos\varphi_{21}\cos\varphi_{cl}) - \frac{V_{21}V_{c1}}{X_1}(\sin\varphi_{21}\sin\varphi_{cl})$$

$$OR \quad Q_{21} = \frac{V_{21}V_{11}}{X_1}\cos\delta_1 - \frac{V^2{}_{21}}{X_1} + V_{cpl} - V_{cql} \tag{7}$$

Some additional parts in equations give the idea of what the contribution of the active V_{cp1} is and reactive V_{cq1} components on power delivered to the receiving-end bus. IPFC has to control both active and reactive power delivered to the receiving-end bus. Let's determine desired powers as follows:

$$P^*_{21} = \text{Constant} \tag{8}$$

$$Q^*_{21} = 0 \tag{9}$$

On the base of this equation we can tell that:

$$P^*{}_{21} = \frac{V_{21}V_{11}}{X_1}\sin\delta_1 + \frac{V_{21}V_{cql}}{X_1} \tag{10}$$

$$Q^*{}_{21} = \frac{V_{21}V_{11}}{X_1}\cos\delta_1 - \frac{V^2{}_{21}}{X_1} + \frac{V_{21}V_{cql}}{X_1} = 0 \tag{11}$$

$$I_{lp} = \frac{V_{11}\sin\delta_1 + V_{cql}}{X_1} \tag{12}$$

$$I_{lq} = \frac{V_{21} - V_{11}\cos\delta_1 - V_{cql}}{X_1} = 0 \tag{13}$$

$$V_{cpl} = \left[Q^*{}_{21} + \frac{V^2{}_{21}}{X_1} - \frac{V_{21}V_{11}}{X_1}\cos\delta_1\right]\frac{X_1}{V_{21}} \tag{14}$$

$$V_{cql} = \left[P^*{}_{21} + \frac{V^2{}_{21}}{X_1} - \frac{V_{21}V_{11}}{X_1}\sin\delta_1\right]\frac{X_1}{V_{21}} \tag{15}$$

So the active power demand of the series inverter's in ith system is

$$P_{IPFC1} = I_{p1}V_{cp1} = (V_{21} - V_{11}\cos\delta_1)\frac{P^*{}_{21}}{V_{21}} \tag{16}$$

When $P_{IPFC1} > 0$, System 1 absorbs active power from System 2;
When $P_{IPFC1} < 0$, System 2 sends active power to System 2;
System 2 (or System 1) can keep P_{IPFC} = cons., Even controlling its own power flow, (Fig.3).

$$P_{Parallel} = \sum_{i=1}^{n}\left[\left(1 - \frac{V_{11}^{\min}}{V_{21}^{\max}}\cos\delta_i^{\max}\right)\frac{P_{21}^{\max}}{V_{21}^{\max}}\right]. \text{ Concept of IPFC} \tag{17}$$

An Interline Power Flow Controller (IPFC), shown in Fig. 3, consists of two series VSCs, whose DC capacitors are coupled, allowing active power to circulate between different power lines. When operating below its rated capacity, the IPFC is in regulation mode, allowing of the P and Q flows on one line, and the P flow on the other line. In addition, the net active power generation by the two coupled VSCs is zero, neglecting power losses.

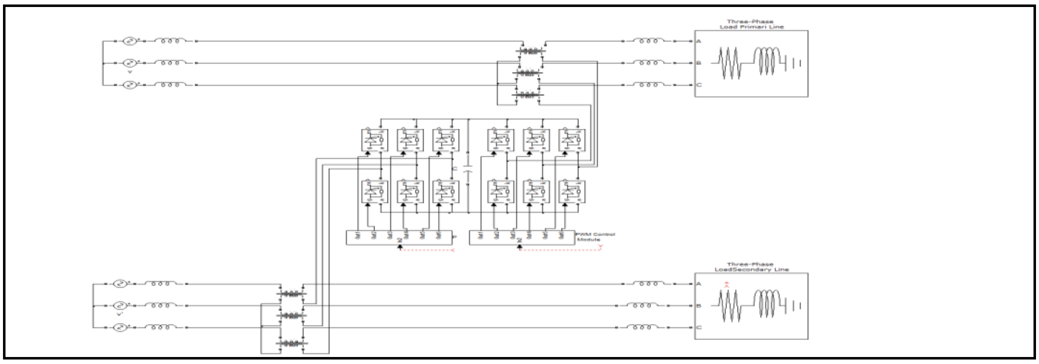


Fig. 3 IPFC Power Circuit Topology.

3.2 IPFC Steady-State Model Development

The operating conditions and power flow will be expressed by the following controls and equations where V_{c1n} is series voltage injected by IPFC connected between buses 1 and n, where n=j, k, n≠i. The interline power Flow Controller and the equivalent circuit shown in figure 4[9].

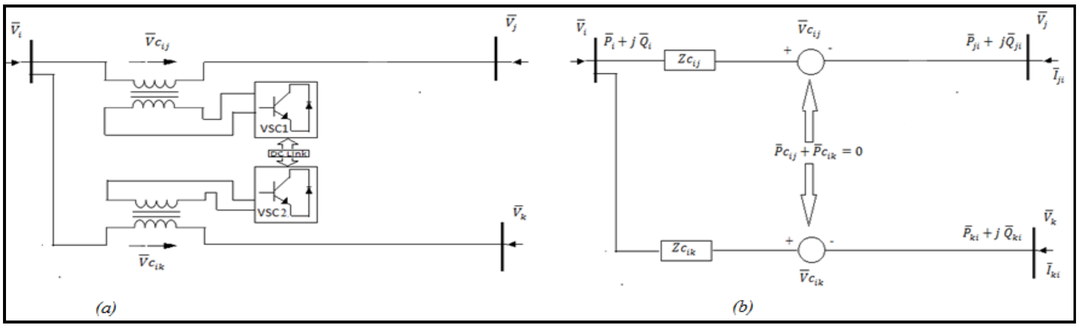


Fig 4. IPFC Model (a) and Equivalent Single Line Circuit (b)

The Voltage Constraints:

$$V_{c1n}^{min} \le V_{c1n} \le V_{c1n}^{max}, -\pi \le \theta_{c1n} \le \pi \qquad (18)$$

The Power Constraints:

$$P_{ni} - P_{ni}^{s} = 0, Q_{ni} - Q_{ni}^{s} = 0 \qquad (19)$$

$$P_d = \sum_n Pc_{in} = 0,\ n=j,\ k,\ n \ne i \qquad (20)$$

$$Pc_{in} = Re(Vc_{in}.Ic_{in}^{*}),\ n = j,\ k,\ n \ne i,\ Ic_{in}^{*}\ \ is\ conjugate\ of\ Ic_{in} \qquad (21)$$

$$Qc_{in} = Im(Vc_{in}.Ic_{in}^{*}),\ n = j,\ k,\ n \ne I \qquad (22)$$

$$P_i = V_i^2 g_{ii} - \sum_n V_i V_n (g_{in}\cos(\theta_i - \theta_n) + b_{in}\sin(\theta_i - \theta_n)) - \sum_n V_i Vc_{in}(g_{in}\cos(\theta_i - \theta c_{in}) + b_{in}\sin(\theta_i - \theta c_{in})) \qquad (23)$$

$$Q_i = -V_i^2 b_{ii} - \sum\ V_i V_n(-g_{in}\sin(\theta_i - \theta_n) + b_{in}\cos(\theta_i - \theta_n)) - \sum\ -V_i Vc_{in}(g_{in}\sin(\theta_i - \theta c_{in}) + b_{in}\cos(\theta_i - \theta c_{in})) \qquad (24)$$

$$P_{ni} = V_n^2 g_{nn} - V_i V_n(g_{in}\cos(\theta_n - \theta_i) + b_{in}\sin(\theta_n - \theta_i) + V_n Vc_{in}(g_{in}\cos(\theta_n - \theta c_{in}) + b_{in}\sin(\theta_n - \theta c_{in}) \qquad (25)$$

$$Q_{ni} = -V_n^2 b_{nn} - V_i V_n(g_{in}\sin(\theta_n - \theta_i) - b_{in}\cos(\theta_n - \theta_i)) + V_n Vc_{in}(g_{in}\sin(\theta_n - \theta c_{in}) - b_{in}\cos(\theta_n - \theta c_{in})) \qquad (26)$$

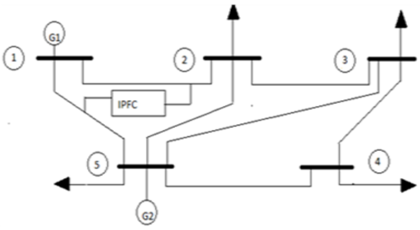
Where $\frac{1}{z_{c12}} = g_{12} + j\,b_{12}$, $\frac{1}{z_{c13}} = g_{13} + jb_{13}$, $\frac{1}{z_{c12}} = g_{12} + j\,b_{12}$, $\frac{1}{z_{c22}} = g_{22} + jb_{22}$, $\frac{1}{z_{c33}} = g_{33} + jb_{33}$

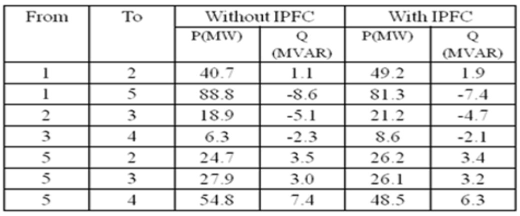
The Interline Power Flow Control with two series converters shown in figure 4 above is utilized to implement the basic principle of IPFC model in Newton power flow algorithm [10]. Taking into account all the power flow control constraints and bus power mismatch constraints, the compact form for three bus system is as follows:

$$\begin{pmatrix}
\frac{\partial P_{21}}{\partial \theta_{c12}} & \frac{\partial P_{21}}{\partial V_{c12}} & 0 & 0 & \frac{\partial P_{21}}{\partial \theta_1} & \frac{\partial P_{21}}{\partial V_1} & \frac{\partial P_{21}}{\partial \theta_2} & \frac{\partial P_{21}}{\partial V_2} & 0 & 0 \\
\frac{\partial Q_{21}}{\partial \theta_{c21}} & \frac{\partial Q_{21}}{\partial V_{c21}} & 0 & 0 & \frac{\partial Q_{21}}{\partial \theta_1} & \frac{\partial Q_{21}}{\partial V_1} & \frac{\partial Q_{21}}{\partial \theta_2} & \frac{\partial Q_{21}}{\partial V_2} & 0 & 0 \\
0 & 0 & \frac{\partial P_{31}}{\partial \theta_{c31}} & \frac{\partial P_{31}}{\partial V_{c31}} & \frac{\partial P_{31}}{\partial \theta_1} & \frac{\partial P_{31}}{\partial V_1} & 0 & 0 & \frac{\partial P_{31}}{\partial \theta_3} & \frac{\partial P_{31}}{\partial V_3} \\
\frac{\partial P_d}{\partial \theta_{c21}} & \frac{\partial P_d}{\partial V_{c21}} & \frac{\partial P_d}{\partial \theta_{c31}} & \frac{\partial P_d}{\partial V_{c31}} & \frac{\partial P_d}{\partial \theta_1} & \frac{\partial P_d}{\partial V_1} & \frac{\partial P_d}{\partial \theta_2} & \frac{\partial P_d}{\partial V_2} & \frac{\partial P_d}{\partial \theta_3} & \frac{\partial P_d}{\partial V_3} \\
\frac{\partial P_1}{\partial \theta_{c21}} & \frac{\partial P_1}{\partial V_{c21}} & \frac{\partial P_1}{\partial \theta_{c31}} & \frac{\partial P_1}{\partial V_{c31}} & \frac{\partial P_1}{\partial \theta_1} & \frac{\partial P_1}{\partial V_1} & \frac{\partial P_1}{\partial \theta_2} & \frac{\partial P_1}{\partial V_2} & \frac{\partial P_1}{\partial \theta_3} & \frac{\partial P_1}{\partial V_3} \\
\frac{\partial Q_1}{\partial \theta_{c21}} & \frac{\partial Q_1}{\partial V_{c21}} & \frac{\partial Q_1}{\partial \theta_{c31}} & \frac{\partial Q_1}{\partial V_{c31}} & \frac{\partial Q_1}{\partial \theta_1} & \frac{\partial Q_1}{\partial V_1} & \frac{\partial Q_1}{\partial \theta_2} & \frac{\partial Q_1}{\partial V_{c2}} & \frac{\partial Q_1}{\partial \theta_3} & \frac{\partial Q_1}{\partial V_3} \\
\frac{\partial P_2}{\partial \theta_{c21}} & \frac{\partial P_2}{\partial V_{c21}} & 0 & 0 & \frac{\partial P_2}{\partial \theta_1} & \frac{\partial P_2}{\partial V_1} & \frac{\partial P_2}{\partial \theta_2} & \frac{\partial P_2}{\partial V_2} & 0 & 0 \\
\frac{\partial Q_2}{\partial \theta_{v21}} & \frac{\partial Q_2}{\partial V_{c21}} & 0 & 0 & \frac{\partial Q_2}{\partial \theta_1} & \frac{\partial Q_2}{\partial V_1} & \frac{\partial Q_2}{\partial \theta_2} & \frac{\partial Q_2}{\partial V_2} & 0 & 0 \\
0 & 0 & \frac{\partial P_3}{\partial \theta_{c12}} & \frac{\partial P_3}{\partial V_{c12}} & \frac{\partial P_3}{\partial \theta_{c12}} & \frac{\partial P_3}{\partial V_{c12}} & 0 & 0 & \frac{\partial P_3}{\partial \theta_{c12}} & \frac{\partial P_3}{\partial V_{c12}} \\
0 & 0 & \frac{\partial Q_3}{\partial \theta_{31}} & \frac{\partial Q_3}{\partial V_{c31}} & \frac{\partial Q_3}{\partial \theta_1} & \frac{\partial Q_3}{\partial V_1} & 0 & 0 & \frac{\partial Q_3}{\partial \theta_3} & \frac{\partial Q_3}{\partial V_{c3}}
\end{pmatrix}
\times
\begin{pmatrix}
\Delta\theta_{c21} \\ \Delta V_{c21} \\ \Delta\theta_{c31} \\ \Delta V_{c31} \\ \Delta\theta_1 \\ \Delta V_1 \\ \Delta\theta_2 \\ \Delta V_2 \\ \Delta\theta_3 \\ \Delta V_3
\end{pmatrix}
=
\begin{pmatrix}
P_{21}^{s} - P_{21} \\ Q_{21}^{s} - Q_{21} \\ P_{31}^{s} - P_{31} \\ P_d \\ \Delta P_1 \\ \Delta Q_1 \\ \Delta P_2 \\ \Delta Q_2 \\ \Delta P_3 \\ \Delta Q_3
\end{pmatrix}$$

3.3 Case study and results

A five bus system has been taken for implementation of model and is presented in Fig 5. IPFC finds its random place between buses 1 and 5 with one converter injecting series controllable voltage in line 1-2 and another VSC in series with line 1-5.





From	To	Without IPFC		With IPFC	
		P(MW)	Q (MVAR)	P(MW)	Q (MVAR)
1	2	40.7	1.1	49.2	1.9
1	5	88.8	-8.6	81.3	-7.4
2	3	18.9	-5.1	21.2	-4.7
3	4	6.3	-2.3	8.6	-2.1
5	2	24.7	3.5	26.2	3.4
5	3	27.9	3.0	26.1	3.2
5	4	54.8	7.4	48.5	6.3

Fig 5: Five Bus System and Line Flows with and Without IPFC

IV. Conclusion

Thus from the results obtained and tabulated as shown in figure 5 above, it is evident that the mathematical model developed above is suitable for solution of implementation of Power Flow Control by IPFC, in case where more than two lines are emerging from a substation. The Newton power flow algorithm is used for convergence to the solution. The impedance of the converter, series transformer and the line susceptance are included in the model. The model can take into account the practical constraints of IPFC. Numerical results have shown the convergence of the IPFC model. The power flow control capability and the constraints enforcement of IPFC are also exhibited. Newton power flow program with this IPFC model is a useful tool for power system planning and operation control of large scale power system and may play an important role in solving potential problems such as transmission network congestion management etc.

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