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Power Quality Enhancement Using the Interline Power Flow Controller

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ABSTRACT

Interline power flow controller (IPFC) is one of the latest generation Flexible AC Transmission system (FACTS). It is able to control simultaneously the power flow of multiple transmission lines. This paper presents a study of the impact the IPFC on profile of voltage, real and reactive power flow in transmission line in power system. The results without and with IPFC are compared in terms of voltage and active power flows to demonstrate the performance of the IPFC model.

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1. INTRODUCTION

The most powerful and versatile FACTS devices is Interline Power Flow Controller (IPFC). It is capable to control at the same time the active and reactive power flow in the transmission line. It is a new member of FACTS controller which is conceived for the compensation and power flow management of multi-line transmission system [1-4].

Interline Power Flow Controller is one of the latest FACTS controller used to control power flow of multiple transmission line [5]. The simplest IPFC consists of two back-to-back, dc-to-ac converters namely Static Synchronous Series Compensators (SSSC), which are connected in series with two transmission lines through series coupling transformers, and the dc terminals of the converters are connected together via a common dc link as shown in Figure 1. This paper investigates the performance of IPFC in a power system network with a detailed mathematical model of IPFC which will be referred as IPFC power injection model as already presented. This model is helpful in understanding the impact of the IPFC on the power system in the steady state. Further, the IPFC injection model can easily be incorporated in the steady state power flow model and the proposed model is used to demonstrate the capabilities of IPFC. This paper shows also that the IPFC has the possibility of regulating voltage bus, active and reactive power flow, and minimizing the power losses simultaneously.

2. EQUIVALENT CIRCUIT OF IPFC

In its general form the IPFC employs a number of dc to ac each providing series compensation for a different line. In other words, the IPFC comprises a number of Static Synchronous Series Compensators

(SSSC) [4]. The IPFC obtained by combing two or more series-connected converters working together extends the concept of power flow control beyond what is achievable with the known one converter series FACTS devices –SSSC. A simplest IPFC, with three FACTS buses – *i, j* and *k* shown functionally in Figure 1, is used to illustrate the basic operation principle [6-7]. The IPFC consists of two converters being series-connected with two transmission lines via transformers. It can control three power system quantities - independent three power flows of the two lines. It can be seen that the sending-ends of the two transmission lines are series connected with the FACTS buses *j* and *k*, respectively.

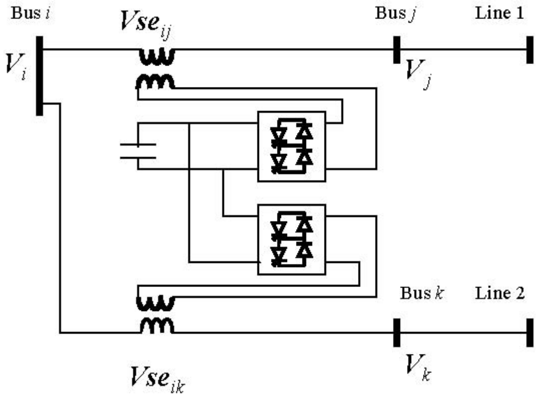

Figure 1. Equivalent circuit of two converters IPFC

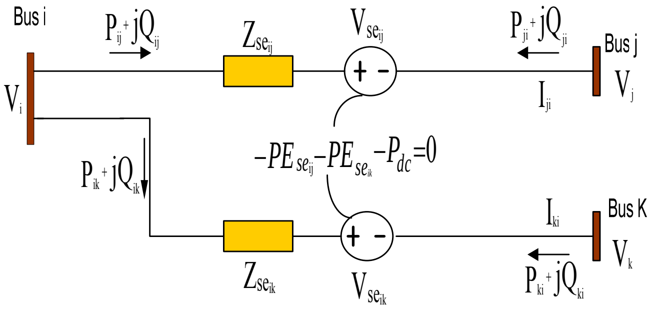

Figure 2. Power injection model of two converters IPFC

An equivalent circuit of the IPFC with two controllable series injected voltage sources is shown in Figure 2 [8-9]. The real power can be exchanged between or among the series converters via the common DC link while the sum of the real power exchange should be zero. Suppose in Figure 2, the series transformer impedance is$\boldsymbol{Z}se_{in}$, and the controllable injected voltage source is$\boldsymbol{V}se_{in} = \boldsymbol{V}se_{in}\angle\theta se_{in}$(n = *j*, *k*). Active and reactive power flows of the FACTS branches leaving buses *i*, *j*, *k*are given by:

$$P_{in} = V_i^2 g_{in} - V_i V_n (g_{in} cos\theta_{in} + b_{in} sin\theta_{in}) - V_i V_{se_{in}} (g_{in} \cos(\theta_i - \theta_{se_{in}}) + b_{in} \sin(\theta_i - \theta_{se_{in}})) \tag{1}$$

$$Q_{in} = -V_i^2 b_{in} - V_i V_n (g_{in} sin\theta_{in} + b_{in} cos\theta_{in}) - V_i V_{se_{in}} (g_{in} \sin(\theta_i - \theta_{se_{in}}) + b_{in} \cos(\theta_i - \theta_{se_{in}})) \tag{2}$$

$$P_{ni} = V_n^2 g_{in} - V_i V_n (g_{in} cos(\theta_n - \theta_i) + b_{in} \sin(\theta_n - \theta_i)) + V_n V_{se_{in}} (g_{in} \cos(\theta_n - \theta_{se_{in}}) + b_{in} \sin(\theta_n - \theta_{se_{in}})) \tag{3}$$

$$Q_{ni} = -V_n^2 b_{nn} - V_i V_n (g_{in} sin(\theta_n - \theta_i) - b_{in} cos(\theta_n - \theta_i) + V_n V_{se_{in}} (g_{in} \sin(\theta_n - \theta_{se_{in}}) + b_{in} \cos(\theta_n - \theta_{se_{in}})) \tag{4}$$

$$P_i = V_i^2 g_{ii} - \sum_{j=1;j\neq i}^{n} V_iV_j(g_{ij}\cos(\theta_i - \theta_j) + b_{ij}\sin(\theta_j - \theta_i) - \sum_{j=1;j\neq i}^{n} V_iV_{seij}(g_{ij}\cos(\theta_i - \theta se_{ij}) + b_{ij}\sin(\theta_j - \theta se_{ij})) \tag{5}$$

$$Q_i = V_i^2 b_{ii} - \sum_{j=1;j\neq i}^{n} V_iV_j(g_{ij}\sin(\theta_i - \theta_j) + b_{ij}\sin(\theta_j - \theta_i) - \sum_{j=1;j\neq i}^{n} V_iV_{seij}(g_{ij}\sin(\theta_i - \theta se_{ij}) + b_{ij}\sin(\theta_j - \theta se_{ij})) \tag{6}$$

Where $g_{in} = Re\left(\frac{1}{Z_{se_{in}}}\right)$, $b_{in} = Im(\frac{1}{Z_{se_{in}}})P_{in}$, $Q_{in}(n{=}j, k)$ are the active and reactive power flows of two IPFC branches leaving bus i while P_{ni}, $Q_{ni}(\ n = j,k)$ are the active and reactive power flows of the series FACTS branch n-i leaving bus n ($n = j, k$), respectively
θ: bus angle
V_{seij} : Magnitude of injected voltage branch i-j
θse_{ij} : Angle of injected voltage branch i-j

In Figure 2, V_i, V_j and V_k are the complex bus voltages at the buses i, j and k respectively, defined as $V_m = V_m\angle\theta_m(m = i, j and k)$. Vse_{in} is the complex controllable series injected voltage source, defined as $Vse_{in} = Vse_{in}\angle\theta se_{in}$ (n=j,k) and $Z_{se_{in}}$ (n=j,k) is the series coupling transformer impedance.

For the IPFC, the power mismatches at buses i, j, k should hold:

$$\Delta P_m = Pg_m - Pd_m - P_m = 0 \tag{7}$$

$$\Delta Q_m = Q_{gm} - Q_{dm} - Q_m = 0 \tag{8}$$

where, without loss of generality, Pg_m, Qg_m(m=i, j, k) are the real and reactive power generation entering the bus m, and Pd_m, Qd_m(m=i, j, k) are the real and reactive power load leaving bus m. P_m, $Q_m(m{=}i, j, k)$ are the sum of real and reactive power flows of the circuits connected to bus m, which include the power flow contributions of the FACTS branches given by equations (7), (8).

According to the operating principle of the IPFC, the operating constraint representing the active power exchange between or among the series converters via the common DC link is:

$$PE_x = -\sum PEse_{in} - P_{dc} = 0 \tag{9}$$

Where $PEse_{in} = Re(Vse_{in}I_{ni}^*)(n = j, k)$. I_{ni}^* means complex conjugate of the current, $I_{ni}(n = j, k)$ is the current through the series converter.

The IPFC shown in Figure 1 and Figure 2 can control both active and reactive power flows of primary line 1 but only active power flow (or reactive power flow) can be controlled in secondary line 2. The active and reactive power flow control constraints of the IPFC are:

$$\Delta P_{ni} = P_{ni} - P_{ni}^{Spec} = 0 \tag{10}$$

$$\text{Where}\begin{cases} P_{ni} = Re(V_n I_{ni}^*) \\ Q_{ni} = Im(V_n I_{ni}^*) \end{cases}\text{and}\begin{cases} P_{ni}^{Spec}\text{are specifed active power flow control references} \\ Q_{ni}^{Spec}\text{are specifed reative power flow control references} \end{cases}$$

$$\Delta Q_{ni} = Q_{ni} - Q_{ni}^{Spec} = 0 \tag{11}$$

$$0 \le \theta_{se_{in}} \le 2\pi \tag{12}$$

$$V_{Se_{in}}^{min} \le V_{se_{in}} \le V_{Se_{in}}^{max} \tag{13}$$

$$-PE_{Se_{in}}^{min} \leq PE_{se_{in}} \leq PE_{Se_{in}}^{max} \tag{14}$$

$$\text{Where} \begin{cases} PE_{Se_{in}}^{max} \text{ is the maximum limit of the power exchange of} \\ \text{series converter with the DC link} \\ PE_{se_{in}} = Re\left(V_{se_{in}} * I_{in}^{*}\right) I_{in}^{max} \text{ is the current rating of the serie converter} \end{cases}$$

$$I_{in} \leq I_{in}^{max} \quad \text{(n=j,k)} \tag{15}$$

3. MODELING OF IPFC IN NEWTON POWER FLOW

Suppose for the IPFC branches i-j, the active and reactive power flows P_{ni} and Q_{ni} can be controlled to power flow control references P_{ni}^{Spec} and Q_{ni}^{Spec} by the series converter *i-j* while for the IPFC branches *i-k* only on the active power flow and reactive power flow can be controlled by the series converter *i-k*, and in the meantime the active power exchange between the two series converters should be balanced. In addition, active and reactive power balance at buses *i, j, k* should also be maintained. Taking into account all these power flow control constraints and bus power mismatch constraints, the compact form of Newton power flow equation with incorporation of the IPFC may be written as:

$$\begin{bmatrix}
\frac{\partial P_{ji}}{\partial \theta_{seij}} & \frac{\partial P_{ji}}{\partial \theta_{seij}} & 0 & 0 & \frac{\partial P_{ji}}{\partial \theta_i} & \frac{\partial P_{ji}}{\partial V_i} & \frac{\partial P_{ji}}{\partial \theta_j} & \frac{\partial P_{ji}}{\partial V_j} & 0 & 0 \\
\frac{\partial Q_{ji}}{\partial \theta_{seij}} & \frac{\partial Q_{ji}}{\partial V_{seij}} & 0 & 0 & \frac{\partial Q_{ji}}{\partial \theta_i} & \frac{\partial Q_{ji}}{\partial V_i} & \frac{\partial Q_{ji}}{\partial \theta_j} & \frac{\partial Q_{ji}}{\partial V_j} & 0 & 0 \\
0 & 0 & \frac{\partial P_{Ki}}{\partial \theta_{seiK}} & \frac{\partial P_{Ki}}{\partial V_{seik}} & \frac{\partial P_{ki}}{\partial \theta_i} & \frac{\partial P_{ki}}{\partial V_i} & 0 & 0 & \frac{\partial P_{ki}}{\partial \theta_k} & \frac{\partial P_{ki}}{\partial V_k} \\
\frac{\partial PE}{\partial \theta_{seij}} & \frac{\partial PE}{\partial V_{seij}} & \frac{\partial PE}{\partial \theta_{seiK}} & \frac{\partial PE}{\partial V_{seiK}} & \frac{\partial PE}{\partial \theta_i} & \frac{\partial PE}{\partial V_i} & \frac{\partial PE}{\partial \theta_j} & \frac{\partial PE}{\partial V_j} & \frac{\partial PE}{\partial \theta_K} & \frac{\partial PE}{\partial V_K} \\
\frac{\partial P_i}{\partial \theta_{seij}} & \frac{\partial P_i}{\partial V_{seij}} & \frac{\partial P_i}{\partial \theta_{seiK}} & \frac{\partial P_i}{\partial V_{seiK}} & \frac{\partial P_i}{\partial \theta_i} & \frac{\partial P_i}{\partial V_i} & \frac{\partial P_i}{\partial \theta_j} & \frac{\partial P_i}{\partial V_j} & \frac{\partial P_i}{\partial \theta_K} & \frac{\partial P_i}{\partial V_k} \\
\frac{\partial Q_i}{\partial \theta_{seij}} & \frac{\partial Q_i}{\partial V_{seij}} & \frac{\partial Q_i}{\partial \theta_{seiK}} & \frac{\partial Q_i}{\partial V_{seiK}} & \frac{\partial Q_i}{\partial \theta_i} & \frac{\partial Q_i}{\partial V_i} & \frac{\partial Q_i}{\partial \theta_j} & \frac{\partial Q_i}{\partial V_j} & \frac{\partial Q_i}{\partial \theta_K} & \frac{\partial Q_i}{\partial V_k} \\
\frac{\partial P_j}{\partial \theta_{seij}} & \frac{\partial P_j}{\partial V_{seij}} & 0 & 0 & \frac{\partial P_j}{\partial \theta_i} & \frac{\partial P_j}{\partial V_i} & \frac{\partial P_j}{\partial \theta_j} & \frac{\partial P_j}{\partial V_j} & 0 & 0 \\
\frac{\partial Q_j}{\partial \theta_{seij}} & \frac{\partial Q_j}{\partial V_{seij}} & 0 & 0 & \frac{\partial Q_j}{\partial \theta_i} & \frac{\partial Q_j}{\partial V_i} & \frac{\partial Q_j}{\partial \theta_j} & \frac{\partial Q_j}{\partial V_j} & 0 & 0 \\
0 & 0 & \frac{\partial P_k}{\partial \theta_{seiK}} & \frac{\partial P_k}{\partial V_{seiK}} & \frac{\partial P_k}{\partial \theta_i} & \frac{\partial P_k}{\partial V_i} & 0 & 0 & \frac{\partial P_k}{\partial \theta_K} & \frac{\partial P_k}{\partial V_k} \\
0 & 0 & \frac{\partial Q_k}{\partial \theta_{seiK}} & \frac{\partial Q_k}{\partial V_{seiK}} & \frac{\partial Q_k}{\partial \theta_i} & \frac{\partial Q_k}{\partial V_i} & 0 & 0 & \frac{\partial Q_k}{\partial \theta_K} & \frac{\partial Q_k}{\partial V_k}
\end{bmatrix} * \begin{bmatrix} \Delta\theta_{seij} \\ \Delta V_{seij} \\ \Delta\theta_{seik} \\ \Delta V_{seik} \\ \Delta\theta_i \\ \Delta V_i \\ \Delta\theta_j \\ \Delta V_j \\ \Delta\theta_k \\ \Delta V_k \end{bmatrix} = \begin{bmatrix} P_{ji}^{Spec} - P_{ji} \\ Q_{ji}^{Spec} - Q_{ji} \\ P_{ki}^{Spec} - P_{ki} \\ -PE_x \\ \Delta P_i \\ \Delta Q_i \\ \Delta P_j \\ \Delta Q_j \\ \Delta P_k \\ \Delta Q_k \end{bmatrix} \tag{16}$$

Hence ΔP_i, ΔQ_i ,ΔP_j,ΔQ_j,ΔP_k , ΔQ_k are the active and reactive power mismatches at buses *i, j, k* respectively. P_i, Q_i, P_j, Q_j, P_k,Q_k are the sum of active and reactive power flows leaving the buses *i, j, k* respectively. In this formulation, the terms of the first four rows of the system jacobian matrix correspond to the IPFC power flow control and active power exchange balance constraints [10].

4. SIMULATION RESULTS

The simulation is done using matlab and the results are presented. Model of 06 nodes (02 nodes generator) with IPFC is shown in Figure 3. The main objective of this contribution is to evaluate the impact of the IPFC on the voltage level, and both active and reactive losses. The Figure 4 shows the location of the IPFC in the network at the bus B4.

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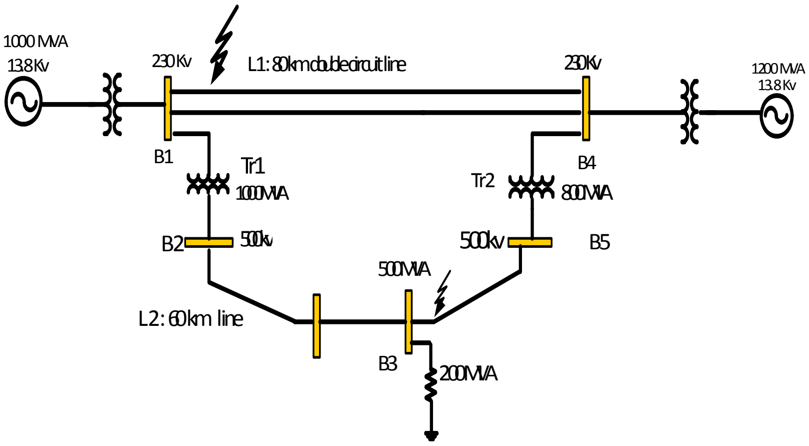

Figure 3. Test power system for analyzing the effect of the IPFC

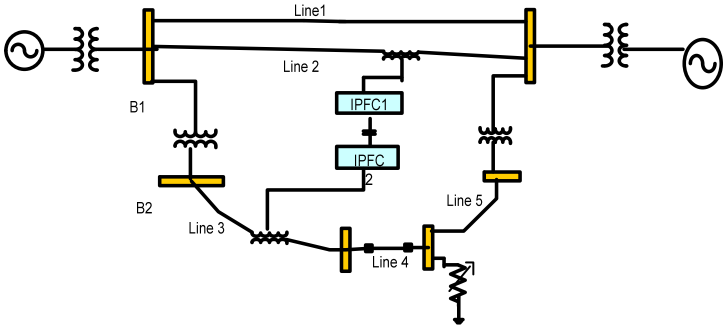

Figure 4. Test power system with IPFC

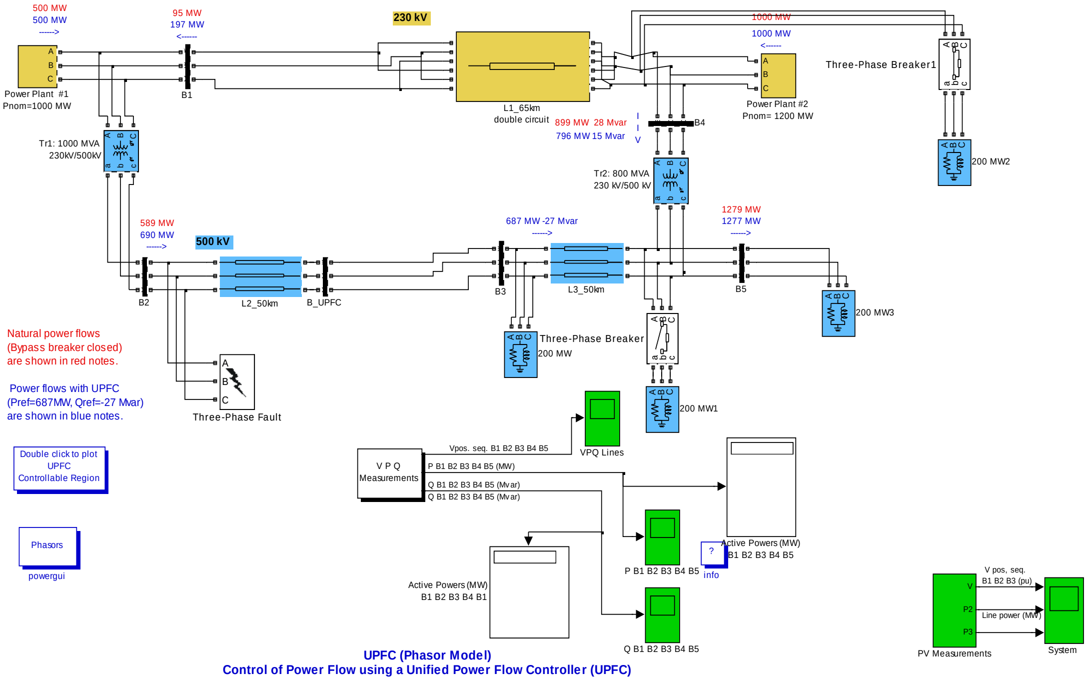

Figure 5. Test power system model in SIMULINK without IPFC

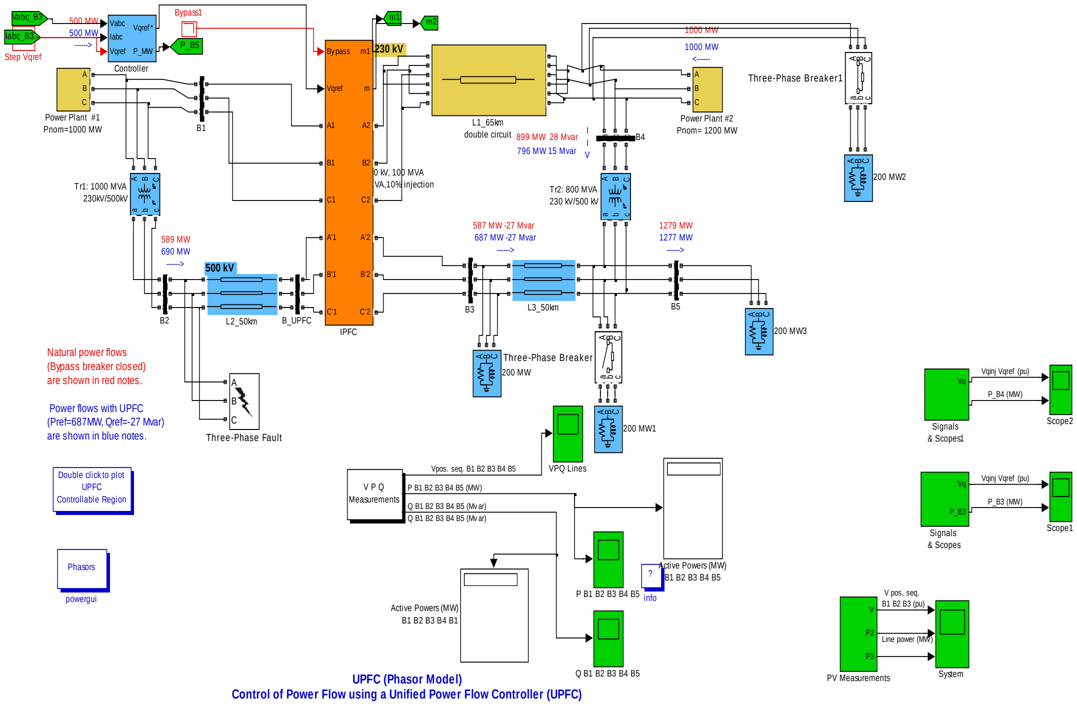

Figure 6. Test power system model in SIMULINK with IPFC

The Figures 5 and 6 represent respectively the simulink models of the Figures 3 and 4.

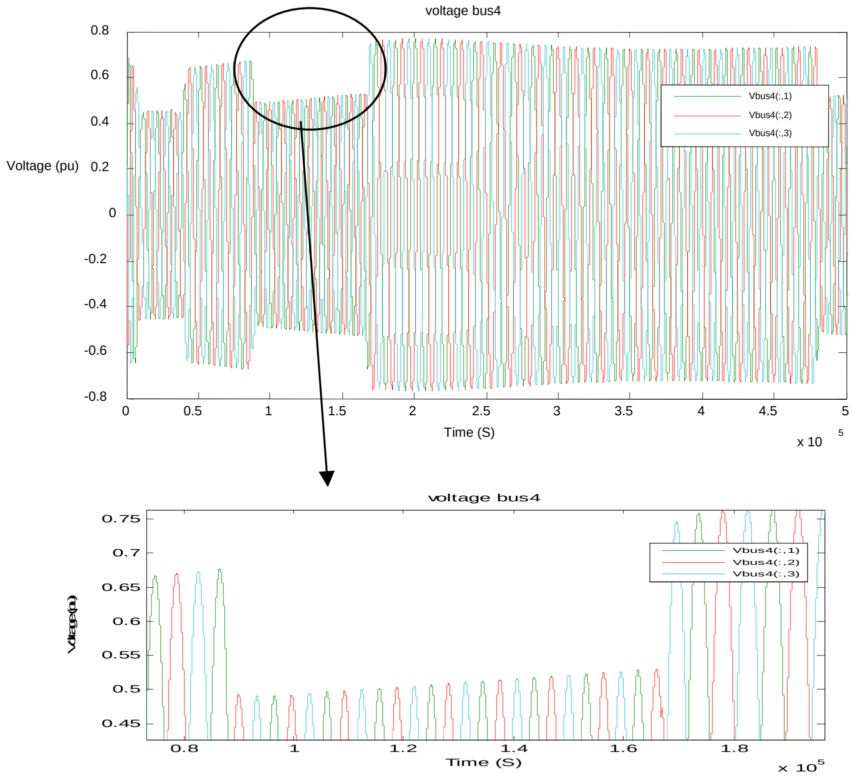

Figure 7. The variation of voltage without IPFC

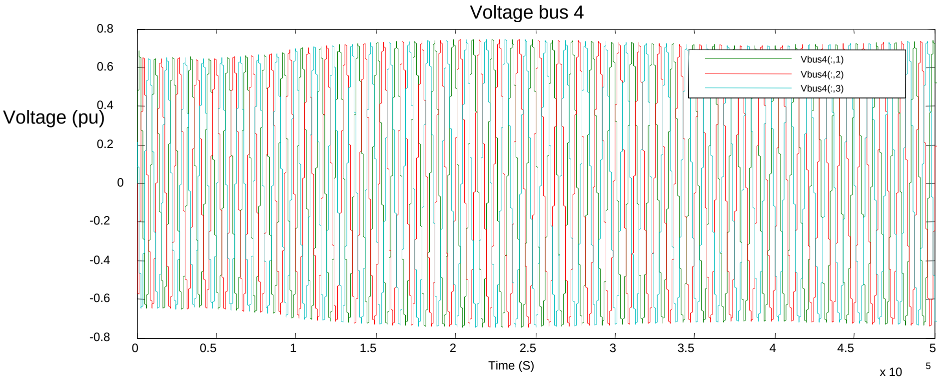

Figure 8. The variation of voltage with IPFC

According to the obtained results using IPFC, we notice that the IPFC has an apparent effect on the voltage level of the network (Figure 7 and Figure 8), despite the disturbances via the short circuit current occurred between the bus B2.

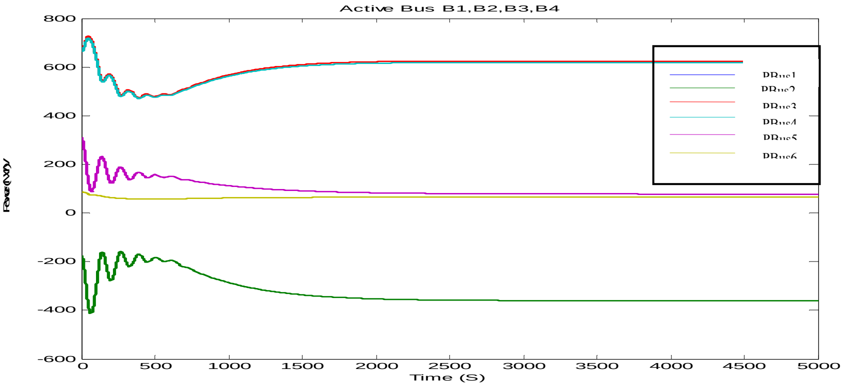

Figure 9. Active power without IPFC

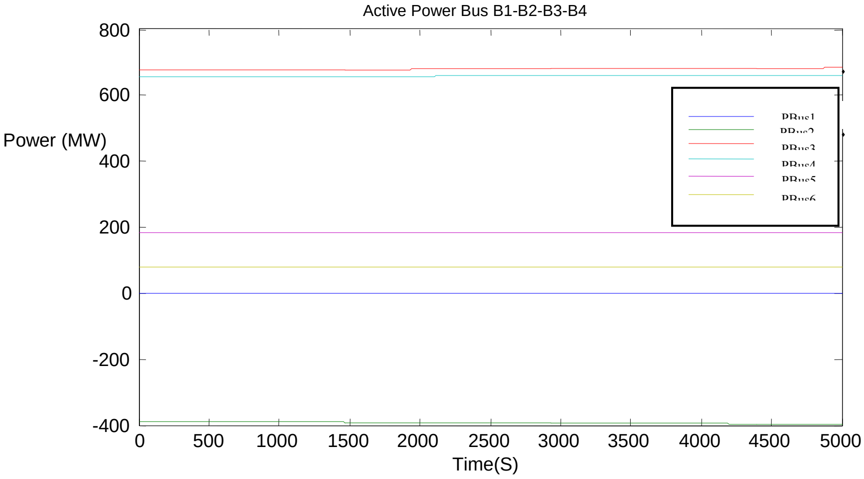

Figure 10. Active power with IPFC

The power flow is maintained constant due to the insertion of the IPFC as is shown respectively on Figure 9 and 10 despite the disturbance.

5. CONCLUSION

The IPFC throughout the obtained has showe that is capable to control the power flow in multiline systems. It is used to improve the power quality by the imbalance which maintains the level voltage in the normalized range its action has a positive impact on the both active and reactive losses.

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