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Voltage Stability Enhancement Using FACTS Controller for 30 Bus Systems in Power System Network

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Abstracts:-

The interline power flow controller (IPFC) is one of the latest generation flexible AC transmission systems (FACTS)controller used to control power flows of multiple transmission lines. This paper presents a mathematical model of IPFC, termed as power injection model (PIM). This model is incorporated in Newton-Raphson (NR) power flow algorithm to study the power flow control in transmission lines in which IPFC is placed. A program in MATLAB has been written in order to extend conventional NR algorithm based on this model. Numerical results are carried out on a standard IEEE 30 bus system. The results with IPFC are compared in terms of voltages, active and reactive power flows to demonstrate the performance of the IPFC model.

Keyword:- Load Flow, Newton-Raphson, IPFC

I. INTRODUCTION

The main aim of power system is to satisfy continuously the electrical power contracted by all customers. This is a problem of great engineering complexity where the following operational policies must be observed: Nodal voltage magnitudes and system frequency must be kept within narrow boundaries. The alternating current (AC) voltage and current waveforms must remain boundaries. Transmission lines must be operated well below their thermal and stability limits. Even short –term interruption must keep to a minimum. Moreover, because of the very competitive nature of electricity supply business in an area of deregulation and open access, transmission costs must be kept as low as possible. The electrical power systems are continuously expanding in size and complexity all over the world. One of the most common computational procedures used in power system analysis is the load flow calculation. Based on the assumed load demands, generation levels and transmission network configuration, the load flow calculations provides the complete steady-state information about the system such as the overall voltage profile (bus voltage magnitudes and bus angles), power flows in the branches, line currents, line losses, and other related variables for a given set of specified conditions. Computer programs to solve load flows are divided into two types—static (off line) and dynamic (real time). Most load flow studies for system analysis are based on static network models. Real time load flows (online) that incorporate data input from the actual networks are typically used by utilities in automatic Supervisory Control And Data Acquisition (SCADA) systemsA practical way to overcome the difficulties is by selection of a limited number of variations of loads. Often this is done arbitrarily, depending on the intuition and experience of engineers. The results are based on partial information and therefore they are inaccurate and they do not include measure of probability. The answer may be under or overestimated and lead to wrong decisions. Since there is also uncertainty regarding generation due to the market influence regarding scheduled units and generation amount In the absence of appropriate methods for modeling uncertainty, majority of load flow algorithms deal with crisp loads/generations and load model coefficients. In order to ensure a range of solutions in the uncertain domain, a large number of crisp load flow simulations needs to be performed spanning the entire data. Obviously this is a brute force approach and is very time consuming.The most powerful and versatile FACTS devices are unified power flow controller (UPFC) and interline power flow controller (IPFC). It is found that, in the past, much effort has been made in the modeling of the UPFC for power flow analysis [1]-[5]. However, UPFC aims to compensate a single transmission line, whereas the IPFC is conceived for the compensation and power flow management of multi-line transmission system. Interline power flow controller (IPFC) is a new member of FACTS controllers. Like the STATCOM, SSSC and UPFC, the IPFC also employs the voltage sourced converter as a basic building block [6].

A simple model of IPFC with optimal power flow control method to solve overload problem and the power flow balance for the minimum cost has been proposed [7].A multiconrol functional model of static synchronous series compensator (SSSC) used for steady state control of power system parameters with current and voltage operating constraints has been presented [8]. The injection model for congestion management and total active power loss minimization in electric power system has been developed Mathematical models of generalized unified power flow controller (GUPFC) and IPFC and their implementation in Newton power flow are reported to demonstrate the performance of GUPFC and IPFC [10].Based on the review above, this paper presents a power injection model of IPFC and its implementation in NR method to study the effect of IPFC parameters on bus voltages, active and reactive power

flows in the lines. Further, the complex impedance of the series-coupling transformer and the line charging susceptance are included in this model.

II. Operating Principle of IPFC

In its general form the inter line power flow controller employs a number of dc-to-ac converters each providing series compensation for a different line. In other words, the IPFC comprises a number of Static Synchronous Series Compensators (SSSC).The simplest IPFC consist of two back-to-back dc-to-ac converters, which are connected in series with two transmission lines through series coupling transformers and the dc terminals of the converters are connected together via a common dc link as shown in Fig.1.With this IPFC, in addition to providing series reactive compensation, any converter can be controlled to supply real power to the common dc link from its own transmission line. The Interline Power Flow Controller (IPFC) stabilizes the system stability by balancing the power between two different branches of the system it is not a good solution to connect IPFC between each line hence to stabilize the system we must have a method which can suggest as the best options of placement of IPFC which not only reduces the number of IPFC required but also the rating of IPFC required. We are here proposing the method for proper placement of IPFC to achieve the above mention benefit. Our method is based of Eigen value in this method we calculate the ranking of the buses according to their effect on system stability & then decides to couple an IPFC between the two buses having the highest & lowest ranking.

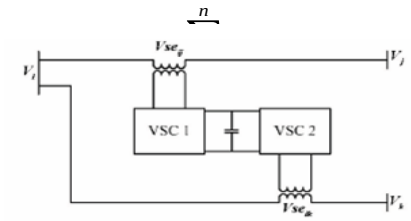
Figure1.Block diagram of the Interline Power Flow Controller (IPFC)

III. Mathematical Modeling

Step 1:- The algorithm starts by reading all input data, forming the system Admittance matrix.(Appendix A)Step 2:- We assume the bus voltage magnitude and phase angle for all the buses except the slack bus where |V| and δ are specified. This is the initial guess X=X0

$$X = \begin{bmatrix} \delta \\ V \end{bmatrix} = \begin{bmatrix} \delta 2 \\ \vdots \\ \delta n \\ V2 \\ \vdots \\ Vn \end{bmatrix} \qquad (1)$$

Step 3:- Substituting these assumed bus voltage magnitude and phase angle, we calculate the real (Pcal) and reactive (Qcal) components of power. For all buses except the slack bus.



$$\text{in}\,\delta_{ik})\,|V_k\,|) \qquad (2)$$

$$_k \sin\delta_{ik} - B_{ik}\cos\delta_{ik})\,|V_k\,|) \qquad (3)$$

$$Y = \begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} Pn \\ Q2 \\ \vdots \\ Qn \end{bmatrix} \qquad (4)$$

Y = g(X)

(5)

Step 4:- Real and Reactive power mismatches are differences between the specified and calculated values.

$\Delta Pi^k = Pspi - Pcali^k$

(6)

$\Delta Qi^k = Qspi - Qcali^k$ i = 1 2 3 …… (N - 1). k = iteration step

(7)

ΔY = Ysp - Ycal

(8)

Where,
Ysp = Specified input vector;
Ycal = Function vector Y evaluated with the latest voltages.
Step 5:- Check whether ΔY for all the buses within a specified tolerance. If yes go to step -9 otherwise go to step 6.

Step 6:- From Jacobian matrix (J) calculate its elements using the estimated bus voltage and calculate bus voltage and calculated power. A set of linear equation is formed.

Jacobian matrix having some sub matrices (H, N, M, L) will have its own diagonal and off-diagonal elements. When i = k; it represents the diagonal and i ≠ k represents the off-diagonal elements .The elements H, N, M, and L matrices are calculated as follows.

$$J = \begin{pmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V} V \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V} V \end{pmatrix} = \begin{pmatrix} H & N \\ M & L \end{pmatrix}$$

1. Calculation of H sub matrix:

$$[H]_{(n-1)\times(n-1)} = \frac{\partial P}{\partial \delta} \quad (9)$$

In H sub matrix the row and column corresponding to slack bus are not present.

(a) off-diagonal elements:

$$H_{ik} = \frac{\partial P_i}{\partial \delta_k} \quad (10)$$

$$Hik = |Vi||Vk|(G_{ik}\cos\delta_{ik} - B_{ik}\sin\delta_{ik}) \quad (11)$$

(b) Diagonal elements:

$$H_{ii} = \frac{\partial P_i}{\partial \delta_i}$$

$$Hii = |Vi| \sum_{\substack{k=1 \\ k\neq i}}^{n} (-G_{ik}\sin\delta_{ik} + B_{ik}\cos\delta_{ik})|V_k| \quad (12)$$

2. Calculation of M sub matrix:

$$[M]_{(n-1-m)\times(n-1)} = \frac{\partial Q}{\partial \delta}$$

In M sub matrix the row and column corresponding to slack bus and rows corresponding to PV-buses are not present.

(a) Off-diagonal elements:

$$M_{ik} = \frac{\partial Q_i}{\partial \delta_k}$$

$$M_{ik} = -|V_i||V_k|(G_{ik}\cos\delta_{ik} + B_{ik}\sin\delta_{ik}) \quad (13)$$

(b) Diagonal elements:

$$M_{ii} = \frac{\partial Q_i}{\partial \delta_i}$$

$$Mii = \{|Vi| \sum_{k=1}^{n} ((G_{ik}\cos\delta_{ik} + B_{ik}\sin\delta_{ik})Vk)\} - G_{ii}|V_i|^2 \quad (14)$$

3. Calculation of N sub matrix:

$$[N]_{(n-1)\times(n-1-m)} = \frac{\partial P}{\partial V} V$$

In N sub matrix the row and column corresponding to slack bus and columns corresponding to PV-buses are not present.

(a) Off –diagonal elements :

$$N_{ik} = \frac{\partial P_i}{\partial |V_k|} |V_k|$$

$$N_{ik} = |V_i||V_k|(G_{ik}\cos\delta_{ik} + B_{ik}\sin\delta_{ik}) \quad (15)$$

(b) Diagonal elements:

$$N_{ii} = \frac{\partial P_i}{\partial |V_i|} |V_i|$$

$$Nii = \{|Vi|\sum_{k=1}^{n}((G_{ik}\cos\delta_{ik} + B_{ik}\sin\delta_{ik})|V_k|\} + G_{ii}|V_i|^2 \quad (16)$$

4. Calculation of L sub matrix:

$$[L]_{(n-1-m)\times(n-1-m)} = \frac{\partial Q}{\partial V} V$$

In L sub matrix the rows and columns corresponding to slack bus and PV-buses are not present.

(a) Off – diagonal elements:

$$L_{ik} = \frac{\partial Q_i}{\partial |V_k|} |V_k|$$

$$L_{ik} = |V_i||V_k|(G_{ik}\sin\delta_{ik} - B_{ik}\cos\delta_{ik}) \quad (17)$$

(b) Diagonal elements:

$$L_{ii} = \frac{\partial Q_i}{\partial |V_i|} |V_i|$$

$$Lii = \{|Vi|\sum_{k=1}^{n}((G_{ik}\sin\delta_{ik} - B_{ik}\cos\delta_{ik}))\} - B_{ii}|V_i|^2$$

Step 7:- The linear equation are solved by direct iterative method for Δδ and ΔV.

ΔX = JIN. ΔY (18)

$$\begin{bmatrix} \Delta\delta 1 \\ \vdots \\ \Delta\delta n \\ \Delta V1 \\ \vdots \\ \Delta Vn \end{bmatrix} = \begin{bmatrix} \frac{\partial P_1}{\partial \delta_1} \cdots\cdots \frac{\partial P_1}{\partial \delta_n} & \frac{\partial P_1}{\partial |V_1|} \cdots\cdots \frac{\partial P_1}{\partial |V_n|} \\ \vdots & \\ \frac{\partial P_n}{\partial \delta_1} \cdots\cdots \frac{\partial P_n}{\partial \delta_n} & \frac{\partial P_n}{\partial |V_1|} \cdots\cdots \frac{\partial P_n}{\partial |V_n|} \\ \frac{\partial Q_1}{\partial \delta_1} \cdots\cdots \frac{\partial Q_1}{\partial \delta_n} & \frac{\partial Q_1}{\partial \delta_1} \cdots\cdots \frac{\partial Q_1}{\partial \delta_n} \\ \vdots & \\ \frac{\partial Q_n}{\partial \delta_1} \cdots\cdots \frac{\partial Q_n}{\partial \delta_n} & \frac{\partial Q_n}{\partial |V_1|} \cdots\cdots \frac{\partial Q_n}{\partial |V_n|} \end{bmatrix}^{-1} \begin{bmatrix} P_{sp}{}^1 - P_{cal}{}^1(\delta_0{}^1 \ldots\ldots, \delta_0{}^n, |V_0{}^1, \ldots\ldots\ldots, |V_0{}^n| \\ \vdots \\ P_{sp}{}^n - P_{cal}{}^n(\delta_0{}^1 \ldots\ldots, \delta_0{}^n, |V_0{}^1, \ldots\ldots\ldots, |V_0{}^n| \\ Q_{sp}{}^1 - Q_{cal}{}^1(\delta_0{}^1 \ldots\ldots, \delta_0{}^n, |V_0{}^1, \ldots\ldots\ldots, |V_0{}^n| \\ \vdots \\ Q_{sp}{}^n - Q_{cal}{}^n(\delta_0{}^1 \ldots\ldots, \delta_0{}^n, |V_0{}^1, \ldots\ldots\ldots, |V_0{}^n| \end{bmatrix}$$

Where JIN=Jacobian inverse matrix. ΔX= State update vector.
This value of voltage correction is used to determine the new estimate of bus voltage magnitude and phase angle as follows:

$$Vi^k = Vi + \Delta Vi^k$$
$$\delta i^k = \delta i + \Delta \delta i^k$$

Where k = is an iteration count.

$$Xi^k = Xi + \Delta Xi^k$$

Step 8:- Next we return to step -3 with updated voltage to recalculated Pcal, Qcal and then ΔP and ΔQ in the next step of the process. This entire process is repeated toll ΔPi and ΔQi at any step of the process in all the buses are within tolerance .Then we go to step 9.
Step 9:- Output latest voltage we using calculation of Line power flow:

$$Z = h(X)$$

Where Z includes the line flow, the reactive power at PV bus
The power flow form the i-th bus to k-th bus through the line connected between these buses are given by,

$$S_{ik} = V_i I_{ik}^* = V_i \left(\frac{V_i - V_k}{Z_{ik}} + V_i y_{ik0} \right)^*$$

$$S_{ik}^* = V_i^* I_{ik} = V_i^* \left(\frac{V_i - V_k}{Z_{ik}} + V_i y_{ik0} \right)$$

$$P_{ik} = \mathrm{Real}\left[V_i^* (V_i - V_k) y_{ik} + V_i^* V_i y_{ik0} \right]$$

$$Q_{ik} = -\mathrm{Im}\left[V_i^* (V_i - V_k) y_{ik} + V_i^* V_i y_{ik0} \right]$$

Similarly the power flow form the k-th bus to i-th bus through the line connected between these buses are given by

$$P_{ki} = \mathrm{Real}\left[V_k^* (V_k - V_i) y_{ik} + V_k^* V_k y_{ik0} \right]$$

$$Q_{ki} = -\mathrm{Im}\left[V_k^* (V_k - V_i) y_{ik} + V_k^* V_k y_{ik0} \right]$$

The total line loss being the summation of all power flow.$\text{Lineloss} = \sum_{i=1}^{n} \sum_{k=1}^{n} \{ (P_{ik} + jQ_{ik}) + (P_{ki} + jQ_{ki}) \}$

Algorithm of Optimal Placement of IPFC

Step 1:- The algorithm starts by reading all input data, forming the system Admittance matrix.(Appendix A)
Step 2:- We assume the bus voltage magnitude and phase angle for all the buses except the slack bus where |V| and δ are specified. This is the initial guess X=X0

$$X = \begin{bmatrix} \delta \\ V \end{bmatrix} = \begin{bmatrix} \delta 2 \\ \vdots \\ \delta n \\ V2 \\ \vdots \\ Vn \end{bmatrix}$$

Step 3:- Substituting these assumed bus voltage magnitude and phase angle, we calculate the real (Pcal) and reactive (Qcal) components of power. For all buses except the slack bus.

$$P_{cali} = |V_i| \sum_{k=1}^{n} ((G_{ik} \cos \delta_{ik} + B_{ik} \sin \delta_{ik}) |V_k|)$$

$$Q_{cali} = |V_i| \sum_{k=1}^{n} ((G_{ik} \sin \delta_{ik} - B_{ik} \cos \delta_{ik}) |V_k|)$$

$$Y = \begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} P2 \\ \vdots \\ Pn \\ Q2 \\ \vdots \\ Qn \end{bmatrix} \qquad Y = g(X)$$

Step 4:- Real and Reactive power mismatches are differences between the specified and calculated values.

$\Delta Pi^k = Pspi - Pcali^k$

$\Delta Qi^k = Qspi - Qcali^k$

i = 1 2 3 …… (N - 1). k = iteration step

$\Delta Y = Ysp - Ycal$

Where,

Ysp = Specified input vector;

Ycal = Function vector Y evaluated with the latest voltages.

Step 5:- Check whether ΔY for all the buses within a specified tolerance.

Step 6:- From Jacobian matrix (J) calculate its elements using the estimated bus voltage and calculate bus voltage and calculated power. A set of linear equation is formed.

Jacobian matrix having some sub matrices (H, N, M, L) will have its own diagonal and off-diagonal elements. When i = k; it represents the diagonal and i ≠ k represents the off-diagonal elements .The elements H, N, M, and L matrices are calculated as follows.

Step 3. Ones we get all the required parameter of the system we also found the correct value of jacobion matrix.

Step 4. From this jacobion matrix we calculate the reduced jacobion matrix.

Step 5. Now the eigenvalues of the reduced jacobion matrix identify the different modes through the system can be unstable. The magnitude of the eigenvalues provides a relative measure of the proximity of instability.

Step 6. Since mathematical derivation shows the greater the eigenvalue lesser the participation of bus in system instability from this way we define the participation factor of the buses.

Step 7. Now we place the IPFC between the buses having maximum & minimum eigenvalues.

Step 8. As we couple the system the power starts flowing between buses at this state we again calculate the eigenvalues & then participation index of buses, now if we found that all eignvalues having sufficient margin from instability point we stop the process else we iterative repeat the process till we found all the buses in which optimal IPFC placement is required.

Following are the mathematical derivation & equations used in the method

Steady state voltage equation of the system

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{P\theta} & J_{PV} \\ J_{Q\theta} & J_{QV} \end{bmatrix} \begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix}$$

Where

ΔP, ΔQ, ΔΘ & ΔV are the incremental changes in bus real power, reactive power, voltage angle & voltage angle respectively.

For small change in real power ΔP with respect to ΔQ & ΔΘ we can get

$$\Delta Q = (J_{QV} - J_{Q\theta} * J_{P\theta}^{-1} * J_{PV}) * \Delta V$$

By rearranging the above equation

$$\Delta V = J_R^{-1} \Delta Q$$

Where

$$J_R = (J_{QV} - J_{Q\theta} * J_{P\theta}^{-1} * J_{PV})$$

Here J_r is called reduced jacobian matrix of the system it relates the voltage magnitude & reactive power of the system.

We can also write it in the format as given below

$$J_R = \xi \Lambda \eta$$

Where ξ Λ & η are the right, left & diagonal eigenvalue matrix of J_r

Participation of k_{th} bus is given by

$$P_{Ki} = \xi_{Ki} \eta_{ik}$$

P

articipation of bus I in voltage instability.

$$PCM_i = \sum_{J=1}^{m} P_{out}(K) \times (\frac{P_{ij}}{\sigma_j})$$

Where

P_{outage} is probability of k_{th} contingency.

Number of critical eignvalues = m.

P_{ij} participation of bus i to critical eignvalue j.

σ_j critical eignvalue j.
then the total Participation of bus i in voltage instability in all critical modes & all contingencies given by

$$TPCM_i = \sum_{k=1}^{L} \sum_{J=1}^{m} P_{out}(k) \times (\frac{P_{ij}}{\sigma_j}) \Delta X = JIN. \Delta Y \quad (20)$$

IV Results

Table :Newton Raphson Load Flow Analysis

Newton Raphson Loadflow Analysis

Bus No	V pu	Angle Degree	Injection MW	Injection MVar	Generation MW	Generation Mvar	Load MW	Load MVar
1	0.0192	3.2945	-0.586	-1.111	-0.586	-1.111	0.000	0.000
2	0.0452	9.4653	0.892	2.194	22.592	14.894	21.700	12.700
3	0.0570	9.9523	2.696	6.998	5.096	8.198	2.400	1.200
4	0.0132	2.1715	-1.430	-2.625	6.170	-1.025	7.600	1.600
5	0.0472	11.3618	0.604	1.251	94.804	20.251	94.200	19.000
6	0.0581	10.1012	3.815	10.601	3.815	10.601	0.000	0.000
7	0.0119	2.3720	-0.485	-0.848	22.315	10.052	22.800	10.900
8	0.0460	6.6463	-0.930	-1.659	29.070	28.341	30.000	30.000
9	0.0267	4.6983	-0.060	0.283	-0.060	0.283	0.000	0.000
10	0.0120	2.4064	-2.479	-3.779	3.321	-1.779	5.800	2.000
11	0.0000	11.9175	0.000	-0.000	0.000	0.000	0.000	0.000

12	0.0000	31.8565	0.000	-0.000	11.200	7.500	11.200	7.500
13	0.0000	11.9175	0.000	-0.000	0.000	0.000	0.000	0.000
14	0.0000	6.3025	0.000	-0.000	6.200	1.600	6.200	1.600
15	0.0000	14.6677	0.000	-0.000	8.200	2.500	8.200	2.500
16	0.0000	8.0214	0.000	-0.000	3.500	1.800	3.500	1.800
17	0.1231	14.6620	8.600	20.679	17.600	26.479	9.000	5.800
18	0.0662	7.4714	-0.044	0.591	3.156	1.491	3.200	0.900
19	0.0945	11.3847	-5.964	-12.511	3.536	-9.111	9.500	3.400
20	0.2210	11.4420	24.885	51.224	27.085	51.924	2.200	0.700
21	0.0824	11.0180	6.836	10.988	24.336	22.188	17.500	11.200
22	0.1073	12.5191	5.031	8.462	5.031	8.462	0.000	0.000
23	0.0639	7.4026	-1.975	-1.265	1.225	0.335	3.200	1.600
24	0.0340	3.8961	-1.390	-1.511	7.310	5.189	8.700	6.700
25	0.0936	11.9748	2.859	4.219	2.859	4.219	0.000	0.000
26	0.0324	4.8415	-0.307	-0.310	3.193	1.990	3.500	2.300
27	0.0348	4.2915	-0.737	-1.135	-0.737	-1.135	0.000	0.000
28	0.0727	8.5886	0.673	3.279	0.673	3.279	0.000	0.000
29	0.0116	1.3522	-0.158	-0.203	2.242	0.697	2.400	0.900
30	0.1000	11.5737	1.351	2.325	11.951	4.225	10.600	1.900
Total			41.697	96.137	325.097	222.337	283.400	126.200

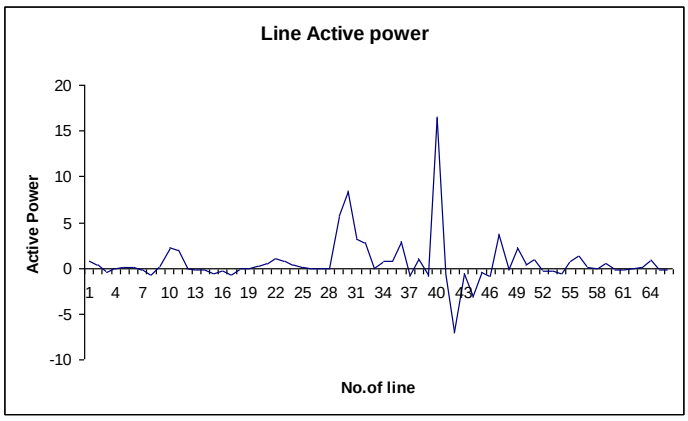


Figure 3 Line Active Power for IEEE 30 Bus System

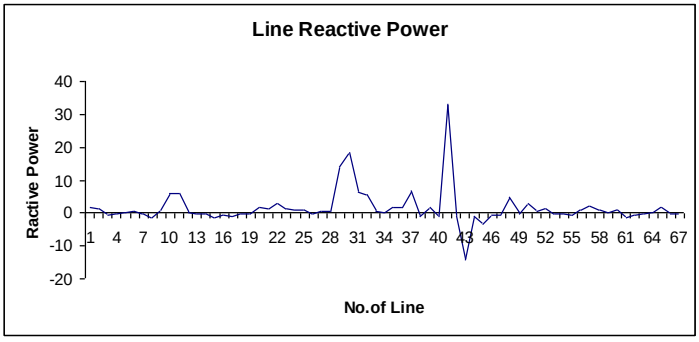


Figure 4 Line Reactive Power for IEEE 30 Bus System

V. Conclusion

A power injection model of the inter line power flow controller (IPFC) and its implementation in Newton-Raphson power flow method has been presented. In this model, the complex impedance of the series coupling transformer and the line charging susceptance are included. Numerical results on the test system have shown the convergence and the effectiveness of the IPFC model .It shows that the incoming of IPFC can increase the bus voltage to which IPFC converters are connected and there is a significant change in the system voltage profile at the neighboring buses, increase in active power flow and decrease in reactive power flow through the lines .Also, the effect of IPFC parameters on active and reactive power flows through the lines in which IPFC is placed has been investigated.

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