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Application of MATPOWER for the Analysis of Congestion in Power System Network and Determination of Generator Sensitivity Factor

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Abstract

The congestion management is considered as one of the key feature of the independent system operator in deregulated power system environment. The rescheduling of the generator is one of the most vital method for congestion management. The congestion in transmission line is caused due to increase in power flow should be identified and proper measures should be taken by the system operator for relieving the congestion. The intent of this paper is to demonstrate the application of MATPOWER, an open source MATLAB simulation software, which is much efficient in solving the rigorous task of power flow for the identification of the congested line in the power system network and the determination of the generator sensitivity factor by changing the MATPOWER source code. In this paper one illustrative example has been presented using Newton Raphson power flow for 5 bus and 30 bus cases from the MATPOWER library. Moreover the paper also presents MATPOWER as one of the most important research tool which will facilitate the study of the power system problem for both the undergraduate and the research scholars.

Keyword: MATPOWER, MATLAB, Congestion, Generator sensitivity, Jacobian

INTRODUCTION

The restructuring in the power system industry have led to the increase in the power trade. This increase in the power trading in the deregulated power environments have led to the extensive use of the transmission line hence leading to the congestion in the transmission line. The insufficient transmission capacity of the transmission lines results in the congestion of the lines. The congestion in the power transmission line is not desirable for the reliable operation of the power system network, so the identification of the congested line is important for the reliable operation of the power system network. The amount of the power flow in the transmission line can be determined by the analysis of the power flow in the lines. The analysis of the power flow involves a lot of mathematics and complex calculation which may be quite time consuming, laborious and also erroneous for the students and research scholars This situation has changed drastically with the advancement in the computer technology. The simulation and the analysis of the large power system network can be done easily with the help of the modern computer technology. The modern computer can efficiently react and provide useful data and information regarding the various responses which have made it feasible for the integration of these computers in the modern power system courses [1].

There have been a large number of software packages like ETAP, ERACS, PSCAD, Power World Simulator which are used to analyze and solve power system problems but these software packages require a pretty decent knowledge of modeling and simulation for solving the problems related to power system analysis. Moreover these software packages do not give the facility to add new algorithms to it nor allow the users to change the source code [2]. This limitation on the software tools is not desirable for the researchers. Moreover, it is highly time consuming and difficult for students to design their own codes for the power flow analysis. This problem can be easily solved by the use of the MATPOWER. There are several other power system software tools [3-5] which uses MATLAB as its common platform and provide the facility for the modification in their codes. Moreover several M-file functions which also use MATLAB have been designed by Sepasian and Seifi [1] for the better understanding of the power system analysis problem for the students and research scholars. However in addition to these, MATPOWER is very simple and robust. It is much more efficient and flexible in computing and displaying much detailed results.

Since power flow studies is considered as one of the most essential tool of the power system courses [6], the cases illustrated in this literature is only confined to the analysis of the power flow in the power system network for the analysis of the congestion in the power system network and determination of Generator Sensitivity Factor (GSF_G). As MATPOWER uses the MATLAB platform, a good introduction to the MATLAB is necessary from the electrical engineering point of view. A good introduction to the MATLAB can be found in [7]. In this paper section II discusses the definition and features of MATPOWER. The analysis of congested line and evaluation of generator sensitivity factor is illustrated with 5 bus and 30 bus test case in section III and section IV respectively by the use of MATPOWER. Section V concludes the paper.

MATPOWER

MATPOWER is considered as an open source power system analysis programming tool for solving the problems related to power flow and optimal power flow. The MATPOWER runs on the MATLAB platform best suited with the version of MATLAB 6 and above. The MATPOWER package was developed at the CORNELL University and can be downloaded from their website [8]. The basic purpose of this software package is to provide facilities to the research scholars, education professionals and also to the industry related issues [9]. The codes of the MATPOWER are simple and the user can modify the codes according to their needs. After downloading the MATPOWER, the MATLAB platform needs to be opened and the core MATPOWER function and test script to be added to the MATLAB path. The installation of MATPOWER 5.1 version is shown as

C:\ProgramFiles\MATLAB\2013b\matpower5.1. After selecting the path, the command window has to be opened and the required M-File name to be typed followed by pressing enter. In order to run a power flow for 30 bus system for example type:

>>runpf('case30')

In the command window followed by enter button. This will give the results of the power flow for a 30 bus system which is already present in the MATPOWER. The MATPOWER uses Gauss Seidal, Newton, DC power flow, XB fast-decouple and BX fast-decouple as solvers for solving the power flow analysis.

The MATPOWER provides us with the advantage of adding new algorithm or to modify its source code as per the requirement of the research problem. The other advantage is that it is an open source package. The MATPOWER can be used to find the congested line and the generator sensitivity index for the generators which are to be rescheduled for the purpose of the congestion management.

DETERMINATION OF CONGESTED LINE

The congestion management is one of the most vital technical issues in deregulated power system environment. In deregulated environment the transmission congestion occur when there is an insufficient transmission capacity to simultaneously accommodate all the transmission constraints. The determination of the congested line in the power system network is analyzed by taking the example of 5 bus system of the MATPOWER 5.1. The normal power flow is run by using the MATPOWER code:

>>runpf('case5')

This MATPOWER code runs the power flow analysis for 5 bus system. The M file of the branch data for 5 bus system is represented in figure 1 in which rate represents the MVA limit of the line. The normal power flow status of the 5 bus system is given in figure 2.

```
%% branch data
%   fbus    tbus    r   x   b   rateA
mpc.branch = [
    1   2   0.00281 0.0281  0.00712 400
    1   4   0.00304 0.0304  0.00658 400
    1   5   0.00064 0.0064  0.03126 400
    2   3   0.00108 0.0108  0.01852 400
    3   4   0.00297 0.0297  0.00674 400
    4   5   0.00297 0.0297  0.00674 240
];
```

Figure 1: M-File of branch data for 5 bus system

Branch Data								
Brnch #	From Bus	To Bus	From Bus Injection P (MW)	From Bus Injection Q (MVAr)	To Bus Injection P (MW)	To Bus Injection Q (MVAr)	Loss (I^2 * Z) P (MW)	Loss (I^2 * Z) Q (MVAr)
1	1	2	249.77	21.60	-248.01	-4.64	1.767	17.67
2	1	4	186.50	-13.61	-185.44	23.58	1.063	10.63
3	1	5	-226.27	22.74	226.60	-22.55	0.331	3.31
4	2	3	-51.99	-93.97	52.12	93.39	0.125	1.25
5	3	4	-28.63	2.65	28.65	-3.08	0.025	0.25
6	4	5	-238.19	32.15	239.91	-15.66	1.716	17.16
						Total:	5.027	50.27

Figure 2: Power flow under normal operating condition of 5 bus system

The congestion in the line may be due to several cases like line outage, increase in the load, tripping of the generator etc. Here the increase in the load is taken as the case study for the analysis of the congested line. The load is increased in every bus by a factor 1.5 and line 4-5 is outage. Power demand in each load bus can be changed by the following steps,

Step1: Loading the case data. In this the load flow input data is prepared.

Step2: Changing the real and the reactive power demand. The real and reactive power demand data are changed from a previous value to a new value.

Step3: Running the power flow

mpc=loadcase('case5');	% read the load flow input data
mpc.bus(2,PD)=450;	% increase the real power demand at bus 2 to 450 MW, PD load demand (MW)
mpc.bus(2,QD)=147.91;	% increase the reactive power demand at bus 2 to 147.91 MVAr, QD load demand (MVAr)
mpc.bus(3,PD)=450;	% increase the real power demand at bus 3 to 450 MW
mpc.bus(3,QD)=147.91;	% increase the reactive power demand at bus 3 to 147.91MVAr
mpc.bus(4,PD)=600;	% increase the real power demand at bus 4 to 600 MW
mpc.bus(4,QD)=197.20;	% increase the reactive power demand at bus 4 to 197.20MVAr
runpf(mpc);	% run AC power flow

Bus Data

Bus #	Voltage Mag(pu)	Voltage Ang(deg)	Generation P (MW)	Generation Q (MVAr)	Load P (MW)	Load Q (MVAr)
1	1.000	4.302	210.00	80.57	-	-
2	0.983	-2.685	-	-	450.00	147.91
3	1.000	-2.622	323.49	322.82	450.00	147.91
4	1.000	0.000*	509.46	218.39	600.00	197.21
5	1.000	6.028	466.51	-41.13	-	-
		Total:	1509.46	580.65	1500.00	493.03

Figure 3: Bus data of 5 bus system with increase in load

Branch Data

Brnch #	From Bus	To Bus	From Bus Injection P (MW)	From Bus Injection Q (MVAr)	To Bus Injection P (MW)	To Bus Injection Q (MVAr)	Loss (I^2 * Z) P (MW)	Loss (I^2 * Z) Q (MVAr)
1	1	2	429.86	44.12	-424.61	7.66	5.248	52.48
2	1	4	245.24	-15.58	-243.41	33.28	1.835	18.35
3	1	5	-465.11	52.03	466.51	-41.13	1.403	14.03
4	2	3	-25.39	-155.58	25.66	156.50	0.275	2.75
5	3	4	-152.17	18.41	152.87	-12.10	0.698	6.98
						Total:	9.459	94.59

Figure 4: Congestions due to increase in the power flow

From the branch data in figure 4 it is observed that due to increase in load to 1.5 times and line 4-5 outage, line 1-2 and line 1-5 gets congested

TABLE I: POWER FLOW IN CONGESTED LINES IN 5 BUS SYSTEM

Line	Power flow	Line limit
1-2	429.86	400
1-5	465.11	400

The analysis of the congested line with a test case of 30 bus system from the MATPOWER library is also shown with increase in the load up to 1.5 times in table II.

TABLE II: POWER FLOW IN CONGESTED LINES IN 30 BUS SYSTEM

Line	Power flow(MW)	Line limit(MW)
6-8	40.39	32

GENERATOR SENSITIVITY FACTOR

Generator sensitivity factor defined as the ratio of change in real power flow in a transmission line k which is connected between bus i and bus j to the change in the power generation of the generator G. Mathematically generator sensitivity (GSF_g) of a line can be represented as following.

$$GSF_G = \Delta P_{ij} / \Delta P_{Gg} \quad (1)$$

ΔP_{ij}= change of real power flow of congested line k

ΔPG_g=change of real power of g^{th} generator

The generator sensitivity factor helps to determine which generator will take part in the rescheduling in order to remove congestion. A positive value of the generator sensitivity factor indicates there is a decrease in the power flow in the congested line with the decrease in the generation and on the other hand the negative value of generator sensitivity factor represents a decrease in the power flow in the congested line with the increase in the generation. The generators having non-uniform and large magnitude of GSF_G will take part in the rescheduling for removal of congestion. The generator sensitivity factor (GSF_G) is computed using the following procedure [10].

$$P_{ij} = -V_i^2 G_{ij} + V_i V_j G_{ij} cos(\theta_i - \theta_j) + V_i V_j B_{ij} sin(\theta_i - \theta_j) \quad (2)$$

Where θ_i and θ_j = bus voltage angle at bus i & j respectively. V_i and V_j are the bus voltages at i^{th} and j^{th} bus respectively. G_{ij} and B_{ij} are the conductance and susceptance of the line connected between i and j. Neglecting the PV coupling the GSF_G Expression can be written as

$$GSF_g = \frac{\partial P_{ij}}{\partial \theta_i} \frac{\partial \theta_i}{\partial P_{G_g}} + \frac{\partial P_{ji}}{\partial \theta_j} \frac{\partial \theta_j}{\partial P_{G_g}} \quad (3)$$

Where,

$$\frac{\partial P_{ij}}{\partial \theta_i} = -V_i V_j G_{ij} sin(\theta_i - \theta_j) + V_i V_j B_{ij} cos(\theta_i - \theta_j) \quad (4)$$

$$\frac{\partial P_{ij}}{\partial \theta_j} = V_i V_j G_{ij} sin(\theta_i - \theta_j) - V_i V_j B_{ij} cos(\theta_i - \theta_j) \quad (5)$$

i.e $\frac{\partial P_{ij}}{\partial \theta_i} = -\frac{\partial P_{ij}}{\partial \theta_j}$

The injection of active power P_i at bus s can be represented as

$$P_i = V_i \sum_{j}^{N} V_j (G_{ij} cos(\theta_i - \theta_j) + B_{ij} sin(\theta_i - \theta_j)) \quad (6)$$

$$P_i = V_i^2 G_{ij} + V_i \sum_{j}^{N} V_j (G_{ij} cos(\theta_i - \theta_j) + B_{ij} sin(\theta_i - \theta_j))$$

Now differentiating the equation with respect to θ_i and θ_j, we obtain

$$\frac{\partial P_{ij}}{\partial \theta_i} = V_i V_j G_{ij} sin(\theta_i - \theta_j) + V_i V_j B_{ij} cos(\theta_i - \theta_j) \quad (7)$$

$$\frac{\partial P_{ij}}{\partial \theta_j} = -V_i V_j G_{ij} sin(\theta_i - \theta_j) + V_i V_j B_{ij} cos(\theta_i - \theta_j) \quad (8)$$

By neglecting the PV coupling the relation between incremental change in active power at system bus and phase angle of voltage can be written in matrix form as

$$[\Delta P]_{n*1} = [J_{11}]_{n*n} * [\Delta \theta]_{n*1} \quad (9)$$

$$[\Delta\theta]_{n*1} = [H]^{-1}_{n*n} * [\Delta P]_{n*1} \tag{10}$$

$$[H]_{n*n} = [J_{11}]_{n*n} \tag{11}$$

n= number of buses

$$[\Delta\theta]_{n*1} = [M]_{n*n} * [\Delta P]_{n*1} \tag{12}$$

$$\left[M\right]_{n*n} = \left[H\right]^{-1}_{n*n} \tag{13}$$

$$\left[H\right]_{n*n} = \begin{bmatrix} \mathbf{0} & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \frac{\partial\theta_2}{\partial P_2} & \cdots & \frac{\partial\theta_2}{\partial P_n} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{0} & \frac{\partial\theta_n}{\partial P_2} & \cdots & \frac{\partial\theta_n}{\partial P_n} \end{bmatrix}_{n\times n} \tag{14}$$

$$[\Delta\theta_{-1}] = [M_{-1}] * [P_{-1}] \tag{15}$$

$$[\Delta\theta]_{n*1} = \begin{bmatrix} 0 & 0 \\ 0 & [M-1] \end{bmatrix} * \left[\Delta P\right]_{n*1} + \Delta\theta_1 \begin{vmatrix} 1 \\ \vdots \\ 1 \end{vmatrix} \tag{16}$$

The second term of the sum in (16) vanishes as being the change in phase angle of slack bus is zero. Accordingly, reduces to

$$[\Delta\theta]_{n*1} = \begin{vmatrix} 0 & 0 \\ 0 & [M-1] \end{vmatrix} * \left[\Delta P\right]_{n*1} \tag{17}$$

Thus value of the generator sensitivity factor is obtained from the above method with respect to the slack bus.

GSF_G denotes how much active power flow over a transmission line connecting bus-i and bus-j would change due to active power injection by generator g. The system operator selects the generators having non uniform and large magnitudes of sensitivity values as the ones most sensitive to the power flow on the congested line and to participate in congestion management by rescheduling their power outputs.

A. Generator Sensitivity Factor Determination with MATPOWER

The calculation of G and B matrices involves the computation of the Y bus for the system. The Y bus matrix can be obtained by altering the coding in the MATPOWER codes: the alteration in the MATPOWER code is given below

```
function [V, converged, i,Y] = newtonpf(Ybus, Sbus, V0, ref, pv, pq, mpopt)
if nargin < 7
    mpopt = mpoption;
end
tol     = mpopt.pf.tol;
max_it  = mpopt.pf.nr.max_it;
converged = 0;
i = 0;
V = V0;
Va = angle(V);
Vm = abs(V);
Y=Ybus;
G=real(Y)
B=imag(Y)
npv = length(pv);
npq = length(pq);
j1 = 1;         j2 = npv;           %% j1:j2 - V angle of pv buses
j3 = j2 + 1;    j4 = j2 + npq;      %% j3:j4 - V angle of pq buses
j5 = j4 + 1;    j6 = j4 + npq;      %% j5:j6 - V mag of pq buses
mis = V .* conj(Ybus * V) - Sbus;
F = [   real(mis([pv; pq]));
        imag(mis(pq))   ];
normF = norm(F, inf);
if mpopt.verbose > 1
    fprintf('\n it    max P & Q mismatch (p.u.)');
    fprintf('\n----  ---------------------------');
    fprintf('\n%3d        %10.3e', i, normF);
end
if normF < tol
    converged = 1;
    if mpopt.verbose > 1
        fprintf('\nConverged!\n');
    end
end
while (~converged && i < max_it)
    i = i + 1;
    [dSbus_dVm, dSbus_dVa] = dSbus_dV(Ybus, V);
    j11 = real(dSbus_dVa([pv; pq], [pv; pq]));
    j12 = real(dSbus_dVm([pv; pq], pq));
    j21 = imag(dSbus_dVa(pq, [pv; pq]));
    j22 = imag(dSbus_dVm(pq, pq));

    J = [   j11 j12;
            j21 j22;    ];
      M=inv(j11);
      X_P=[0 zeros(1,29); zeros(29,1) M]
    dx = -(J \ F);
```

Figure 5: Modification in MATPOWER Source Code

The real and the imaginary part of the admittance matrix are represented by G and B matrices respectively. The values of G matrix and the B matrix obtained for a 5 bus system computed by the altering the MATPOWER coding is given below

$$G = \begin{bmatrix} 22.2507 & -3.5235 & 0 & -3.2569 & -15.4703 \\ -3.5235 & 12.6911 & -9.1676 & 0 & 0 \\ 0 & -9.1676 & 12.5013 & -3.3337 & 0 \\ -3.2569 & 0 & -3.3337 & -9.9242 & 3.3337 \\ -15.4703 & 0 & 0 & 3.3337 & 18.8040 \end{bmatrix}$$

$$B = \begin{bmatrix} -222.4844 & 35.2348 & 0 & 32.5690 & 154.7030 \\ 35.2348 & -126.8979 & 91.6758 & 0 & 0 \\ 0 & 91.6758 & -124.9999 & 33.3367 & 0 \\ 32.5690 & 0 & 33.33367 & -99.2324 & 33.3367 \\ 154.7030 & 0 & 0 & 33.3367 & -188.0206 \end{bmatrix}$$

The generator sensitivity factor is obtained by substituting the values of $\frac{\partial P_{ij}}{\partial \theta_i}$, $\frac{\partial P_{ij}}{\partial \theta_j}$, $\frac{\partial \theta_i}{\partial P_g}$ and $\frac{\partial \theta_j}{\partial P_g}$ in equation 3. The values of $\frac{\partial P_{ij}}{\partial \theta_i}$ and $\frac{\partial P_{ij}}{\partial \theta_j}$ is calculated from the equation 4. The values of the other half of the equation 3 i.e. the $\frac{\partial \theta_i}{\partial P_g}$ and $\frac{\partial \theta_j}{\partial P_g}$ can be obtained from the inverse of J_{11} matrix from the Jacobian matrix. The MAPOWER built in source code is modified for obtaining the values of $\frac{\partial \theta_i}{\partial P_g}$ and $\frac{\partial \theta_j}{\partial P_g}$ from the inverse of J_{11}. The modification in the coding is shown in the figure 5. In order to obtain the generator sensitivity factors the values of $\frac{\partial \theta_i}{\partial P_g}$ and $\frac{\partial \theta_j}{\partial P_g}$ is substituted from M matrix in equation 3. M matrix is the inverse of the J_{11} matrix. J_{11} is a component of the Jacobian Matrix. The value of M matrix for the 5 bus system is given below

$$M = \begin{bmatrix} 0.0212 & 0.0093 & 0.0211 & 0.0127 \\ 0.0090 & 0.0212 & 0.0090 & 0.0180 \\ 0.0212 & 0.0093 & 0.0275 & 0.0127 \\ 0.0124 & 0.0180 & 0.0123 & 0.0246 \end{bmatrix}$$

The value of M matrix is required to determine the value of $\frac{\partial \theta_i}{\partial P_g}$ and $\frac{\partial \theta_j}{\partial P_g}$. Finally we get GSF_G values.

TABLE III: GENERATOR SENSITIVITY FACTOR FOR 5 BUS SYSTEM

Congested Line	GSF1	GSF2	GSF3	GSF5
1-2	0.2670	-0.0468	0.4580	-0.2745
1-5	0.7140	-0.1520	0.1580	0.1892

TABLE IV: GENERATOR SENSITIVITY FACTOR FOR 30 BUS SYSTEM

Congested Line	GSF2	GSF13	GSF22	GSF23	GSF27
6-8	-0.0231	-0.0375	-0.0831	-0.0410	0.0823

The generator sensitivity factors for the 5 bus system are shown in the figure 6 and figure 7 for the congested line 1-2 and 1-5. Same method has been followed to determine the GSF_G along the congested line of a 30 bus system. The generator sensitivity values obtained are with respect to the slack bus as the reference. So the sensitivity of the slack bus generator to any congested line in the system is always zero. The generators having large and non uniform values of sensitivity factor will take part in the congestion management. It is observed from Figure 6 and Figure 7 that all the generators are having non-uniform GSF_G values, so all the generators will take part in congestion relief. The generators with positive GSF_G values will decrease their generation and the generators with negative GSF values will increase their generation. In case of the 30 bus system in figure 8 the generators G2, G22 and G27 having high sensitivity index will take part in the congestion management scheme.

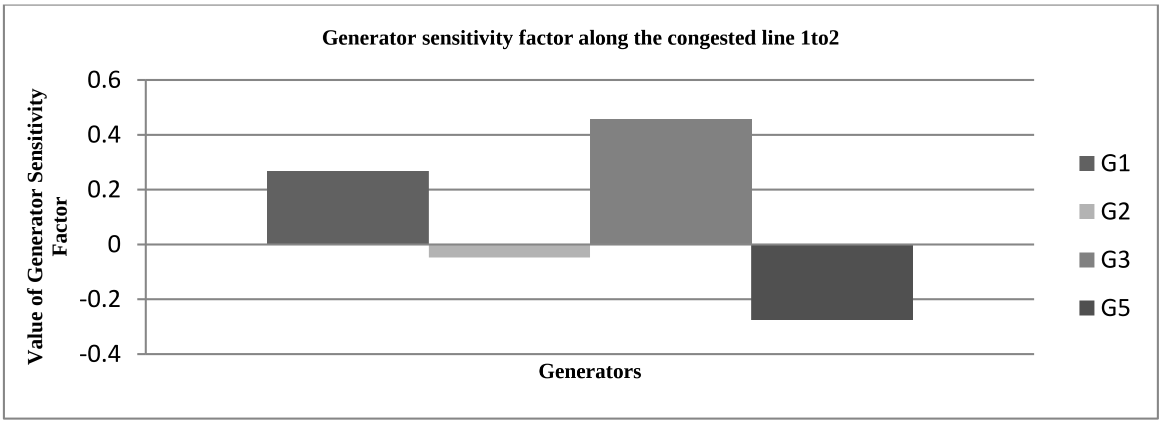

Figure 6: Generator sensitivity factor along the congested line 1-2 for 5 bus system

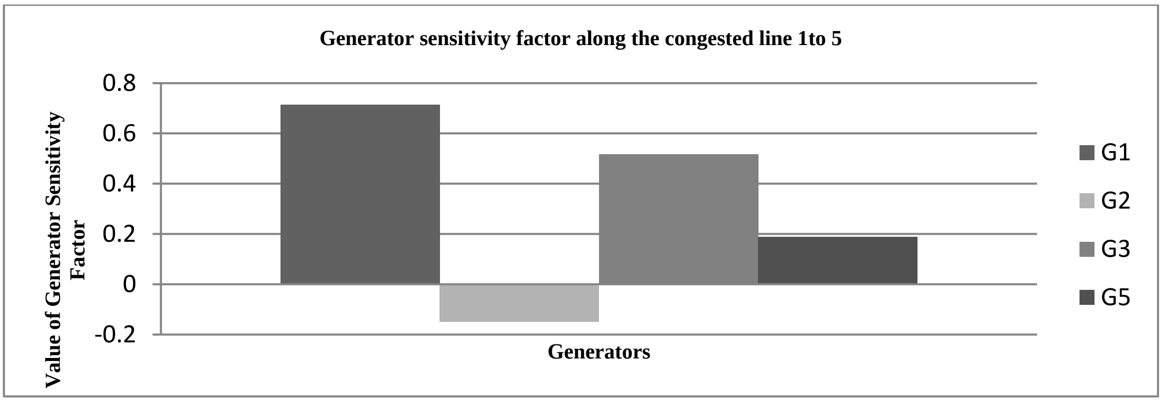

Figure 7: Generator Sensitivity Factor along the congested line 1- 5 for 5 bus system

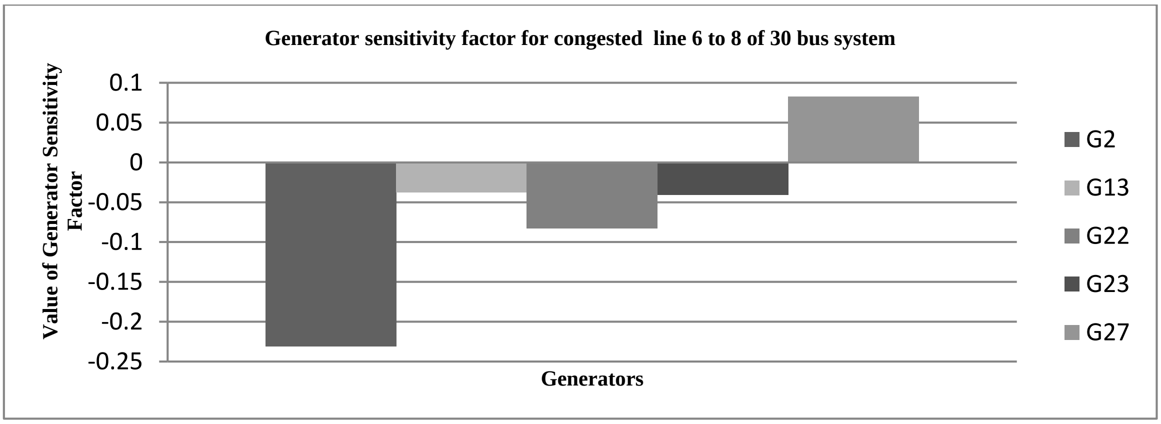

Figure 8: Generator Sensitivity Factor along the congested line 6-8 line for 30 bus system

CONCLUSION

This paper has presented the use of MATPOWER as an efficient tool for the analysis of the congestion in the power system network and the calculation of the generator sensitivity factor for the selection of the generators which has to be rescheduled for the elevation of congestion in the power system network. Apart from this MATPOWER is a proficient tool for high level power flow studies that will enhance the performance of the research scholars and students by reducing the huge amount of time invested in laborious efforts to design the power flow programs and solve complex calculations in the respective field of the power system studies. The inbuilt power flow solver is well efficient to deal with small as well as large system. The MATPOWER also displays several other details like the active and reactive power losses, magnitude of the maximum and minimum voltages etc. The ability of the user to change the source code according to their requirement gives an advantage to deal with complex problem like calculation of the generator sensitivity factor and also the other contingency analysis like line outage.

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