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Comparison between Different Load Flow Methodologies by Analyzing Various Bus Systems

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Abstract

Load flow study is a numerical analysis of the flow of power in an inter-connected power system. This analysis has been done at the state of planning, operation, control and economic scheduling. Results of such an analysis have been presented in terms of active power, reactive power, voltage magnitude and phase angle. Steady state active power and reactive power supplied at a bus has been expressed as non-linear algebraic equations. Iterative methods have been required for solving these equations. Objective of this paper is to develop a MATLAB program to calculate voltage magnitude and phase angle, active power & reactive power at each bus for IEEE 6, 9, 14, 30 and 57 bus systems. In this paper three methods for load flow analysis: Gauss-Siedel method, Newton-Raphson method and Fast-Decoupled method, have been used. The three load flow methods have been compared on the basis of number of iterations obtained.

Keywords: Load Flow Analysis, Bus Admittance Matrix [Y_{bus}], Power Systems, Bus Power, Jacobian Matrix, Static Load Flow Equations

1. INTRODUCTION

In a power system, power flows from generating stations to load centres. So investigation has been required to find the bus voltages and amount of power flow through transmission lines. Hence it is convenient to work with power injected at each bus into the transmission system, called the ‘Bus Power’. Power flow study aims at reaching the steady state solution of complete power networks.
Performing a load flow study on an existing system recommends optimized operation of power system [1].

Each transmission line has been presents admittance between the bus and the ground. If there is no transmission line between i^{th} and j^{th} bus, then the corresponding element of Bus Admittance matrix Y_{ij} is 0 [4].

$$I_{bus} = Y_{bus} . V_{bus}$$

$$\begin{bmatrix} I_1 \\ \vdots \\ I_i \\ \vdots \\ I_n \end{bmatrix} = \begin{bmatrix} Y_{11} & \cdots & Y_{1i} & \cdots & Y_{1n} \\ \vdots & & \vdots & & \vdots \\ Y_{i1} & \cdots & Y_{ii} & \cdots & Y_{in} \\ \vdots & & \vdots & & \vdots \\ Y_{n1} & \cdots & Y_{ni} & \cdots & Y_{nn} \end{bmatrix} \begin{bmatrix} V_1 \\ \vdots \\ V_i \\ \vdots \\ V_n \end{bmatrix}$$

where Y_{ij} is Admittance of line between i^{th} and j^{th} bus, V_i is i^{th} bus voltage and I_i is bus current at i^{th} bus.

Each method has its advantages and disadvantages. Comparison of these methods has been made useful to select the best method for a typical network. This paper analyzes and compares the most important methods for load flow studies of power system. The methods have been introduced and analysed in second section. Proposed work and results have been presented in the third section followed by work evaluation and conclusion. The Bus data and Line data required for load flow analysis have been taken from [2, 3].

2. LOAD FLOW METHODS

The most important load flow methods are categorised as: Gauss-Siedel method, Newton-Raphson method and Fast Decoupled method [5].

The Nomenclature used in Load flow analysis is: V_i - i^{th} bus voltage; V_j - j^{th} bus voltage; Y_{ij} - Admittance of line between i^{th} and j^{th} bus; Y_{ii} - Self admittance of line connected to i^{th} bus; P_i - Real power injected into i^{th} bus; Q_i - Reactive power injected into i^{th} bus; I_i - Bus current at i^{th} bus; θ_{ij} - Angle of Y_{ij} element of Y_{bus}; δ_i- Voltage angle of i^{th} bus; i, j - Integer (0 to n); N - No. of buses.

The common procedure adopted for analysing power flow in a power system by using any of the load flow techniques is discussed in the pseudo-code shown in Fig.1 [7].

```
# Start
# Create Ybus
# Make initial assumptions as the old values
# Substitute the old values into power equations for the next iteration
# Obtain the new value
# New value – Old value
# If (New value – Old value) < specified tolerance; then end otherwise go to step 4.
```

Fig.1: Pseudo-code for procedure for analysing load flow in a power system

2.1 Gauss-Siedel (GS) load flow method

With the slack bus voltage assumed (usually $V_1 = 1\angle 0^o$ p.u.), the remaining (n-1) bus voltages are found through iterative process as follows [4]:

$$P_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}|\cos(\theta_{ij} - \delta_i + \delta_j) \tag{1}$$

$$Q_i = -\sum_{j=1}^{n} |V_i||V_j||Y_{ij}|sin(\theta_{ij} - \delta_i + \delta_j) \tag{2}$$

The equation 1 and 2 are called static load flow equations.

$$I_i = \frac{P_i - jQ_i}{V_i^*} \tag{3}$$

$$V_i = \frac{1}{Y_{ii}}\left(I_i - \sum_{\substack{j=1 \\ j\neq 1}}^{n} Y_{ij}V_j\right) \quad i = 2,3,4\ldots n \tag{4}$$

For $(k+1)^{th}$ iteration, the voltage equation becomes

$$V_i^{(k+1)} = \frac{1}{Y_{ii}}\left[\frac{P_i - jQ_i}{(V_i^k)^*} - \sum_{j=1}^{i-1}(Y_{ij}\,V_j^{k+1}) - \sum_{j=i+1}^{n}(Y_{ij}V_j^k)\right] \tag{5}$$

2.2 Newton-Raphson (NR) load flow method

Because of the quadratic convergence, Newton-Raphson method is mathematically superior to Gauss siedel method [8]. It is found to be more efficient method for large power systems. The Jacobian matrix gives the linearized relationship between small changes in voltage angle $\Delta\delta$ and voltage magnitude ΔV with the small changes in active and reactive power ΔP and ΔQ.

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = [\,\mathrm{J}\,]\begin{bmatrix}\Delta\delta\\ \Delta V\end{bmatrix}$$

$$\text{here } [\mathrm{J}] = \begin{bmatrix}\mathrm{J1} & \mathrm{J2}\\ \mathrm{J3} & \mathrm{J4}\end{bmatrix}$$

The matrix of partial differentials is called the Jacobian matrix [J]. The elements of the Jacobian are calculated by differentiating the active power and reactive power Eqs.1 & 2 and substituting the estimated values of voltage magnitude and phase angle. Table 1 describes the details of Jacobian Matrix [6].

Table 1: Description of Jacobian matrix

Element of J matrix	Order of J matrix elements	Diagonal elements	Off-diagonal elements
J1	(n-1) x (n-1)	$\frac{\partial P_i}{\partial\lvert\delta_i\rvert} = \sum_{j\neq i}\lvert V_i\rvert\lvert V_j\rvert\lvert Y_{ij}\rvert \sin(\theta_{ij} - \delta_i + \delta_j)$	$\frac{\partial P_i}{\partial\lvert\delta_j\rvert} = -\lvert V_i\rvert\lvert V_j\rvert\lvert Y_{ij}\rvert \sin(\theta_{ij} - \delta_i + \delta_j)\,,\ j\neq i$
J2	(n-1) x (n-1-n_{pv})	$\frac{\partial P_i}{\partial\lvert V_i\rvert} = 2\lvert Vi\rvert\lvert Yii\rvert \cos\theta_{ii} + \sum_{j\neq i}\lvert V_i\rvert\lvert Y_{ij}\rvert \cos(\theta_{ij} - \delta_i + \delta_j)$	$\frac{\partial P_i}{\partial\lvert V_j\rvert} = \lvert V_i\rvert\lvert Y_{ij}\rvert \cos(\theta_{ij} - \delta_i + \delta_j)\,,\ j\neq i$
J3	(n-1-n_{pv}) x (n-1)	$\frac{\partial Q_i}{\partial\lvert\delta_i\rvert} = \sum_{j\neq i}\lvert V_i\rvert\lvert V_j\rvert\lvert Y_{ij}\rvert \cos(\theta_{ij} - \delta_i + \delta_j)$	$\frac{\partial Q_i}{\partial\lvert\delta_j\rvert} = -\lvert V_i\rvert\lvert V_j\rvert\lvert Y_{ij}\rvert \cos(\theta_{ij} - \delta_i + \delta_j)$
J4	(n-1-n_{pv}) x (n-1-n_{pv})	$\frac{\partial Q_i}{\partial\lvert V_i\rvert} = -2\lvert Vi\rvert\lvert Yii\rvert \sin\theta_{ii} - \sum_{j\neq i}\lvert V_i\rvert\lvert Y_{ij}\rvert \sin(\theta_{ij} - \delta_i + \delta_j)$	$\frac{\partial Q_i}{\partial\lvert V_j\rvert} = -\lvert V_i\rvert\lvert Y_{ij}\rvert \sin(\theta_{ij} - \delta_i + \delta_j)\ \ j\neq i$

Where n_{pv} is the number of PV buses.

The terms ΔP_i^r and ΔQ_i^r are the difference between the scheduled and calculated valued, known as mismatch vector or power residuals, given by

$$P_i\ (\text{scheduled}) - P_i^r\ \text{calculated} = \Delta P_i^r$$

$$Q_i\ (\text{scheduled}) - Q_i^r\ \text{calculated} = \Delta Q_i^r \tag{6}$$

Q_i (scheduled) – Q_i^r calculated = ΔQ_i^r (6) to update voltage magnitude and angles:

$$|V|^{(r+1)} = |V|^r + |\Delta V|^r$$

$$\delta(r+1) = \delta\, r + \Delta\delta\, r \qquad (7)$$

where r = no. of iteration

2.3 Fast Decoupled load flow (FDLF) method

In FDLF method, the convergence is geometric, 2 to 5 iterations are normally required for practical accuracies, speed for iterations of the FDLF is nearly five times that of NR method or about two-thirds that of the GS method [9]. Here B_{ii} -Imaginary part of diagonal elements of Y_{bus} ; B_{ij} - Imaginary part of off-diagonal elements of Y_{bus} ; θ_{ii}-Angle of Y_{ii} element of Y_{bus} ; B'-Imaginary part of Y_{bus} of order (n-1) x (n-1) ; B''- Imaginary part of Y_{bus} of order (n-1-n_{pv}) x (n-1-n_{pv}).

The diagonal elements of J_1 described by [5]

$$\frac{\partial P_i}{\partial \delta_i} = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}|sin(\theta_{ij}-\delta_i+\delta_j) - |V_i|^2|Y_{ii}|sin\theta_{ii}$$

Replacing the first term of the above equation with - Q_i, as given by

$$\frac{\partial P_i}{\partial \delta_i} = - Q_i - |V_i|^2|Y_{ii}|sin\theta_{ii}$$
$$= - Q_i - |V_i|^2 B_{ii}$$

$$B_{ii} >> Q_i,\ and\ |V_i|^2 \approx |V_{ii}|$$

$$\frac{\partial P_i}{\partial \delta_i} = - |V_i|B_{ii}$$

Similarly, $\frac{P_i}{\partial \delta_i} = - |V_i|B_{ij}$

The diagonal elements of J_4 described by

$$\frac{\partial Q_i}{\partial |V_i|} = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}|sin(\theta_{ij}-\delta_i+\delta_j) - |V_i||Y_{ii}|sin\theta_{ii}$$

$$\frac{\partial Q_i}{\partial |V_i|} = Q_i - |V_i||Y_{ii}|\ sin\theta_{ii} \text{ since } B_{ii} = Y_{ii}\sin\theta_{ii} >> Q_i$$

$$\frac{\partial Q_i}{\partial |V_i|} = - |Vi|Bii$$

Again, assuming θ_{ij}-δ_i+δ_j $\approx\theta_{ij}$, yields

$$\frac{\partial Q_i}{\partial |V_j|} = - |V_i| B_{ij}$$

With these assumptions, now equation becomes

$$\frac{\Delta P}{|V_i|} = -B' \Delta\delta \tag{8}$$

$$\frac{\Delta Q}{|V_i|} = -B'' \Delta|V| \tag{9}$$

Now the value of $\Delta\delta$ and $\Delta|V|$ is obtained by

$$\Delta\delta = -[B'] \frac{\Delta P}{|V|} \tag{10}$$

$$\Delta|V| = -[B''] \frac{\Delta Q}{|V|} \tag{11}$$

3. PROPOSED WORK & RESULTS

By implementing different load flow techniques in the MATLAB environment, the codes have been developed and the results obtained. Graph series 3.1 describes the Voltage magnitude v/s bus number for various IEEE buses by using Gauss-Siedel, Newton-Raphson and Fast-Decoupled methods. Graph series 3.2 describes the Voltage Angle across Bus number for various IEEE buses by using Gauss-Siedel, Newton-Raphson and Fast-Decoupled methods. Graph series 3.3 presents the Active Power across Bus number for various IEEE buses by using Gauss-Siedel, Newton-Raphson and Fast-Decoupled methods whereas Graph series 3.3 presents the Reactive Power across Bus number for various IEEE buses by using Gauss-Siedel, Newton-Raphson and Fast-Decoupled methods. Figure (a) of each series stands for IEEE 6 bus system, Figure (b) for IEEE 9 bus system, Figure (c) for IEEE 14 bus system, Figure (d) for IEEE 30 bus system and Figure (e) for IEEE 57 bus system.

3.1 Voltage magnitude *v/s* bus number for various IEEE buses by using Gauss-Siedel, Newton-Raphson and Fast-Decoupled methods:

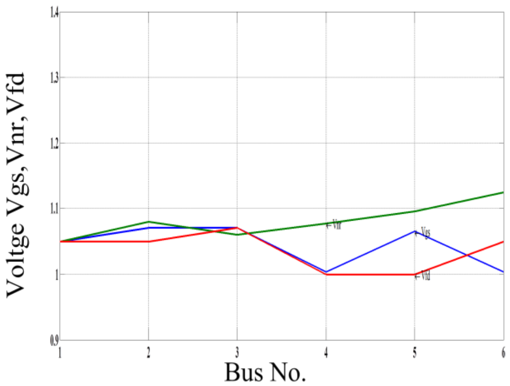


Fig 3.1(a)

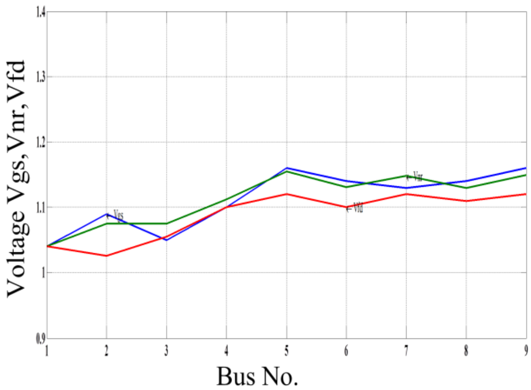


Fig 3.1(b)

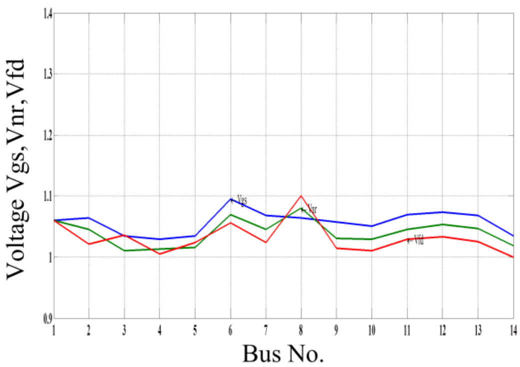


Fig 3.1(c)

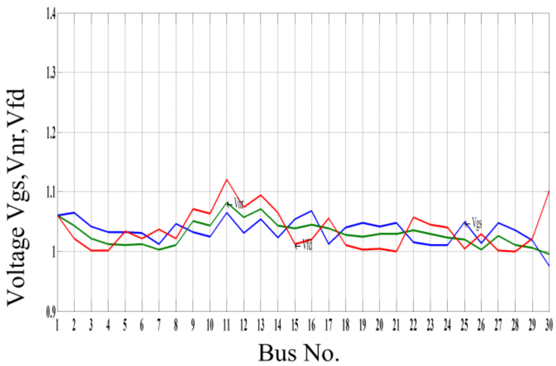


Fig 3.1(d)

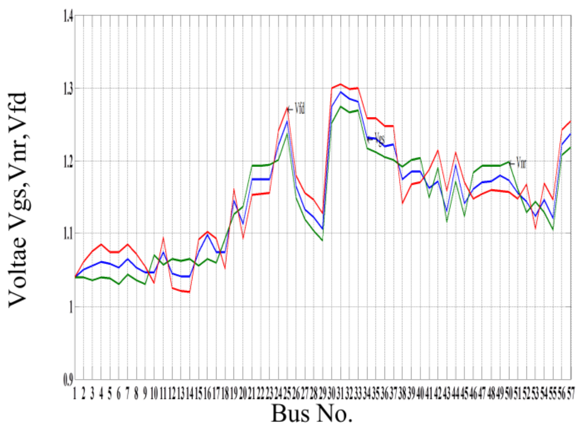


Fig 3.1(e)

3.2 Voltage Angle across Bus number for various IEEE buses by using Gauss-Siedel, Newton- Raphson and Fast-Decoupled methods:

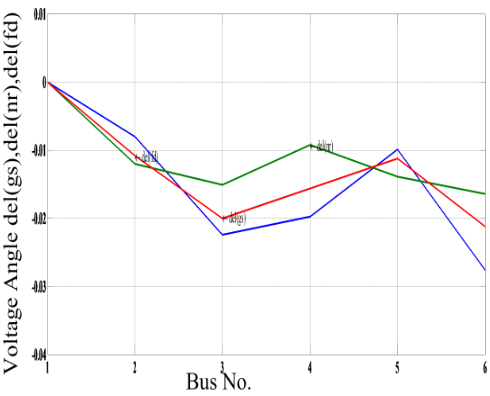


Fig 3.2(a)

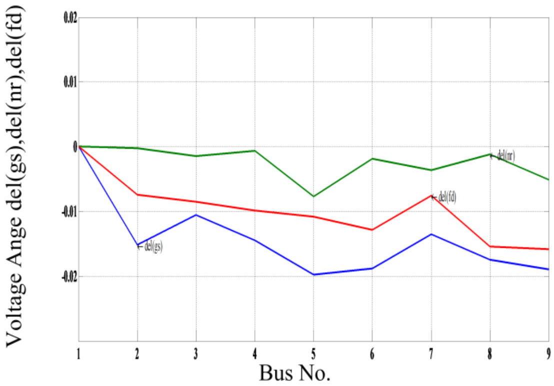


Fig 3.2(b)

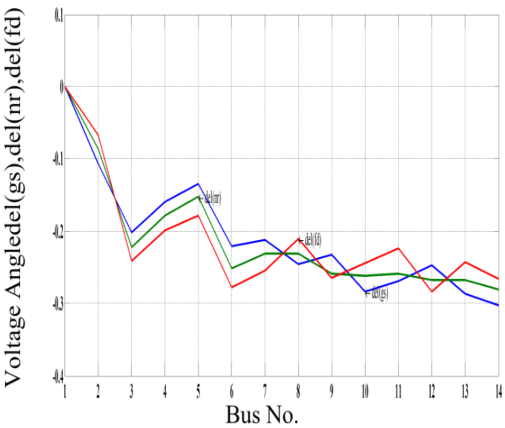


Fig 3.2(c)

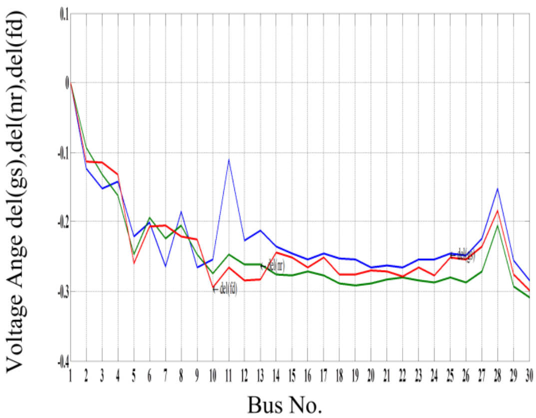


Fig 3.2(d)

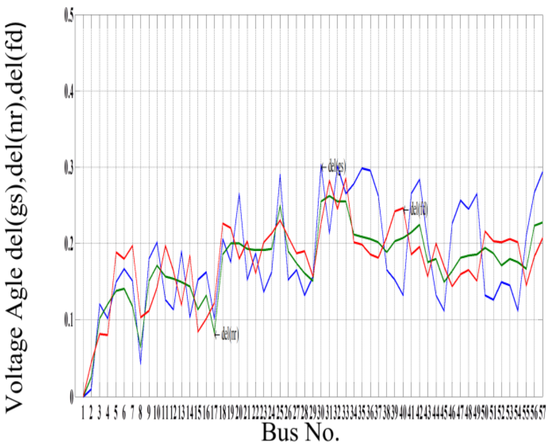


Fig 3.2(e)

3.3 Active Power across Bus number for various IEEE buses by using Gauss-Siedel, Newton-Raphson and Fast-Decoupled methods:

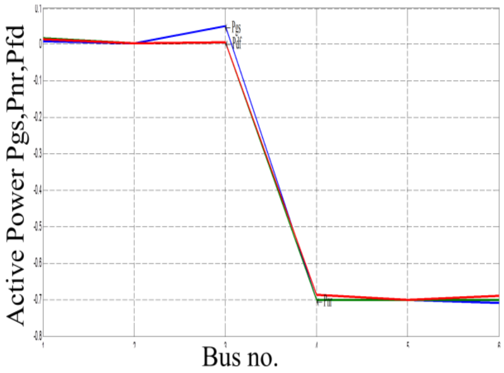
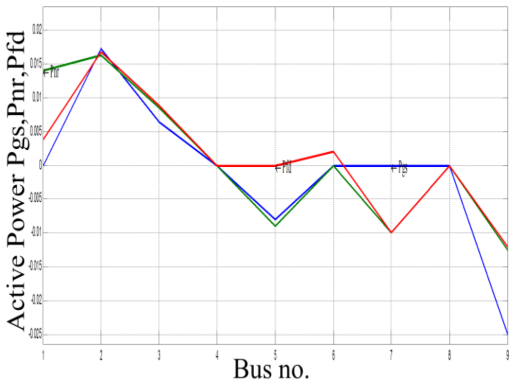
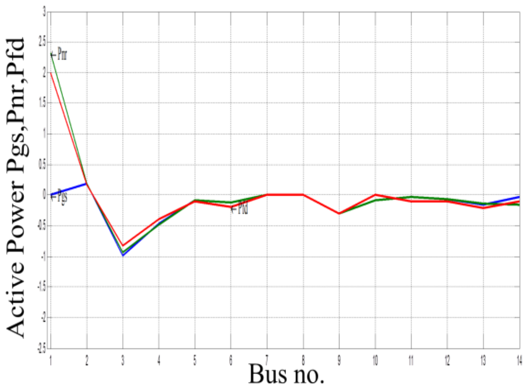


Fig 3.3(a)





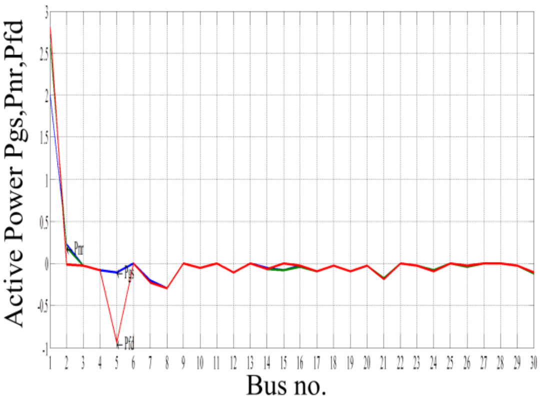


Fig 3.3(d)

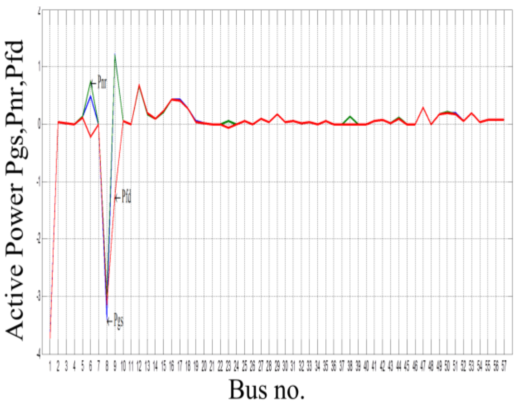


Fig 3.3(e)

3.4 Reactive Power across Bus number for various IEEE buses by using Gauss-Siedel, Newton-Raphson and Fast-Decoupled methods:

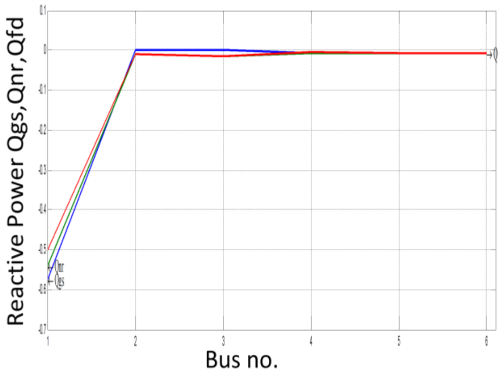


Fig 3.4(a)

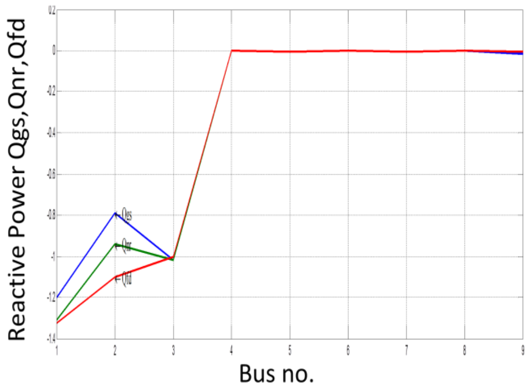


Fig 3.4(b)

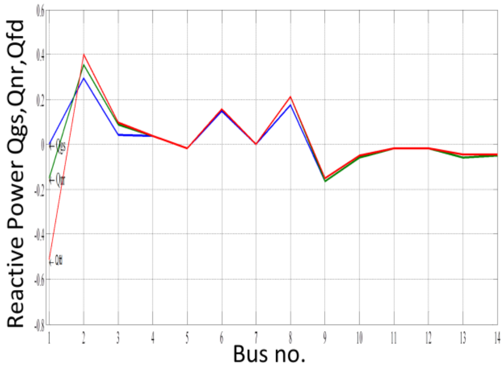


Fig 3.4(c)

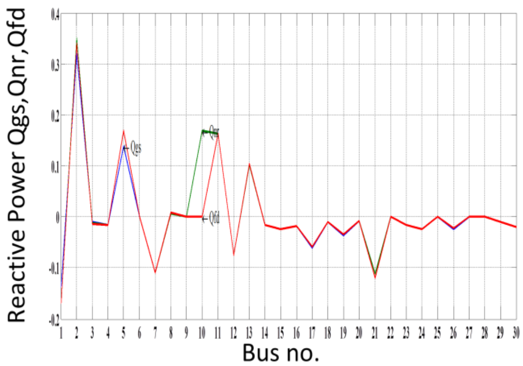


Fig 3.4(d)

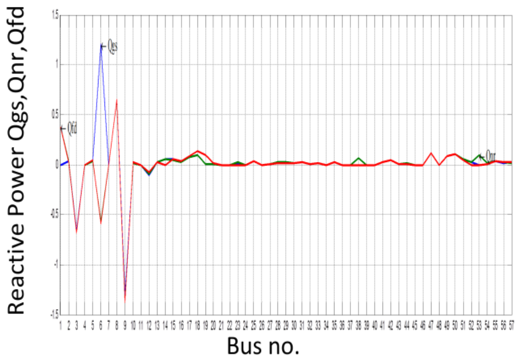


Fig 3.4(e)

4. WORK EVALUATION

The above results show that Gauss-Siedel method is simple and easy to execute but it consumes more time (more iterations) as the number of buses increases; Newton Raphson method is more accurate than all other methods and it provides better results in less number of iterations; Fast Decoupled method is the fastest of all methods but is less accurate since assumptions are taken for fast calculation.

Table 2: No. of iterations by applying various load flow methods on various bus systems

Method Used→ Bus No.↓	**Gauss-Siedel Method**	**Newton - Raphson method**	**Fast-Decoupled method**
6	24	11	2
9	182	11	2
14	384	7	2
30	648	5	2
57	864	11	2

CONCLUSION

This paper concludes that out of all the conventional load flow methods discussed above, Gauss- Siedel method needs more iterations as compared to other methodologies for the same values of |V|, angle, active and reactive power. Also, Newton Raphson method gives better results than GS method for a fewer no. of iterations. Fast Decoupled method gives the approximately same results as obtained by NR method with least no. of iterations.

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