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Comparative Analysis of Load Flow Methods for Different Network System

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Abstract - The objective of this paper is to develop a MATLAB program to calculate voltages magnitude, angle of voltage, active and reactive power at each bus for IEEE 9, IEEE 14 bus, IEEE 30 and IEEE 57 bus system. At first IEEE 9 bus system MATLAB program is executed with the input data then IEEE 14, IEEE 30 and IEEE 57 bus is executed with the input data. This type of analysis is useful for solving the power flow problem in different power systems which will useful to calculate the unknown quantities. Simulation is carried out using MATLAB for test cases of IEEE 9-Bus, IEEE 14-Bus, IEEE 30-Bus and IEEE 57-Bus system. The simulation results were compared for number of iteration and tolerance value. The compared results show that Newton-Raphson is the most reliable method because it has the least number of iteration and converges faster.

***Keywords* - Load Flow, Gauss-Seidel, Newton-Raphson, Fast-Decoupled, Voltage, Phase angle, Active Power, Reactive Power, Iteration, Convergence.**

1. Introduction

The power system analysis and design is generally done by using power flow analysis. This analysis is carried out at the state of planning, operation, control and economic scheduling. The main information obtained from the load flow or power flow analysis comprises magnitudes and phase angles of load bus voltages, reactive powers and voltage phase angles at generator buses, real and reactive power flows on transmission lines together with power at the reference bus; other variables being specified. The problem that faces power industry is how to determine which method is most suitable for a power system analysis. In power flow analysis, high degree accuracy and a faster solution time are required to determine which method is best to use. For this work the Gauss-Seidel method, Newton-Raphson Method and Fast-Decoupled Method are used for numerical analysis.

2. Bus Classification

A bus is a point or node in which one or many transmission lines, loads and generators are connected. In a power system study, every bus is associated with four quantities, such as magnitude of voltage (|V|), phase angle of voltage (δ), active power (P) and reactive power (Q) [3]. The buses are classified depending on the two known quantities that have been specified. Buses are divided into four categories.

2.1 Slack Bus/ Swing Bus/ Reference Bus

This bus is the first to respond to a changing load condition. Voltage magnitude $|V_i|$ and phase angle δ_i are specified for this bus. This bus is distinguished from the remaining types by the fact that real and reactive powers at this bus are not specified. Usually, there is only one bus of this type in a given power system. For convenience, the slack bus is numbered 1. After the load flow solution is complete, the real power at slack bus (P_1) is known, and hence the real power generation P_{G1} is known and P_{D1} is known from the load forecasting. As V_1 is already specified for a slack bus, such slack bus must be a generator bus or we can say a generator bus with maximum generating capacity is chosen as slack bus. Without slack bus load flow problem never converges that why slack bus is needed for load flow solution.

2.2 PQ Bus/ Load Bus

At this type of bus, the real power P_i and reactive power Q_i are known.

$$P_i + jQ_i = (P_{Gi} - P_{Di}) + j(Q_{Gi} - Q_{Di})$$

Where P_{Di} and Q_{Di} are known from the load forecasting and P_{Gi} and Q_{Gi} are specified variables. The unknowns are $|V_i|$ and δ_i .

PQ bus is called load bus , if there is no generating facility at this bus, i.e. $P_{Gi} = Q_{Gi} = 0$. PQ buses are the most common buses, comprising almost 85% of all the buses in a power system. Voltage control buses are also considered as PQ buses.

2.3 PV Bus/ Generator Bus

A PV bus has always must be equipped with either generator or by voltage control equipment. At this bus P_i and $|V_i|$ are specified variables and Q_i and δ_i are unspecified variables. Here P_{Di} is known from the load forecasting. PV buses comprise about 10% of all the buses in a power system.

2.4 Voltage Controlled Bus

The PV bus and voltage controlled bus are group together. But they are slightly different in calculation strategies and have some physical differences. The voltage control bus has voltage control capabilities, and instead a generator they use a tap-adjustable transformer and/ or static var compensator. At this bus $P_{Gi} = Q_{Gi} = 0$. Hence $P_i = -P_{Di}$, $Q_i = -Q_{Di}$, and $|V_i|$ are known at these buses and the unknown is δ_i .

3. Power Flow Analysis Methods

The numerical analysis involving the solution of algebraic simultaneous equations forms the basis for solution of the performance equations in computer aided electrical power system analyses e.g. for load flow analysis. The first step in performing load flow analysis is to form the *Y*-bus admittance using the transmission line and transformer input data. The nodal equation for a power system network using *Y* bus can be written as follows:

$$I = Y_{Bus} V \qquad (1)$$

The complex power injected by the source into the i[th] bus of a power system is

$$S_i = P_i + jQ_i = V_i I_i^* \qquad (2)$$

Where

$$i = 1, 2, \dots, n$$

It is appropriate to work with I_i instead of I_i^*, so the complex conjugate of the above equation is considered,

$$P_i - jQ_i = V_i^* I_i, \qquad (3)$$

for $i = 1, 2, \dots, n$

Substituting $I_i = \left(\Sigma_{k=1}^{n}(Y_{ik}V_k)\right)$ in the above equation, we have

$$P_i - jQ_i = V_i^*\left(\Sigma_{k=1}^{n}(Y_{ik}V_k)\right) \qquad (4)$$

$$i = 1, 2, \dots, n$$

Separating real and imaginary parts, we get

P_i (Real power) = Real $\left(V_i^*\left(\Sigma_{k=1}^{n}(Y_{ik}V_k)\right)\right)$

Q_i(Reactive power) =
- Imaginary $\left(V_i^*\left(\Sigma_{k=1}^{n}(Y_{ik}V_k)\right)\right)$

Let $V_i = |V_i|e^{j\delta_i}$, $V_k = |V_k|e^{j\delta_k}$
$Y_{ik} = |Y_{ik}|e^{j\delta_{ik}}$

Then

$$P_i(Real\ Power) = |V_i|\sum_{k=1}^{n}|V_k||Y_{ik}|\,cos(\theta_{ik} + \delta_k + \delta_i) \qquad (5)$$

$$Q_i(Reactive\ Power) = -|V_i|\sum_{k=1}^{n}|V_k||Y_{ik}|\,sin(\theta_{ik} + \delta_k + \delta_i) \qquad (6)$$

$$i = 1, 2, \dots, n$$

3.1 Gauss-Seidel Method

The Gauss-seidel method is an iterative algorithm for solving a set of non-linear algebraic equations. The total current entering the k^{th} bus of an n-bus system is given by

$$I_k = Y_{k1}V_1 + Y_{k2}V_2 + \cdots + Y_{kn}V_n = \sum_{i=1}^{n} Y_{ki}V_i \qquad (7)$$

The complex power injected into the k^{th} bus is given by

$$S_k = P_k + jQ_k = V_k I_k^* \qquad (8)$$

The complex conjugate of above equation is given as

$$S_k = P_k - jQ_k = V_k^* I_k \qquad (9)$$

$$I_k = \frac{1}{V_k^*}(P_k - jQ_k) \qquad (10)$$

Eliminate I_k from equation

$$Y_{k1}V_1 + Y_{k2}V_2 + \cdots + Y_{kk}V_k + \cdots + Y_{kn}V_n = \frac{1}{V_k^*}(P_k - jQ_k) \quad (11)$$

Therefore, the voltage at bus k is given by

$$V_k = \frac{1}{Y_{kk}}\left[\frac{P_k - jQ_k}{V_k^*} - \sum_{\substack{i=1 \\ i \neq k}}^{n} Y_{ki}V_i\right] \quad (12)$$

Where P_k and Q_k are specified.

At bus 2,

$$V_2 = \frac{1}{Y_{22}}\left[\frac{P_2 - jQ_2}{V_2^*} - Y_{21}V_1 - Y_{23}V_3 - \cdots - Y_{2n}V_n\right]$$

At bus 3,

$$V_3 = \frac{1}{Y_{33}}\left[\frac{P_3 - jQ_3}{V_3^*} - Y_{31}V_1 - Y_{32}V_2 - Y_{34}V_4 - \cdots - Y_{3n}V_n\right]$$

3.2 Newton-Raphson Method

The Newton-Raphson method is a powerful method which can be applied for linear or non-linear algebraic equations. It works faster as compared to the Gauss-Seidel (GS) method. It has only one drawback that is large requirement of computer memory which can be overcome by using a compact storage scheme.

There are two methods for power flow problem using NR method. The first uses rectangular coordinates form and other one uses polar coordinates for the variables which depending upon bus voltages may be expressed in the rectangular form or polar form. The polar coordinates method is used widely.

$$S_i = P_i + Q_i = V_i \sum_{k=1}^{n} Y_{ik}^* V_k^* \quad (13)$$

$$\sum_{k=1}^{n} |V_i||V_K||Y_{ik}| \angle(\delta_i - \delta_k - \theta_{ik}) \quad (14)$$

$$P_i = \sum_{k=1}^{n} |V_i||V_K||Y_{ik}| \cos(\delta_i - \delta_k - \theta_{ik}) \quad (15)$$

$$Q_i = \sum_{k=1}^{n} |V_i||V_K||Y_{ik}| \sin(\delta_i - \delta_k - \theta_{ik}) \quad (16)$$

$$\Delta P_i = \frac{\partial P_i}{\partial \delta_1}\Delta\delta_1 + \frac{\partial P_i}{\partial \delta_2}\Delta\delta_2 + \cdots + \frac{\partial P_i}{\partial \delta_n}\Delta\delta_n + \frac{\partial P_i}{\partial |V_1|}\Delta|V_1| + \frac{\partial P_i}{\partial |V_2|}\Delta|V_2| + \cdots + \frac{\partial P_i}{\partial |V_n|}\Delta|V_n| \quad (17)$$

And

$$\Delta Q_i = \frac{\partial Q_i}{\partial \delta_1}\Delta\delta_1 + \frac{\partial Q_i}{\partial \delta_2}\Delta\delta_2 + \cdots + \frac{\partial Q_i}{\partial \delta_n}\Delta\delta_n + \frac{\partial Q_i}{\partial |V_1|}\Delta|V_1| + \frac{\partial Q_i}{\partial |V_2|}\Delta|V_2| + \cdots + \frac{\partial Q_i}{\partial |V_n|}\Delta|V_n| \quad (18)$$

For $i = 1, 2, 3 \ldots n$.

3.3 Fast Decoupled Power Flow Method

Decoupled method is an advance version of the NR method, while fast decoupled method is an advance version of the decoupled method. In fast decoupled method the power flow calculations can be made faster by making suitable assumptions.

Fast-decoupled method converges very reliably and fast in two to five iterations. In other words, a good approximate solution is obtained after first or second iteration.

4. Input Data

Figure 1 show IEEE 9-Bus System one line diagram.

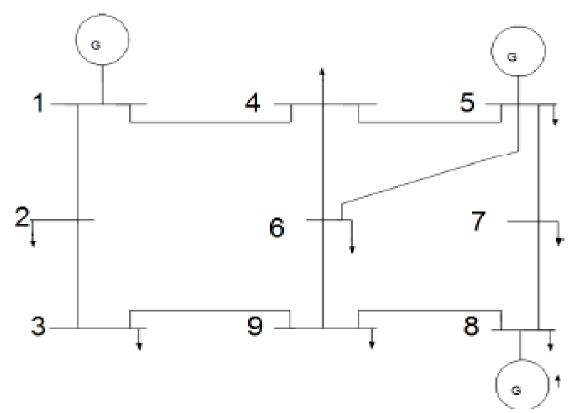


Fig1: IEEE 9 Bus System

IEEE 9 bus system represented in Figure 1 consist of Bus 1 which act as a slack bus. It consist of 8 load buses, which are bus connected to load and 2 generator buses which are connected to generator.

Table 1: Input Line Data of IEEE 9 Bus System.

From Bus	To Bus	R (p.u)	X (p.u)	B/2(p.u)	X'mer Tap (a)
1	2	0.0180	0.0540	0.0045	1
1	4	0.0150	0.0450	0.0038	1
2	3	0.0180	0.0560	0.0000	1
3	9	0.0200	0.0600	0.0000	1
4	5	0.0130	0.0360	0.0030	1
4	6	0.0200	0.0660	0.0000	1
5	6	0.0600	0.0300	0.0028	1
5	7	0.0140	0.0360	0.0030	1
6	9	0.0100	0.0500	0.0000	1
7	8	0.0320	0.0760	0.0000	1
8	9	0.0220	0.0650	0.0000	1

Table 2: Bus Data Input of IEEE 9 Bus System.

Bus No	Bus Type	Voltage	Angle	Pg	Qg	Pl	Ql	Qmin	Qmax
1	1	1.0300	0	0	0	0	0	0	0
2	2	1.0000	0	10	5	0	0	-40	50
3	2	1.0000	0	25	15	0	0	0	40
4	3	1.0000	0	60	40	0	0	0	0
5	3	1.0600	0	10	5	80	0	0	0
6	2	1.0000	0	100	80	0	0	-6	24
7	3	1.0000	0	80	60	0	0	0	0
8	2	1.0100	0	40	20	120	0	-6	24
9	3	1.0000	0	20	10	0	0	0	0

The Matlab program works according to the given data (Table 1) at the input and gives us Ybus matrix. Ybus play an important role to determine the load flow condition without this its impossible. This Ybus is used to determine the active power flow, reactive power flow, voltage magnitude and load angle at different buses.

5. Simulation Results

The simulation for Gauss-Seidel Method, Newton-Raphson Method and Fast Decoupled method is carried out using Matlab for test cases of IEEE 9. The simulation results are shown in Table 3, Table 4 and Table 5 for Gauss-Seidel Method, Newton-Raphson Method and Fast Decoupled Method respectively.

Table 3: Show Simulation Result For IEEE 9 Bus System Using Gauss-Seidel.
No. of iteration =45

Bus No	voltage	Angle	P	Q
2	1.0253	0.1687	1.6194	0.5249
3	1.0254	0.0849	0.8463	0.3804
4	0.9959	- 0.0403	0.0304	0.0115
5	0.9661	- 0.0652	-0.9195	-0.3042
6	1.0045	0.0365	0.0170	0.0051
7	0.9795	0.0144	-0.9999	-0.3517
8	0.9978	0.0690	0.0009	0.0045
9	0.9510	-0.0723	-1.2485	-0.4902

Table 4: Show Simulation Result of IEEE 9 Bus System Using Newton-Raphson.
No. Of iteration = 5

Bus No	voltage	Angle	P	Q
1	1.0300	0	-1.3975	0.1899
2	1.0200	1.6837	0.1000	-0.4019
3	1.0300	2.7222	0.2500	-0.0889
4	1.0511	2.1250	0.6000	0.4000
5	1.0480	2.0508	-0.7000	0.0500
6	1.0500	3.7179	1.0000	-0.4371
7	1.0635	2.5855	0.8000	0.6000
8	1.0300	1.5256	-0.8000	-0.3252
9	1.0415	2.9129	0.2000	0.1000

Table 5: Show Simulation Result of IEEE 9 Bus System Using FDLF Method
No. Of iteration =9

Bus No	voltage	Angle	P	Q
1	1.0400	0	0.7073	0.7970
2	1.0253	0.1687	1.6194	0.5249
3	1.0254	0.0849	0.8463	0.3804
4	0.9959	- 0.0403	0.0304	0.0115
5	0.9661	- 0.0652	-0.9195	-0.3042
6	1.0045	0.0365	0.0170	0.0051
7	0.9795	0.0144	-0.9999	-0.3517
8	0.9978	0.0690	0.0009	0.0045
9	0.9510	-0.0723	-1.2485	-0.4902

6 Discussion

6.1 Tolerance

The selected tolerance value used for the simulation is shown in Table 6. This is used to determine accuracy of a solution. Thus, using a high tolerance value for a simulation increases the accuracy of the solution whereas when a low tolerance value is used, it reduces the accuracy of the solution and number of iterations. The selected tolerance value used for the simulation is 0.001 and 0.1 except for the IEEE 57 bus system solution for fast decoupled, which does converge with tolerance value 0.001. The only selected tolerance value used for IEEE 57 bus system is the 0.1.

Table 6: Comparison of Tolerance Value

Test System	Gauss-Seidel	Newton-Raphson	Fast-Decoupled
IEEE 9 Bus	0.001/0.1	0.001/0.1	0.001/0.1
IEEE 14 Bus	0.001/0.1	0.001/0.1	0.001/0.1
IEEE 30 Bus	0.001/0.1	0.001/0.1	0.001/0.1
IEEE 57 Bus	0.001/0.1	0.001/0.1	0.1

6.2 Iteration Number

Table 7 and Table 8 show the number of iterations for the power flow solution using selected tolerance value of 0.001 and 0.1 respectively to converge for the three load flow methods. Gauss-Seidel has the highest number of iterations before it converges. The number of iteration increases as the number of buses in the system increases. In IEEE 9 bus system, IEEE 14 bus system and IEEE 30 bus system, Newton-Raphson has the least number of iteration to converge. For the 57 bus system using fast decoupled, the load flow solution did not converge using 0.001. Then another selected value of 0.1 was chosen for the iteration.

Table 7: Comparison of Iteration Number Using Selected Tolerance Value of 0.1.

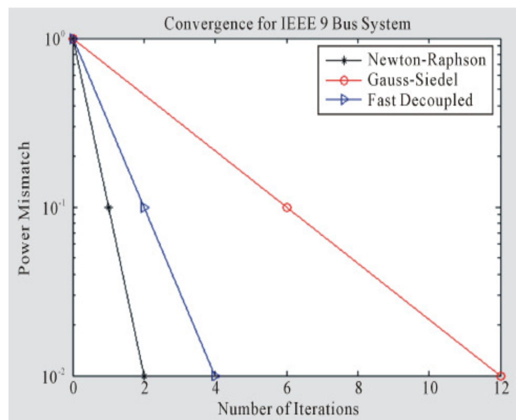
Test System	Gauss-Seidel	Newton-Raphson	Fast-Decoupled
IEEE 9 Bus	45	5	9
IEEE 14 Bus	50	7	13
IEEE 30 Bus	113	9	20
IEEE 57 Bus	176	11	25

Table 8: Comparison of Iteration Number Using Selected Tolerance Value of 0.001

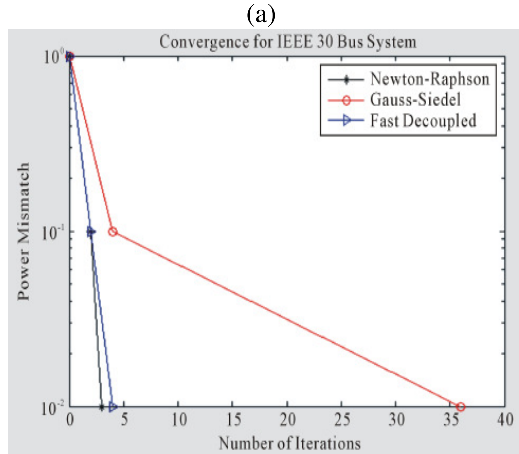
Test System	Gauss-Seidel	Newton-Raphson	Fast-Decoupled
IEEE 9 Bus	12	2	4
IEEE 14 Bus	22	3	3
IEEE 30 Bus	36	5	6
IEEE 57 Bus	17	10	

6.3 Convergence

Convergence is used to determine how fast a power flow reaches its solution. The rate of convergence is determined by plotting a graph of maximum power mismatch against the number of iterations. Figures 2(a)-(b) shows the graph for convergence on IEEE-9 and IEEE-30 Bus System respectively using selected tolerance value of 0.001. Figures 3(a)-(b) shows the graph for convergence on IEEE-9 and IEEE-30 Bus System respectively using selected iteration value of 0.1.

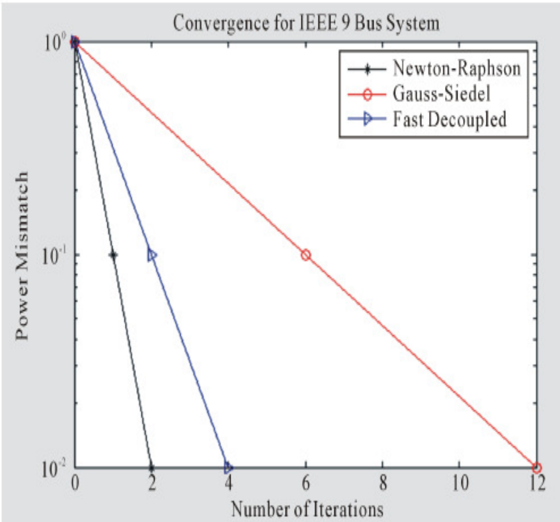


(a)

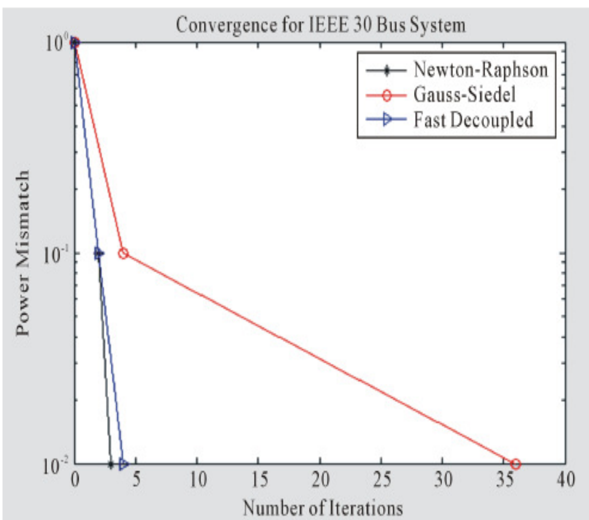


(b)

Figure 2 **(a)** Convergence for IEEE 9 bus system using selected tolerance value of 0.001; **(b)** Convergence for IEEE 30 bus system using selected tolerance value of 0.001.



(a)



(b)

Figure 3. (a) Convergence for IEEE 9 bus system using selected tolerance value of 0.1; **(b)** Convergence for IEEE 30 bus system using selected tolerance value of 0.1.

7. Conclusion

In the load flow analysis methods simulated, the tolerance values used for simulation are 0.001 and 0.1 for all the simulation carried out except for the IEEE 57-bus using the fast decoupled method, which did not converge with the tolerance values. This explains why the Fast Decoupled method is not as accurate as Newton-Raphson method because a lower tolerance value of 0.1 was used to carry out the simulation for the IEEE 57-bus Fast Decouple Method. The results of this paper suggest that the planning of a power system can be carried out by using Gauss-Seidel method for a small system which having low tolerance value with less computational complexity due to the good computational characteristics it exhibited. The effective and most reliable amongst the three load flow methods is the Newton-Raphson method because it converges fast and is more accurate.

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