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Case Study

AN INVESTIGATION OF LOAD FLOW SOLUTION METHODS IN POWER SYSTEM: A CASE STUDY OF NIGERIAN 330KV TRANSMISSION NETWORK

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Abstract: The main objective of a modern electrical power system is to provide quality and reliable electric power to consumers of electricity; the quality is determined by the voltage magnitude and the frequency at which it is delivered. Load flow analysis is essential for power system planning, operation, and expansion. The Nigerian 330kV transmission network faces persistent challenges, including voltage instability, high technical losses, and inadequate power supply despite the country's significant energy resources. This work presents a comprehensive investigation of load flow solution methods — Gauss-Seidel (GS), Newton-Raphson (NR) and Fast Decoupled (FDLF comparing their performance, convergence characteristics, and computational efficiency. A model of a power system generates non-linear algebraic equations, and to solve these equations, three solution algorithms based on power equations for the three methods were adopted. The result reveals the well-known properties of these algorithms: speed, rate of convergence and the convergence characteristics. The findings indicate that Newton-Raphson offers superior convergence, speed and accuracy for ill-conditioned systems, Fast Decoupled provides adequate accuracy with reduced computational requirements, and Gauss-Seidel remains useful for small-scale implementations despite slower convergence. Recommendations for practical implementation in the Nigerian context are provided. Findings provide practical guidance for grid operators and planners in selecting appropriate load flow methods for specific applications within the Nigerian power system.

Keywords: Power System, Load Flow, Gauss-Seidel, Newton-Raphson, Fast-Decoupled, Voltage Magnitudes.

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1. INTRODUCTION

Power flow analysis is a solution for the steady-state operating conditions of a power system. It presents a ‘‘frozen’’ picture of a scenario with a given set of conditions and constraints. (Das 2002). (http://en.wikipedia.org/wiki/power) It is a fundamental computational tool in power system planning and operation (Adepoju etal 2011). The analysis determines the steady-state operating conditions of an electrical network, including voltage magnitudes and phase angles at each bus, real and reactive power flows in transmission lines, and system losses (Onohacbi & Ogbinovia, 2008). In a developing nation like Nigeria, where electricity supply inadequacy is a critical constraint to socio-economic development, accurate load flow analysis is essential for identifying system weaknesses, planning expansions, and ensuring reliable operation (Akabogu etal,2025). In its basic form, the load flow problem involves solving a set of nonlinear algebraic equations which represents the network under steady-state conditions. Owing to the nonlinear nature of the power flow equations, the numerical solution is reached by iteration (Acha, *etal,* 2004). Several load flow solution methods have been developed over the past decades, each with distinct mathematical formulations, convergence properties, and computational requirements This work investigate and carry out a comparative analysis of the three methods — Gauss-Seidel (GS), Newton-Raphson (NR) and Fast Decoupled (FDLF when it is applied to the Nigerian power system. The study specifically investigates the three load flow solution methods comparing their performance, convergence characteristics, and computational efficiency when it is applied to the Nigerian power system. Test cases were carried out on IEEE 5-bus, IEEE 30-bus and Nigerian 28 –bus 330KV electrical power system network. In the investigation, a power flow analysis was carried out on the tested electrical power system network using the three methods of load flow solution techniques. (Adejumobi. *etal*, 2013)

2.0 LOAD FLOW SOLUTION METHODS IN POWER SYSTEM

The load flow analysis, in power system is the steady state solution of the power system network. The power flow problem involves determining voltages and line flows, in a large sparse electrical network, for a given load and generation schedule (Stevenson & Granger, 1994), In this analysis, the power system network is modeled as an electric network and solved for the steady state power, voltages at various buses and hence the power at the slack bus and power flows through inter connecting power channels (Nagrath & Kothari,2006). Four quantities which are associated with each bus are voltage magnitude $|v|$, phase angle δ, real power P, and reactive power Q. The system buses are generally classified into three types namely: Slack bus, Load buses and Generator buses where two variables are specified and others two to be determined (Ravi Kumar & Siva Nagaraju, 2007).

2.1 Gauss-Seidel Method

The Gauss-Seidel method is an iterative algorithm for solving a set of nonlinear algebraic equations. It is one of the solution methods used in load flow analysis. In the Gauss-Seidel method, a solution vector is assumed, and one of the equations is used to obtain the revised value of a particular variable and the solution vector is immediately updated in respect of this variable. This process is then repeated for all the variables thereby completing one iteration and the iterative process is then repeated till the solution vector converges within prescribed accuracy (Saadat, 2010). The advantages of the method are simplicity of the technique, small computer memory requirement, and less computational time per iteration. However, the disadvantages are slow rate of convergence, large numbers of iterations, increase of numbers of iteration directly with the increase in the number of buses and effect of convergence due to choice of slack bus. However, the Gauss-Seidel method is used only for system having small number of buses (Grupta, 2006),

2.2 Newton-Raphson Method

It is an iterative method which approximates a set of non-linear simultaneous equations to a set of linear simultaneous equations using Taylor's series expansion and the terms are limited to the first approximation (Wadhwa, 1991). Many advantages are attributed to the Newton-Raphson (NR) approach. Its convergence characteristics are relatively more powerful compared to other alternative processes and the reliability of Newton- Raphson approach is comparatively good, since it can solve cases that lead to divergence with other popular processes. Failures do occur on some ill-conditioned problems (Nagrath & Kothari, 2006).

2.3 Fast-Decoupled Method

When the storage and computing requirements of the Newton-Raphson method is reduced very significantly by introducing a series of well-sustained simplifying assumptions. These assumptions are based on physical properties exhibited by electrical power system, in particular in high-voltage transmission system. The resulting formulation is no longer a Newton-Raphson method but a derived formulation described as Fast-decouple Newton- Raphson. The power mismatch equations of both solution methods are identical but their Jacobians are quite different; the Jacobians elements of the Newton –Raphson are voltage–dependent, whereas that of the Fast decouple method are voltage independent (i.e. constant parameters). Moreover, the number of Jacobian entries used in the Fast-decouple is only half of those used in the Newton-Raphson method but has strong convergence characteristics. However, an asset of the Fast decouples method is the fact that the decoupled equation requires considerably less time to solve compared to the time required for the solution by the Newton- Raphson Method (Acha, *eta*l 2004)

3.0 Power Flow Equation

Consider a typical bus of a power system network as shown in Figure 1. Transmission lines are represented by their equivalent π models where impedances have been converted to per – unit admittances on a common MVA base.

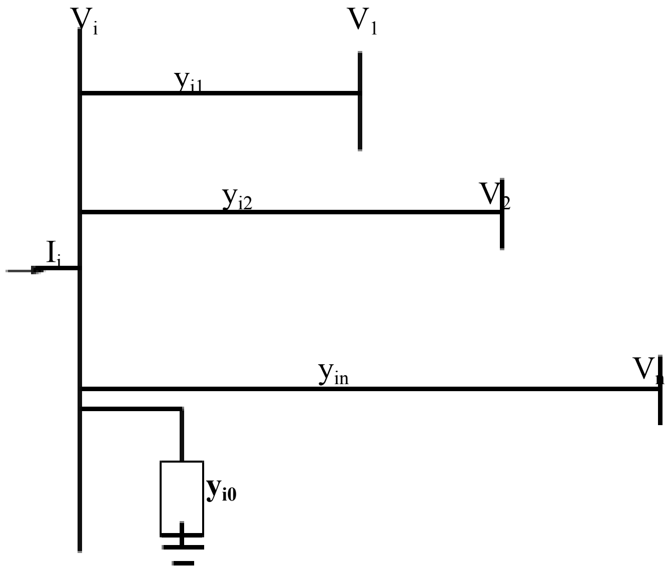

Figure 1: Typical bus of the power system (Saadat, 2010),

Application of Kirchhoff's current Law (KCL) to this bus results in

$$I_i = y_{i0}V_i + y_{i1}(V_i - V_1) + y_{i2}(V_i - V_2) + \cdots y_{in}(V_i - V_n)$$

$$= (y_{i0} + y_{i1} + y_{i2} + \cdots + y_{in})V_i - y_{i1}V_1 - y_{i2}V_2 - \cdots - y_{in}V_n \quad \ldots\ldots\ldots\ldots\ldots (1)$$

Or

$$I_i = V_i \sum_{j=0}^{n} y_{ij} - \sum_{j=1}^{n} y_{ij} V_j \qquad j \neq I \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

The real and reactive power at bus í is

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

Or $$I_i = \frac{P_i - jQ_i}{V_i^*} \qquad (4)$$

Substituting for Ii in equation (2) will yield

$$I_i = \frac{P_i - jQ_i}{V_i^*} = V_i \sum_{j=0}^{n} y_{ij} - \sum_{j=1}^{n} y_{ij} V_j \qquad j \neq i \qquad (5)$$

$$I_i = \frac{P_i - jQ_i}{V_i^*} = V_i \sum_{i=0}^{n} y_{ij} - \sum_{i=1}^{n} y_{ij} V_j$$

From equation (5), the mathematical formulation of the power flow problem results in a system of algebraic non- linear equations which must be solved by iterative techniques.

3.1 Gauss – Seidel power flow solution

In the power flow study, it is necessary to solve the set of non – linear equations represented by equation (5). In the Gauss – Seidel method equation (5) is solved for i V and the iterative sequence becomes,

$$V^{(k+1)} = \frac{\frac{p^{sch} - jQ_i^{sch}}{V_i^{*(k)}} - \sum y_{ij} V_j^{(k)}}{\sum y_{ij}} \qquad j \neq I \qquad (6)$$

Where, y_{ij} y_{ij} shown in lower case letters is the actual admittance in per unit. P^{sch} and Q^{sch} are the net real and reactive powers expressed in per unit. In writing the KCL, current entering bus i was assumed positive. Thus, for buses where real and reactive powers are injected into the bus, such as generator buses, P^{sch} and Q^{sch} have positive values. For load buses where real and reactive powers are flowing away from the bus, P^{sch} and Q^{sch} have negative values. If relation (3.6) is solved for P_i and Q_i, we have,

$$P_i^{(k+1)} = \text{Real}\,[V_i^{*(k)}\{V_i^{(k)} \textstyle\sum^{n}_{j=0} y_{ij} - \sum^{n}_{j=1} y_{ij} V_j^{(k)}\}] \qquad (7)$$

$$Q_i^{(k+1)} =]\ \text{Imaginary}\,[V_i^{*(k)}\{V_i^{(k)} \textstyle\sum^{n}_{j=0} y_{ij} - \sum^{n}_{j=1} y_{ij} V_j^{(k)}\}] \qquad j \neq i \qquad (8)$$

The power flow equation is usually expressed in terms of the elements of the bus admittance matrix. Since the off-diagonal elements of the bus admittance matrix Y bus shown by uppercase letters are Y_{ij} = - y_{ij} and the diagonal elements are $Y_{ij} = - \sum Y_{ij}$ $Y_{ij} = -\sum Y_{ij}$ then (6) above becomes,

$$V^{(k+1)} = \frac{\frac{p^{sch} - jQ_i^{sch}}{V_i^{*(k)}} - \sum^{n}_{j=i} y_{ij} V_j^{(k)}}{y_{ii}} \qquad (9)$$

and

$$P_i^{(k+1)} = \text{Real}\,(V_i^{*(k)}\{V_i^{(k)} Y_{ii} + \textstyle\sum^{n}_{i=1,\, j\neq i} y_{ij} V_j^{(k)}\}) \qquad j \neq i \qquad (10)$$

$$Q_i^{(k+1)} = -\ \text{Imaginary}\,(V_i^{*(k)}\{V_i^{(k)} Y_{ii} + \textstyle\sum^{n}_{i=1,\, j\neq i} y_{ij} - V_j^{(k)}\}) \qquad j \neq i \qquad (11)$$

Y_{ii} includes the admittance to ground of line charging Susceptance and any other fixed admittance to ground.

3.2 Newton –Raphson method

The load flow problem can also be solved by using the Newton-Raphson method. For the typical bus of the power system shown in Figure (1) the current entering bus i written in terms of the bus admittance matrix as.

$I_i = V_i \sum_{j=0}^{n} V_{ij} - \sum_{j=1}^{n} Y_{ij} V_j$

This equation can be rewritten in terms of the bus admittance matrix as.

$I_i = \sum_{j=1}^{n} Y_{ij} V_j$ $$I_i = \sum_{j=1}^{n} Y_{ij} V_j \qquad (12)$$

In the above equation, j includes bus j. Expressing this equation in polar form, we have;

$I_i = \sum_{j=1}^{n} |Y_{ij}|\,|V_j| < (\Theta_{ij} + \delta_j)$ $$I_i = \sum_{j=1}^{n} |Y_{ij}|\,|V_j| < \theta_{ij} + \delta_j \qquad (13)$$

The complex power at bus i is

$P_i - jQ_i = V_i^* I_i$ $$P_i - jQ_i = V_i^* I_i \qquad (14)$$

Substituting from (13) for *i I* in (14)

$P_i - jQ_i = |V_i| < -\delta_i \sum_{j=1}^{n} |Y_{ij}|\,|V_j| < \delta_{ij} + \delta_j$ $$P_i - jQ_i = |V_i| < -\delta_i \sum_{j=1}^{n} |Y_{ij}|\,|V_j| < \delta_{ij} + \delta j \qquad (15)$$

Separating the real and imaginary parts

$P_i = \sum_{j=1}^{n} |V_i|\,|V_j|\,|Y_{ij}| cos\,(\Theta_{ij} - \delta_i + \delta_j)$ $$P_i = \sum_{j=1}^{n} |V_i|\,|V_j|\,|Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) \qquad (16a)$$

$Q_i = -\sum_{j=1}^{n} |V_i|\,|V_j|\,|Y_{ij}| sin\,(\Theta_{ij} - \delta_i + \delta_j)$ $$P_i = \sum_{j=1}^{n} |V_i|\,|V_j|\,|Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j)$$
$$Q_i = -\sum_{j=1}^{n} |V_i|\,|V_j|\,|Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j) \qquad (16b)$$

Equations (16a) and (16b) constitute a set of non – linear algebraic equations in terms of the independent variables, voltage magnitude in per – unit and phase angle in radians. We have two equations for each load bus given by (16a) and (16b), and one equation for each voltage-controlled bus, given by (16a). Expanding (16a) and .16b) in Taylor's series about the initial estimate and neglecting all higher order terms results in a set of linear equations. These equations after linearization can be written in matrix form as.

$$\begin{pmatrix} \Delta P \\ \Delta Q \end{pmatrix} = \begin{pmatrix} J_1 & J_2 \\ J_3 & J_4 \end{pmatrix} \begin{pmatrix} \Delta \delta \\ \Delta |V| \end{pmatrix} \qquad (17)$$

Here element J_1, J_2, J_3, J_4 are elements of Jacobian matrix.

In obtaining the power flow solution by the Newton method, consider equation (17)

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix}$$
$$\begin{matrix} \Delta P \\ \Delta Q \end{matrix} = \begin{pmatrix} J_1 & J_2 \\ J_3 & J_4 \end{pmatrix} \begin{pmatrix} \Delta \delta \\ \Delta |V| \end{pmatrix}$$

For voltage-controlled buses, the magnitudes are known. Therefore, if m buses of the system voltage controlled, m equation involving ΔQ and ΔV and the corresponding column of the Jacobian matrix are eliminated. Accordingly, there are n-1-m reactive power constraints, and the Jacobian matrix is of order (2n-2-m) x (2n – 2 - m). J_1 is of the order (n - 1) x (n - 1), J_2 is of the order (n – 1) x (n- 1 – m), J_3 is of the order (n- 1 - m) x (n -1), and J_4 is of the order (n – 1 - m) x (n – 1- m). where n is the load bus and m is generator bus. The diagonal and off-diagonal elements of J_1 are;

$$\frac{\partial P_i}{\partial \delta_j} = \sum\nolimits^{n}_{j\neq 1} |V_i|\,|V_j|\,|Y_{ij}| sin\,(\Theta_{ij} - \delta_i + \delta_j) \tag{18}$$

$$\frac{\partial P_i}{\partial \delta_j} = -\,|V_i|\,|V_j|\,|Y_{ij}| sin\,(\Theta_{ij} - \delta_i + \delta_j) \qquad j \neq i \tag{19}$$

The diagonal and off-diagonal elements of J_2 are;

$$\frac{\partial P_i}{\partial \delta_j} = 2|Vi|\,|Y_{ii}|\,cos\Theta_{ii} + \sum\nolimits_{j\neq 1} |V_j|\,|Y_{ij}|\,cos\,(\Theta_{ij} - \delta_i + \delta_j) \tag{20}$$

$$\frac{\partial P_i}{\partial |V_j|} = |V_i|\,|Y_{ij}|\,cos\,(\Theta_{ij} - \delta_i + \delta_j) \qquad j \neq i \tag{21}$$

$\frac{\partial P_i}{\partial |V_j|} = |V_i||\mathrm{Y_{ij}}|\cos\,(\theta_{ij} - \delta_i + \delta_j)$ The diagonal and off-diagonal elements of J_3 are

$$\frac{\partial P_i}{\partial \delta_j} = \sum\nolimits_{j\neq 1} |Vi|\,|V_j|\,|Y_{ij}|\,cos\,(\Theta_{ij} - \delta_i + \delta_j) \tag{22}$$

$$\frac{\partial P_i}{\partial \delta_j} = -\,|Vi|\,|V_j|\,|Y_{ij}|\,cos\,(\Theta_{ij} - \delta_i + \delta_j) \qquad j \neq i \tag{23}$$

The diagonal and off diagonal element of J_4 are.

$$\frac{\partial P_i}{\partial |V_i|} = -\,2|Vi|\,|Y_{ii}|\,sin\Theta_{ii} + \sum\nolimits_{j\neq 1} |V_j|\,|Y_{ij}|\,sin\,(\Theta_{ij} - \delta_i + \delta_j) \tag{24}$$

$$\frac{\partial Q_i}{\partial |V_j|} = -\,|Vi|\,|Y_{ii}| sin\,(\Theta_{ij} - \delta_i + \delta_j) \qquad j \neq I \tag{25}$$

The term $\Delta P_i^{(k)}$ $\Delta P_i^{(k)}$ and $\Delta Q_i^{(k)}$ $\Delta Q_i^{(k)}$ are the difference between the scheduled and calculated values, known as the power residuals given by

$$\Delta\, P_i^{(k)} = P^{sch} - P_i^{(k)} \tag{26}$$

$$\Delta Q_i^{(k)} = Q_i^{sch} - Q_i^{(k)} \qquad \Delta Q_i^{(k)} = Q^{sch} - Q_i^{(k)} \tag{27}$$

The new estimates for bus voltages are

$\delta_i^{(k+1)} = \delta_i^{(k)} + \Delta \delta_i^{(k)}$ $\delta_i^{(k+1)} = \delta_i^{(k)} + \Delta\delta_i^{(k)}$ (28)

$|V_i^{(k+1)}| = |V_i^{k}| + \Delta\ |V_i^{(k)}|$ (29)

3.3 Fast decoupled power flow solution

This is an extension of Newton – Raphson method formulated in polar coordinates with certain approximation which results in fast algorithm for load flow solution. The first assumption under decoupled load flow method is that real power changes (ΔP) are less sensitive to changes in voltage magnitude and are mainly sensitive to changes in phase angle (Δδ)$\Delta\delta$. Similarly, the reactive power is less sensitive to changes in phase angle $\Delta\delta$ Δδ but mainly sensitive to changes in voltage magnitude. With these assumptions, equation (17) reduces to

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & 0 \\ 0 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix} \tag{30}$$

$$\text{or} \qquad \Delta P = J_1\ \Delta\delta = \left|\frac{\partial P}{\partial \delta}\right| \Delta\delta \tag{31}$$

$$\Delta Q = J_4\ \Delta|V| = \left|\frac{\partial P}{\partial |V|}\right| \Delta|V| \tag{32}$$

Equations (31) and (32) show that the matrix equation is separated into two decoupled equations requiring considerably less time to solve compared to the time required for the solution of (18). Furthermore, considerable simplification can be made to eliminate the need for re-computing J_1 and J_4 during each iteration. This procedure results in Fast decoupled power flow equations developed by Scott and Alsac (Sadat, 2010)

4.0 RESULTS AND DISCUSSION

Case Study

In this work, test cases are carried out on IEEE 5-bus, IEEE 30-bus and a real Nigerian 28 –bus electrical power systems network. Power flow analysis was carried out on the tested electrical power system network using the three well known load flow solution methods: Gauss-Seidel, Newton-Raphson and Fast decoupled methods. The system is assumed to be balanced; this allows a single-phase representation of the system.

Structure of IEEE 5 Bus System

The IEEE 5 bus network contains three generators (PV) buses at buses 1, 2, 3 and two load bus, (PQ) buses at 4 and 5 totaling five buses with seven transmission lines. Bus 1 with its Voltage set at 1.06 p.u is taken at the slack bus

Structure of IEEE 30 – Bus System

The total number of voltages regulated bus, PV bus are five while the load bus (PQ) buses are 24. Bus 1 is taken as slack bus. (Sadat, 2010)

Structure of the Nigerian 28–bus system

The power stations in Nigeria are mainly hydro and thermal plants. Power Holding Company of Nigeria (PHCN) generating plants sum up 6200MW of which 1920MW is hydro and 4280 MW thermal, mainly gas-fired. The Nigerian transmission grid network has a total number of nine PV buses, nineteen load buses (totaling twenty-eight buses) and fifty transmission lines for the analysis.

4.1 Investigation and Comparative Analysis of the Power Flow Solution Methods of the test cases.

The power flow analysis of the test cases was implemented using MATLAB programming techniques on the three algorithms. The performance of these formulations on a personal computer is comparatively discussed by using the results of the actual implementation.

CPU – Time Requirement

The CPU time Requirement of the three algorithms under full load conditions recorded on the Dell personal computer of 2.20GHz are shown in table in Table 1.

Table I: CPU Time (seconds) requirement for the Algorithms

Test Systems	Gauss-Seidel	Newton Raphson	Fast Decouple
IEEE 5 Bus	0.0156002	0.0312002	0.0156001
IEEE 30 Bus	0.0312002	0.0468003	0.0124801
Nigerian 28 Bus	0.0780005	0.0936006	0.0780000

Computing time requirement

Table 1 shows that the time per iteration in both Gauss-Seidel and Newton-Raphson methods increases almost directly as the number of buses of the system, while the computational time per iteration of the Fast Decoupled method is less than that of the Newton-Raphson method. Shown in Figure 2 is the bar chart showing the three algorithms with the computing time.

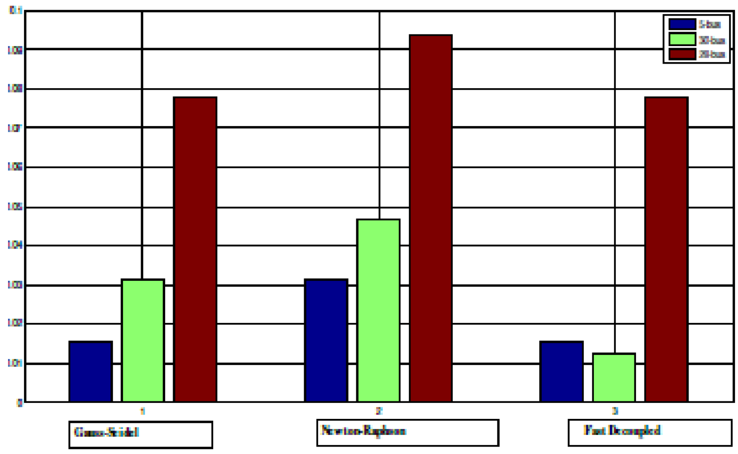

Figure 2: Comparison of the Execution Time obtained with the 3- Test Bus Systems.

Iteration Requirement

As seen from Table 2 the Gauss-Seidel method needs a larger number of iterations to converge to a given power mismatch tolerance, compared to the other two methods. The Fast decouples method needs more iterations to converge than the Newton-Raphson. But as indicated in the last discussion, the computing time requirement for the Fast decouple method per iteration is much less than the Newton-Raphson method. Shown in Figure 3 is the bar chart showing the three algorithms with the necessary number of iterations.

Table II: Iteration Number Requirements

Test Systems	Gauss-Seidel	Newton Raphson	Fast Decouple
IEEE 5 bus	12	3	6
IEEE 30 bus	34	4	15
Nigerian 28 bus	69	4	5

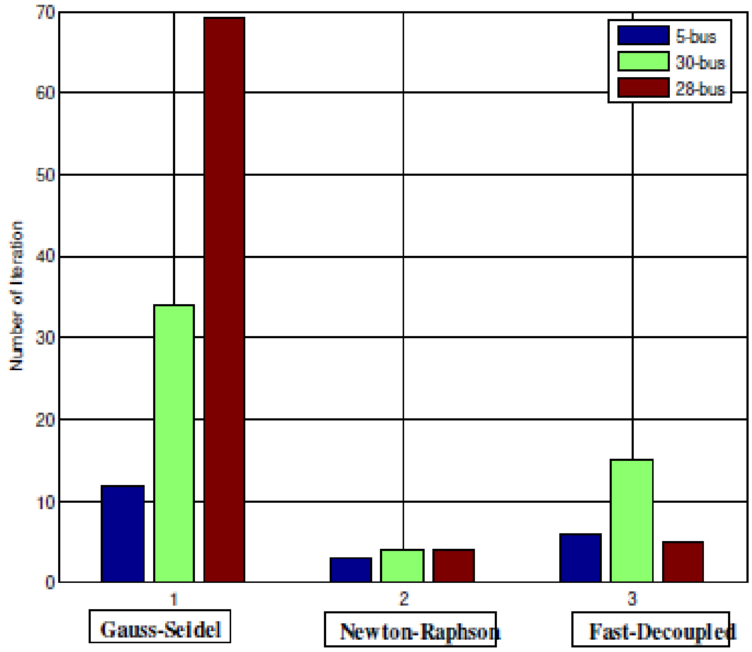

Figure 3: Comparison of the number of Iteration obtained with the 3- Test Bus Systems

Convergence Characteristics

The convergence characteristic of an algorithm is best described by plotting the maximum power mismatch at each iteration versus the number of iterations. Figure 3 through Figure 5 shows the maximum power mismatches for the three-test system as a function of the number of iterations for the three algorithms. As seen in from the Figures the mismatches monotonously decrease for all cases under full load conditions and the Newton Raphson methods exhibit fastest convergence rate. However, from the curves it shows the unique characteristic the three algorithms: Gauss-Seidel, Newton Raphson and Fast decouple.

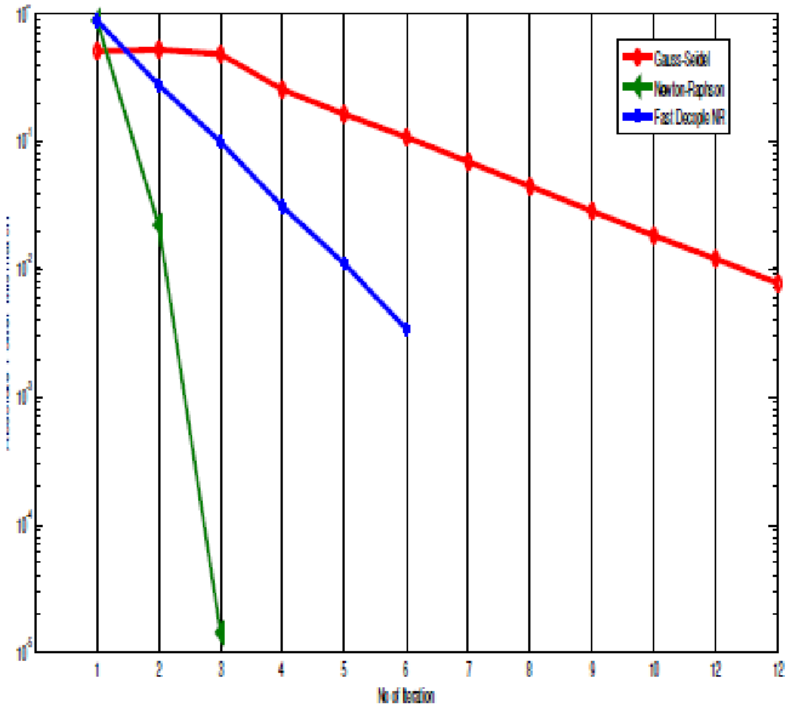

Fig 5: Absolute power mismatches as a function of the number of iterations for the IEEE5-bus system

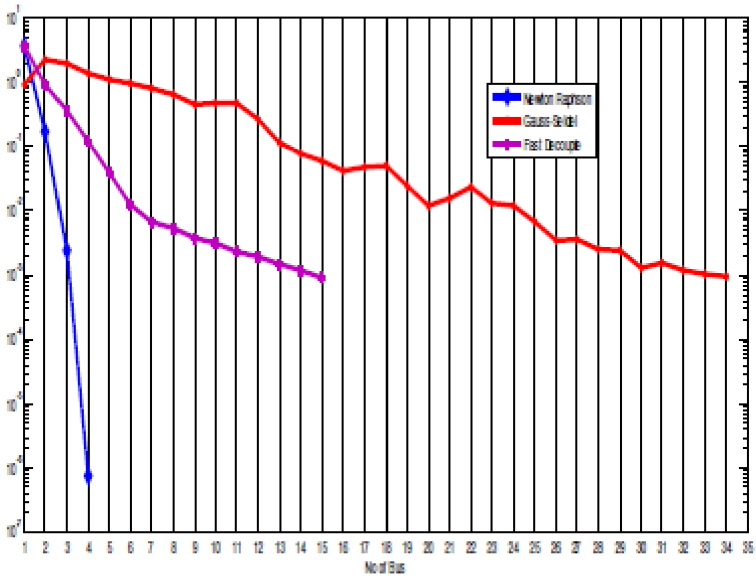

Fig 6: Absolute power mismatches as a function of the number of iterations for the IEEE 30-bus system

Fig.7: Absolute power mismatches as a function of the number of iterations for the 28-bus system

5.0 CONCLUSION

In this study, an investigation and performance evaluation of three algorithms for running power flow programs is presented and they were implemented for the IEEE 5 bus, the IEEE 30 bus and the Nigerian 28 bus test power systems. The simulations are analyzed with regard to CPU times, convergence patterns, and the number of iterations. The well-known properties of these algorithms: speed, rate of convergence and the convergence characteristics were confirmed by the case study results. The Newton-Raphson method is reliable and rapid in convergence, whereas the Gauss-Seidel method is slower and may even fail to converge under severe ill conditioning. In general, the Newton-Raphson algorithm takes the least number of iterations to converge, despite its longer CPU time and high accuracy is obtained in only a few iterations. It is therefore realistic and more reliable than any of the methods.

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