Development and Testing of Q-Basic Computer Software for Newton-Raphson Power Flow Studies

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***Abstract*—There had been obvious system insecurity in Nigerian power systems' grid which often lead to frequent power system collapse. Studies have shown that the Privatized power companies that emanated as a result of power sector reform carried out recently in Nigeria are not fully on ground in network argumentation, planning and analysis of the network. For example, it is required that for any proposed capital project execution which would add to the existing Networks; certain analysis via system simulation need to be carried out. Such analysis would display the likely situation after the project is completed and commissioned. These analyses include investigating the bus voltage profile, power flow, losses, overvoltage condition etc. Consequently, this paper presents a development of Q-basic computer software package on Newton- Raphson power flow algorithm and subsequent testing on a 3 - Bus power system network with known solutions. Steady state operating conditions of busbars, generation, branch power flows and circuit system losses were determined. The obtained results are presented and discussed. These results are accurate and reliable, because they agree with the known solutions of the network. Conclusions are drawn, and necessary recommendations are presented.**

***Index Terms*—System Collapse, Simulation, Grid, Argumentation, Newton-Raphson, Power Flow, Q-Basic Software Package, Busbars.**

I.ⁿ INTRODUCTION

Electric power has become virtually indispensable in modern societies in the sense that most industrial, commercial, domestic and social activities are heavily dependent on availability of electric energy. Electric power generating stations are often located far from the load (or power consumption) centers. Conventionally, several generating stations are connected and to the load centers via transmission lines to form an electric power system also known as the grid [1], [2]. A power system is required to maintain a continuous balance between electrical generation and a varying load demand so that system frequency and voltage are maintained at their statutory levels, while guaranteeing system security.

The performance of the electrical power systems is continually and extensively analyzed to assess its quality. Such analysis is used in planning expansion schemes on the system to cater for the ever-increasing power demand [3]–[7]. Some of the analysis problems in system planning, requiring attention include power (or load) flow, fault level, stability and reliability.

However, power flow studies frequently precede and, in most cases, provide the starting conditions for complicated system analysis such as optimization. Fault level, stability and outage security assessment. Generally, the problem encountered in transmission network planning has always been the multitude of situations to be examined in order to guarantee that a projected network is necessary and enough for a given year. Such situations arise from load variations, hydraulic variations, generation unit's unavailability leading to a reorganization of the generation program with every failure, and finally unavailability's due to transmission equipment (i.e lines and transformers) [8], [9].

In Nigeria, Electricity Companies comprising Genco, TCN and Disco are responsible for planning, installation, generation, transmission and distribution of electrical energy in the country and some neighbouring countries. They have several generating stations including a mix of hydro and thermal power plants mostly located in the southern and middle parts of the country. Several papers had been written and research had been carried out on power flow analysis for power system grid using the Gauss, Gauss-Seidel, Fast decoupling as well as other several iterative approaches which are all slow in convergence [10]–[18]. Newton- Raphson Iterative method is generally believed to be faster in convergence [1], [4], [5], [7]. Thus, a suitable software package for power flow method is developed.

II.ⁿ NEWTON-RAPHSON METHOD

The method involves the idea of finding a vector $x \in IR^N$ such that,

$$F(x) = 0 \tag{1}$$

Where F is a vector valued function of dimension N.
Expanding equation (1) in a Taylor Series and due to the error in neglecting the higher order terms in the Taylor series, Value x can be iteratively determined as,

$$x^{(k)} = x^{(k-1)} - J^{-1}F\left(x^{(k-1)}\right) \quad (2)$$

Where, k = iteration, J = A square matrix of same dimension as x and F, and its entries are partial derivatives defined as [4], [8], [18], [19],

$$J_{pq} = \frac{\partial F_p}{\partial x_q}\Big|_{x^{(k-1)}} \quad (3)$$

Where, p and q denote buses. This matrix is the Jacobian matrix of the system of equation (1).

Applying this method to power flow problem, the derivatives of the mismatch form of the power flow equation are used to force the bus power mismatch to zero. An equation is written for each bus p

$$P_p + jQ_p = E_p I_p^* \quad (4)$$

Where,

$$I_{P=} \sum_{K=1}^{NB} Y_{pk}\ E_k \quad (5)$$

Then,

$$P_p + jQ_p = E_p \sum_{K=1}^{NB} Y_{pk}\, E_k^*$$
$$= |E_p|^2 Y_{pp}^* + \sum_{\substack{K=1 \\ K\neq p}}^{NB} Y_{pk}^*\, E_p E_k^* \quad (6)$$

For p= 1, 2, 3 …… NB, excluding the slack bus.
The parameters contained in the above equations and the subsequent ones are clearly defined in table 1.
A set of starting voltages is often used to commence the iteration process. The power $P + jQ$ calculated using equation (6) is subtracted from the scheduled power $P_s + jQ_s$ at the bus and the resulting errors stored in a vector. Polar co-ordinates are generally employed for the voltages. The voltages' magnitudes and phase angles are adjusted as separate independent variables. Each bus injection equation is differentiated with respect to all independent variables. Thus, for each bus the power mismatch is calculated as [17], [18], [19],

$$\Delta P_p = \sum_{k=1}^{NB} \frac{\partial P_p}{\partial \theta_k}\, \Delta\theta_k + \sum_{K=1}^{NB} \frac{\partial P_p}{\partial |E_k|} \Delta |E_k| \quad (7)$$

$$\Delta Q_p = \sum_{K=1}^{NB} \frac{\partial Q_p}{\partial \theta_k}\, \Delta\theta_k + \sum_{K=1}^{NB} \frac{\partial Q_p}{\partial |E_k|}\, \Delta\,|E_k| \ldots \quad (8)$$

The partial differentials are arranged in a Jacobian matrix so that the equations (7) and (8) can be written in matrix vector form as,

$$\begin{bmatrix} \Delta P_1 \\ \Delta P_{NB-1} \\ \hline \Delta Q_1 \\ \Delta Q_{NB-1} \end{bmatrix} = \left[\begin{array}{ccc|ccc} \frac{\partial P_1}{\partial \theta_1} & \cdots & \frac{\partial P_1}{\partial \theta_{NB-1}} & \frac{\partial P_1}{\partial |E_1|} & \cdots & \frac{\Delta P_1}{\Delta |E_{NB-1}|} \\ \frac{\partial P_{NB-1}}{\partial \theta_1} & \cdots & \frac{\partial P_{NB-1}}{\partial \theta_{NB-1}} & \frac{\partial P_{NB-1}}{\partial |E_1|} & \cdots & \frac{\Delta P_{NB-1}}{\partial |E_{NB-1}|} \\ \hline \frac{\partial Q_1}{\partial \theta_1} & \cdots & \frac{\partial Q_1}{\partial \theta_{NB-1}} & \frac{\partial Q_1}{\partial |E_1|} & \cdots & \frac{\Delta Q_1}{\partial |E_{NB-1}|} \\ \frac{\partial Q_{NB-1}}{\partial \theta_1} & \cdots & \frac{\partial Q_{NB-1}}{\partial \theta_{NB-1}} & \frac{\partial Q_{NB-1}}{\partial |E_1|} & \cdots & \frac{\Delta Q_{NB-1}}{\partial |E_{NB-1}|} \end{array}\right] \begin{bmatrix} \Delta\theta_1 \\ \Delta\theta_{NB-1} \\ \hline \Delta|E_1| \\ \Delta|E_{NB-1}| \end{bmatrix} \quad (9)$$

The solution to Newton-Raphson problem runs according to flowchart in Figure 1.

TABLE I
DEFINITION OF PARAMETERS

S/N	Symbol	Description
1	P	Active (or real power) in megawatts
2	Q	Reactive (or imaginary power) in megavolt ampere
3	J	Jacobian matrix
4	K	Iteration count
5	I	Current
6	E	Bus voltage in complex form
7	| |	Modulus
8	Y	Admittance
9	NB	Number of buses
10	*	Conjugate
11	∑	Summation
12	Δ	Incremental value
13	∂	Partial differential
14	Є	Mathematical representation of member
15	kV	Kilovolt
16	Genco	Generation Company
17	TCN	Transmission company of Nigeria
18	DISCO	Distribution Company of Nigeria
19	AF	Acceleration Factor
20	NR	Newton Raphson

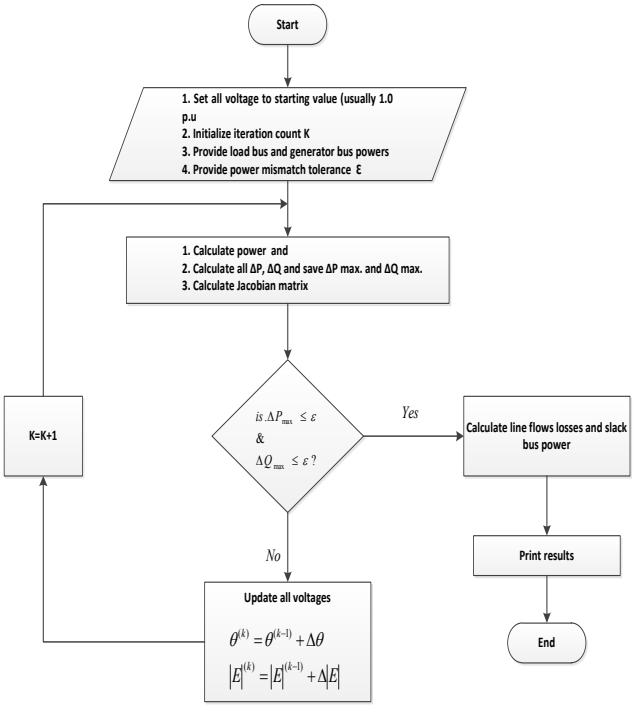


Fig. 1. Flowchart of the Newton – Raphson power flow solution

For a fast convergence [7], [12], common method used is to multiply the voltage corrections by a constant at the end of each iteration. This constant is called acceleration factor [2], [3], [9], [12], i.e

$$Q_p^{(k)}(\text{Accelerated}) = Q_p^{(k-1)} + \propto \Delta Q_p^{(k-1)} \ldots \quad (10)$$

$$|E_p|^{(k)}(\text{Accelerated}) = |E_p|^{(k-1)} + \propto \Delta |E_p|^{(k-1)} \quad (11)$$

Where, ∝ = acceleration Factor 0.7 <∝> 1.4

III. DEVELOPMENT OF A NEWTON-RAPHSON POWER FLOW (NRPF) SOFTWARE PACKAGE

To enable the solution of power flow problem using the N-R method, a suite of computer programs has been written to create a power flow software package. This NRPF package was developed and implemented using a personal computer (PC). Iterative conversational mode was employed to interface the package with its users. The package was structured in such a way as to fit into the limited core memory of PC. This is achieved by use of the overlay technique described in section A.

A. Structure of the power flow package

Overlaying together with interactive conversational mode are used. Overlaying permits reduction of the working memory of the computer and enables modularization of the package. For the purpose of overlaying, the package is divided into three stands – alone modules such that only one module is resident in core memory at any given time. The CHAIN command of Quick Basic is used to interface the supervisor module NRPF to each of the modules LAMBE 1 and LAMBE 2 as shown in Figure 2. In the next section the functions of the modules are described.

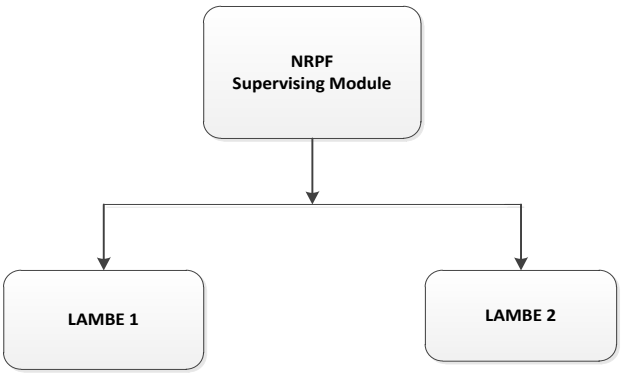


Fig. 2. Structure of NRPF Package

B. Package Description and Functions of the Modules

All programs are coded in Microsoft's Quick Basic (QB). Each module together with its subroutine procedures (if any) is complete. The modules are:

1. NRPF Supervising module
2. LAMBE 1 Power system data entry and Management
3. LAMBE 2 Newton – Raphson power flow solution.

1) Supervising Module (NRPF)

NRPF is the package supervisor. It controls the solution procedure by enabling the user to choose which path of the overlaying structure is to be followed. At system level the command

C: \>Quick Basic NRPF

Loads the module into memory and executes it. When the module is active the display screen is as shown in Figure 3.

NEWTON- RAPSON POWER FLOW PROGRAM
1. System data entry
2. Power Flow solution
3. Exit form package

Enter the number (1- 3) of your choice.

Fig. 3. NRPF menu display screen

2) System Data Entry Module (LAMBE 1)

The main function of this module is to permit the power system data to be entered into the computer by the user. The module is loaded and executed by selecting option 1 available on NRPF's menu. The module interactively solicits for the following data from user.

1. Number of buses (NB) in the network
2. Number of transmission lines (NL)
3. Transmission line data
   - Start bus, (SB)
   - End Bus, (EB)
   - Series resistance, R
   - Series reactance, X\
   - Line charging admittance, Y_{sh}
4. Bus scheduled active and reactive powers (P_s and Q_s). The module then formulates bus admittance matrix, Y_{bus} . Due to the non – availability of in – built complex arithmetic functions in Quick Basic, the real and imaginary parts of the elements of Y_{bus} are formed separately. The Y_{bus} building algorithm is as follows;

   Y_{pp} The diagonal entries of Y_{bus} are formed by summing the primitive admittance of lines and line charging admittance.

   Y_{pq} The off-diagonal entries are the negatives of the admittance buses p and q. if there is no line between p and q this term is zero.

All data entered or generated in this module are stored into appropriate data files for future use, so that this module need not be called if the data files are already available. On exit from the module, the NRPF module is reloaded into memory and executed.

3) Power Flow Solution Module (LAMBE 2)

This module implements the Newton- Raphson power flow solution method. It is loaded into memory and executed when option 2 of module NRPF's menu is selected. It makes use of data files created by LAMBE 1. If such data files are not available, the program returns an error message to the effect that the file is not available. Thus, before this module is run, the user must be sure that LAMBE 1 has already been executed.

Again, since Quick Basic does not have in – built complex arithmetic library functions, the Newton – Raphson power flow solution has to be reformulated in rectangular co-ordinates (rather than the polar co- ordinates) so that real

and imaginary parts of variables and parameters are handled separately.

The module consists of a main programme and the following five subroutine procedures.

1. Sub Powers
2. Sub Currents
3. Sub Jacobian
4. Sub Voltage
5. Sub Power flows

The flowchart for the program's logic is shown in Figure 4.

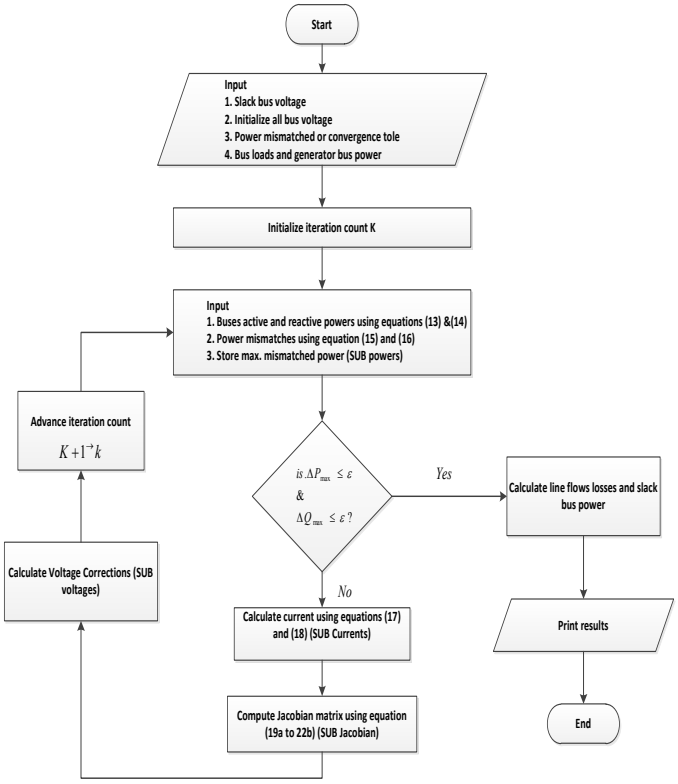


Fig. 4. Flowchart for module LAMBE 2

Consider now the application to an n- bus power system. The solution starts with the iteration counter K set to zero and all the buses except the slack bus being assigned voltages,

$$\mathbf{V}p = 1 + j\,0\ perunit \quad (12)$$

For a line connecting buses p and q of admittance,

$$P_p = \sum_{q=2}^{NB} [\, e_p(\, e_q G_{pq} + f_q B_{pq}) + f_p(\, f_q G_{pq} - e_q B_{pq})\,] \quad (13)$$

$$Q_p = \sum_{q=2}^{NB} [\, f_p(e_q G_{pq} + f_q B_{pq}) - e_q(f_q G_{pq} - e_q B_{pq})] \quad (14)$$

It has been assumed that the slack bus is the bus number 1 of the network. The main program then calls SUB Powers which computes P and Q using equations (13) and (14). It also calculates the power mismatches using equation (15) and (16);

$$\Delta \mathrm{p}_\mathrm{p}^{(\mathrm{k})} = \mathrm{P}_{\mathrm{sp}} - \mathrm{P}_\mathrm{p}^{(\mathrm{k})} \quad (15)$$

$$\Delta \mathrm{Q}_\mathrm{p}^{(\mathrm{k})} = \mathrm{Q}_{\mathrm{sp}} - \mathrm{Q}_\mathrm{p}^{(\mathrm{k})} \quad (16)$$

For p = 2, 3, - - - - - - - NB, p ≠ Generator buses.

Furthermore, the maximum mismatches ΔPmax and ΔQmax are stored in memory. If ΔPmax ≤ ϵ per unit and ΔQmax ≤ ϵ per unit, then the iterative process has converged and control transfers to SUB Power flows otherwise control transferred to SUB currents to compute the bus currents using equation (17) and (18)

$$C_p^{(k)} = \frac{P_p^{(k)} e_p^{(k)} + Q_P^{(k)} f_p^{(k)}}{(e_p^k)^2 + (f_p^k)^2} \quad (17)$$

$$d_p^{(k)} = \frac{Q_p^{(k)} e_p^{(k)} - P_p^{(k)} f_p^{(k)}}{(e_p^{(k)})^2 + (f_p^{(k)})} \quad (18)$$

For p = 2, 3, ---------- NB, p ≠ Generator buses.

After the currents have been calculated, control transfers to SUB Jacobian which computes the elements of the Jacobian matrix using equations (19a) to (22b).

The entries of the Jacobian matrix are computed using equations (19a) to (22b) [19], [20]

Submatrix J^1

$$J_{pq}^1 = \frac{\partial P_p}{\partial e_q} = e_p G_{pq} - f_p B_{pq},\ p \neq q \quad (19a)$$

$$J_{pq}^1 = \frac{\partial P_p}{\partial e_q} = e_p G_{pp} - f_p B_{pp} + C_p \quad (19b)$$

Submatrix J^2

$$J_{pq}^2 = \frac{\partial P_p}{\partial e_p} = e_p B_{pq} + f_p G_{pq},\ p \neq q \quad (20a)$$

$$J_{pq}^2 = \frac{\partial P_p}{\partial f_p} = e_p B_{pp} + f_p G_{pp} + d_p \quad (20b)$$

Submatrix J^3

$$J_{pq}^3 = \frac{\partial Q_p}{\partial e_q} = e_p B_{pq} + f_p G_{pq},\quad p \neq q \quad (21a)$$

$$J_{pp}^3 = \frac{\partial Q_p}{\partial e_p} = e_p B_{pq} + f_p G_{pp} - d_p \quad (21b)$$

Submatrix J^4

$$J_{pq}^4 = \frac{\partial Q_p}{\partial f_q} = -e_p G_{pq} + f_p B_{pq},\ p \neq q \quad (22a)$$

$$J_{pp}^4 = \frac{\partial Q_p}{\partial f_p} = -e_p G_{pp} + f_p B_{pp} + c_p \quad (22b)$$

SUB Voltages is then called to solve the linear system of equations (23) for the voltages Δe and Δf. This subroutine makes use of triangular factorization and forward and back substitution to solve for the voltages.

$$\left[\frac{\Delta P}{\Delta Q}\right] = \begin{bmatrix} \frac{\partial p}{\partial e} \cdots \frac{\partial p}{\partial f} \\ \vdots\vdots \\ \frac{\partial Q}{\partial e} \cdots \frac{\partial Q}{\partial f} \end{bmatrix} \left[\frac{\Delta e}{\Delta f}\right] = [J][\frac{\Delta e}{\Delta f}] \quad (23)$$

Where J is the Jacobian matrix which for convenience may be partitioned as:

$$J = \left[\frac{J^1}{J^3} \vdots \frac{J^2}{J^4}\right]$$

The entries of the Jacobian matrix are computed using equations (19a) to (22b) [19], [20]. This completes the solution for the voltage corrections, $\Delta e^{(p)}$ and $\Delta f^{(p)}$. The subroutine then updates the voltages for the next iteration as,

$$e_p^{(k+1)} = e_p^{(k)} + \Delta e_p^{(k)} \quad (24)$$

$$f_p^{(k+1)} = f_p^{(k)} + \Delta f_p^{(k)} \quad (25)$$

The iteration count is increased by 1, i.e, k = k+1, and control is transferred to SUB Powers. When the power mismatch becomes negligible, then control is transferred to SUB Power flows which evaluate the power flows as well as the power losses in the lines. In SUB Power flows the power

flowing from Bus p to Bus q and measured at Bus p is given by equation (26),

$$P_{pq} = G_{pq}\left(e_p^2 + f_p^2\right) + \left(e_p f_q - f_p e_q\right) - G_{pq}(e_p e_q + f_p f_q) \quad (26a)$$

$$Q_{pq} = B_{pq}\left(e_p^2 + f_p^2\right) + G_{pq}\left(f_p e_q - e_p f_q\right) - B_{pq}\left(e_p e_q + f_p f_q\right) + \frac{Y_{sht}\,(e_p^2 + f_p^2)}{2} \quad (26b)$$

Similarly, the power from q to p and metered at q is given by:

$$P_{qp} = G_{pq}\left(e_q^2 + f_q^2\right) + B_{pq}\left(e_q f_p - f_q e_q\right) - G_{pq}\left(e_q e_p + f_q f_p\right) \quad (27a)$$

$$Q_{pq} = B_{pq}\left(e_q^2 + f_q^2\right) + G_{pq}\left(f_q e_p - e_q f_p\right) - B_{pq}\left(e_q e_p + f_q f_p\right) + \frac{Y_{sht}(e_q^2 + f_q^2)}{2}) \quad (27b)$$

Power losses in each branch of the network are obtained as the algebraic sum of the power calculated using equations (26a) and (27a) and that calculated using equations (26b) and (27b) for active power P and reactive power Q respectively. While the total power losses in the system is the sum of the absolute values of the calculated power losses in each branch of the network. The slack bus power is determined by summing the power flows on the lines terminating at the slack bus.

IV." APPLICATION OF THE DEVELOPED SOFTWARE PACKAGE TO A KNOWN SOLUTION OF POWER SYSTEM NETWORK

In this section, usage of the NRPF package is illustrated by testing it for a simple three bus power system whose exact solution is known [19]. The network is shown in Figure 5. The example was used to test each step of the program. Per unit impedances of the lines are clearly written in the Network diagram of figure 5. Other given data are,

$v_1 = 1.05 + j\,0$ (slack bus)

Number of buses = 3

Number of lines = 3

The scheduled power for buses 2 and 3 are

$$P_{s2} = 0.096\,, Q_{s2} = -2.07pu$$

$$P_{s3} = 3.15\,, Q_{s3} = 2.85pu$$

Power mismatch tolerance ϵ = 0.001 per unit

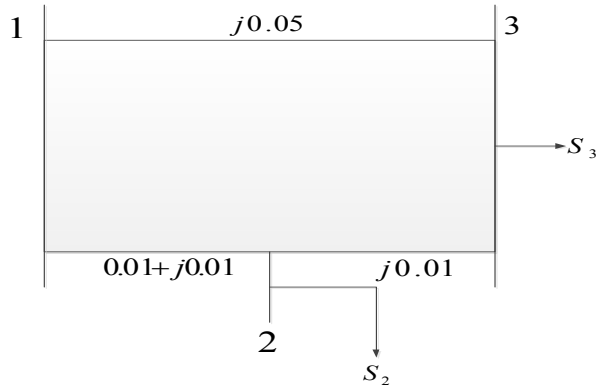


Fig. 5. Simple power system to illustrate usage of the power flow software package [19].

LAMBE 1 is used to input and store the system data:

Number of buses, NB; Number of lines, NL; Start bus, SB, and End bus, EB for each line; Line resistance, R; Line reactance, X; Line susceptance, B; Busbar scheduled power P_s and Q_s.

LAMBE 1 then assembles the bus admittance matrix, Y bus. A11 data are stored in data files (e.g Y2BUS. DAT and PQ2BUS.DAT).

LAMBE 2 then executes with bus voltages initialized to the slack bus voltage value V = 1.05 + j 0 per unit. The Newton-Raphson iteration process converged with power mismatch tolerance ϵ = 0.001 per unit in 5 iterations. The results are as follows:

Number of Buses = 3; Number of Lines = 3; Slack Bus Number = 1, Slack Bus Voltage = 1.05 + j 0; Program Converged in Iteration IT = 5, Power Mismatch Tolerance = .001.

TABLE 2
CALCULATED BUSBAR VOLTAGES OF THE TEST NETWORK IN PER UNIT

Bus	Voltage
1	1.00 + j 0
2	1.069 + j - .036
3	1.042 + j - .05

TABLE 3
CALCULATED BUSBAR VOLTAGE MAGNITUDES, PHASE ANGLES, ACTIVE AND REACTIVE POWER OF THE TEST NETWORK IN PER UNIT

	Voltage		Power	
Bus No	Magnitude	Phase Angle (Degree)	Active	Reactive
1	1	0	0	0
2	1.07	-1.929	9.61	-2.07
3	1.043	-2.967	3.15	2.849

TABLE 4
POWER FLOWS BETWEEN BUSES OF THE TEST NETWORK

Bus		Power flow per unit	
From	To	Active	Reactive
1	2	1.65	-5.25
2	1	-1.953	5.553
1	3	-1.08	-8.4
3	1	1.08	0.93
2	3	-2.021	2.821
3	2	2.021	-2.716

Total Power Losses = - .303 + -j0.292 per unit

Slack Bus Power = 2.73 + j 6.09 per unit

V." DISCUSSION OF RESULTS

In power flow analysis, a generator bus is often used as the slack bus. Hence, bus 1 was chosen as the slack bus and its voltage is 1.0 < 0 per unit for the analysis. The voltage of the generator buses would have been constrained to be 1.0 < 0 per unit but unfortunately none of the buses are with generator.

From table 3, there is a wide variation of voltage profile, thus, for any meaningful analysis, it becomes necessary to identify buses with minimum voltage profile and buses with

maximum voltage profile. The minimum and maximum voltage values acceptable for a normal power system network are 0.95 and 1.05 per unit respectively [17]–[20]. On this basis, buses whose voltage magnitude falls above maximum acceptable value are can also be seen from the same overloaded [5]. It would have also been seen on the same table that generator buses in the network and whose voltages values are fixed at 1.0 < 0 per unit falls within the accepted range and therefore not overloaded. Similarly, based on these results, loaded buses such as bus 1 and 2 in the network have their calculated voltages within the permissible range and hence, they are not overloaded. Therefore, there exist no overloaded bus in the network perhaps the distance of the buses from the source of supply are not far.

From the flow pattern shown in Table 4 of the results, it is observed that for a steady state situation, there are no overloaded lines. For example, on Table 4, the active and reactive power flow from bus 2 to bus 3 measured at bus 3 are - 2.021 and 2.821 per unit respectively. While the returned power flow measured at bus 2 are 2.021 and - 2.716 per unit respectively. This implies that there is a negligible active power loss on this line. Furthermore, there is a reduction in reactive power flow when measured at bus 2, which accounts for the losses. However, it is 'unhealthy' of any power system to have higher reactive power flow than active power flow as is the case for bus 2 – bus 3 and bus 1 – bus 2 transmission lines in the network.

Also, in Table 4, power flow analysis shows that the slack bus active power is 1.65 per unit. This suggests that for the Practical feasibility of the network as a power system, the rated capacity of the Generator to be installed at bus 1 should be far greater than 1.65 per unit (165MVA).

VI. Conclusion

The paper has presented a review of Newton Raphson power flow analysis. A computer software package is developed for Newton- Raphson power flow studies. The package was tested for a three Bus-bar network as case study. The results of this analysis converged at the fifth iteration. The quick convergence of the solutions of the power flow analysis for the network considered in this paper satisfied the theoretical reports of Newton Raphson power flow iterative method. Newton – Raphson approach to power flow solutions was observed to be the most sophisticated and very difficult to program. However, it converges faster than the other methods and the results are often more reliable. Thus, it is worth mentioning that the obtained power flow analysis results are in conformity with the known solution of the Network.

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