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The IEEE 33 Bus Distribution System Load Flow Analysis Using Newton Raphson Method

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***Abstract*—In this paper, the IEEE Bus Distribution System load flow analysis using Newton Raphson method is presented. Fundamental equations for load flow analysis of n-bus system are presented along with the algorithm for Newton Raphson load flow analysis and the case study IEEE 33-Bus System dataset. Then, Newton Raphson load flow MATLAB program was developed and used to determine the bus voltages and phase angles at each bus of the case study IEEE 33 bus system. With Newton Raphson method, convergence occurred at the 4th iteration. The results also show that only four buses (namely, bus 1,2, 19 and 20) out of the 33 buses have voltages that satisfy the acceptable voltage level of 95% or 0.95 p.u. The rest of the buses have voltage values that are below the acceptable value. The result presented in this paper is relevant for evaluating the stability of the power system. With most of the bus voltages below the acceptable minimum value, it calls for voltage profile enhancement on the bus system**

Keywords— IEEE 33 Bus Distribution System, Bus Voltage, Load Flow Analysis, Phase Angle, Newton Raphson Method

1.0 Introduction

Successful deployment and sustenance of power system network require proper planning and design. Particularly, there is need to determine the present and future load demand and design the power network for such know and expected future load profile [1,2,34,5,6,7,8]. However, even when such measures are taken, load flow analysis is required to understand voltage profiles on the buses and to ensure that the voltages are within the acceptable range for proper functioning of the power network [9,10,11,12,13,14].

Also, in some power networks, distributed generating technique is adopted [15,16,17,18]. In such case, different power generators ranging from hydro, solar, wind, fossil fuel-based options are incorporated into the power source mix [19,20, 21,22, 23,24, 25,26, 27,28, 29,30, 31,32, 33,34,35, 36,37, 38,39, 40,41, 42,43, 44,45]. Again, load flow analysis is required to ascertain the stability of the power system when the distributed generating solution is adopted [46,47]. Also, overloading and unbalanced loads in the power network can cause problems in the network. Load flow analysis will help the power system engineer to simulate such scenarios and evaluate their impact on the power network.

Notably, load flow analysis can be performed using different iterative methods as well as using data-driven models. One of the iterative solution is the Newton Raphson method which has been widely applied in diverse areas and has performed better than some other contending iterative algorithms [48,49,50,51,52,53,54,55,56,57,58,59,60,61]. As such, this paper presents load flow analysis on a case study IEEE 33 Bus Distribution System using Newton Raphson (NR) method [62,63,64]. The detailed mathematical models for the NR iterative load flow solution are presented along with the NR load flow analysis procedure. Specifically, the analysis in this paper yielded the voltage and phase angles at each bus of the case study IEEE 33 bus system. The resulting voltage and phase angle profile are used to assess the voltage and power stability of the case study bus network.

2.0 Methodology

2.1 Derivation of Fundamental Equations for Load Flow Analysis of N-bus System

Consider an n-bus system comprising of voltages, admittances and line real and reactive power flows between pairs of buses indexed at say i, k; then the real and reactive power can be deduced by taking into consideration the current flowing into bus i for an N-bus network.

The current received at bus i from the generator or power grid is given as;

$$I_i = Y_{i1} V_1 + Y_{i2} V_2 + . . + Y_{ik} \quad = {}^{n}{}_{ik=1} Y_{ik} V_k \qquad (1)$$

Considering magnitude and phase angle, the voltage and admittance will be given as:

$$V_k = V_K \angle \delta_k \text{ (voltage at the bus k)} \quad (2)$$

$$Y_{ik} = Y_{ik} \angle \theta_{ik} \text{ (admittance between bus i and bus k)} \quad (3)$$

Substitute Equation 2 and Equation 3 into Equations 1 gives

$$I_i = {}^{n}{}_{ik=1} Y_{ik} \angle \theta_{ik} \quad V_k \angle \delta_k \quad (4)$$

where $\delta i, \delta k$ *are phase angles of* bus i and k, while δ_{ik} is the angular difference between bus i and k. The conjugate of the injected current at bus i will be;

$$I_i^* = {}^{n}{}_{ik=1} Y_{ik} \angle -\theta_{ik} V_k \angle -\delta_k \quad (5)$$

The apparent power available at bus i will be;

$$S_i^* = V_i I_i = P_i + jQ_i \quad (6)$$

where P_i and Q_i denote its real and reactive powers

Substituting Equation 5 into Equation 6, considering the magnitude and angle gives:

$$P_i + jQ_i = V_i \angle \delta_i {}_{i,=1} Y_{ik} \angle -\theta_{ik} V_k \angle -\delta_k \quad (7)$$

Rearranging Equation 7 gives;

$$P_i + jQ_i = {}_{i,=1} Y_{ik} V_i V_k \angle(-\theta_{ik} + \delta_i - \delta_k) \quad (8)$$

However,

$$\delta_{ik} = \delta_i - \delta_k \quad (9)$$

(The angle difference is defined by δik = δi − δk.)

$$-\theta_{ik} = \theta_{ik} \quad (10)$$

Substituting the relations in Equation 9 and Equation 10 into Equation 8 gives

$$P_i + jQ_i = {}^{n}{}_{i,=1} Y_{ik} V_i V_k \angle(\theta_{ki} + \delta_{ik}) \quad (11)$$

From the (11, the active real and imaginary power will be;

$$P_i = {}^{n}{}_{i,=1} Y_{ik} V_i V_k \cos(\theta_{ki} + \delta_{ik}) \quad (12)$$

$$Q_i = {}^{n}{}_{i,=1} Y_{ik} V_i V_k \sin(\theta_{ki} + \delta_{ik}) \quad (13)$$

Equation 12 and Equation 13 are used to obtain calculated values of real and reactive power. Note that when the bus generates electrical power, it is termed a generator bus otherwise it is a load-bus; a slack bus is also often necessary to accommodate (suck-up) the excess power flows.

The line flows may further be expressed as changes in the computed real bus/or generator powers with respect to pre-specified real bus/or generator values and is expressed as:

$$\Delta P_i = P_i^{sp} - P_i^{cal} \quad (14)$$

Where P_i^{sp} = the specified real bus powers at power exchange sequence, P_i^{cal} = the computed real bus powers at power exchange sequence i, using Equation 12. Similarly, the reactive power changes may be expressed as:

$$\Delta Q_i = Q_i^{sp} - Q_i^{cal} \quad (15)$$

Where Q_i^{sp} = the specified reactive bus powers at power exchange sequence i, Q_i^{cal} = the computed reactive bus powers at power exchange sequence i, using Equation 13. Typically, the admittances, line power demand and generations are given while the bus voltages and angles are obtained by making an initial guess and solving using a load-flow program. The net power balance is then expressed as the sum over all bus power sequence exchanges as:

$$\Delta P_{net} = {}^{n}{}_{i} \Delta P^2{}_i \quad (16)$$

And,

$$\Delta Q^{net} = {}^{n}{}_{i} \Delta Q^2{}_i \quad (17)$$

Working data was obtained for the three feeders considered from IEEE 33 bus system as regards transformer and feeder parameters. Based on the acquired data, calculations were done using per unit system to get the MVAs for easy representation of the system schematic diagram. Let the base MVA be 100 for a per unit voltage of unity, knowing that:

$$Z_{p.(new)} = Z_{p.u\,(old)} \times \frac{\text{MVA}_{\text{new}}}{\text{MVA}_{\text{old}}} \quad (18)$$

$$Z_{1new} = 0.1217 \times \frac{100}{30} = 0.3651 p.u \quad (19)$$

$$Z_{2new} = 0.1028 \times \frac{100}{60} = 0.1542 p.u \quad (20)$$

Transformer 1(T_1) and Transformer 2 (T_2) are connected in parallel and as such their equivalent impedance will be gotten using Equation 8.

$$Z_{p.uequi.} = \frac{z_{1p.u} \times z_{2p.u}}{z_{1p.u} + z_{2p.u}} \quad (21)$$

$$Z_{p.uequi.} = \frac{0.3651 \times 0.1542}{0.3651 + 0.1542} = 0.1084 p.u \quad (22)$$

Then we proceeds from substituting values into Equation18, Equation 19 and Equation 20, this is used for the network schematic shown in Figure 1, which is a IEEE 33 bus system comprising of a grid, distribution lines, high voltage circuit breakers and lumped loads representing feeder loads.

2.2 Load Newton Raphson Flow Analysis Procedure and the case study IEEE 33-Bus System

The load flow analysis using Newton Raphson method can be implemented using the following procedure;

STEP 1: Select the error tolerance value, ε and initialise the iteration counter k =0

STEP 2: Read the load flow dataset and formulate the Y_{ij} nodal admittance

STEP 3: Choose the initial bus voltage values (where the voltage, V_i magnitude is $|V_i|^k$ and the voltage, V_i phase angle is $\delta_i{}^k$) and the n bus is set as the reference bus, where;

$V_i = V_{i,spec} < 0°$ for all the PV buses

$V_i = 1 < 0°$ for all the PQ buses

STEP 4: At the k+1 iteration, by using $V_i{}^k$ the values of $P_i{}^{k+1}$ (the real power) are computed for all the PV buses using the equation given as;

$$P_i, cal^{k+1} = P_i = G_{ii}|V_i|^2 + \sum_{j=1}^{n} \left(|V_i||V_j| \left(G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij} \right) \right)$$

Where $\theta_{ij} = \theta_i - \theta_j$ is the difference in the angle between bus i and bus j while G_{ij} and B_{ij} denote to conductance and the susceptance of the bus system respectively.

STEP 5: At the k+1 iteration, by using $V_i{}^k$ the values of $Q_i{}^{k+1}$ (the reactive power) are computed for all the PQ buses using the equation given as;

$$Q_i, cal^{k+1} = Q_i = -B_{ii}|V_i|^2 + \sum_{j=1}^{n} \left(|V_i||V_j| \left(G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij} \right) \right)$$

STEP 6: By using $V_i{}^k$ along with its elements spread over the H, N, K and L submatrices form the Jacobian matrix $[J^k]$.

STEP 7: Compute ΔP_i and ΔQ_i (which are the active and reactive power differences or mismatches respectively, for I = 1,2,3,…n-1 where

$$\Delta P_i{}^k = P_{i,spec} - P_i, cal^{k+1}$$

$$\Delta Q_i{}^k = Q_{i,spec} - Q_i, cal^{k+1}$$

STEP 8: Compute

$$\begin{bmatrix}\Delta\delta_i{}^k \\ \frac{\Delta v^k}{v}\end{bmatrix} = [J^k]^{-1}\begin{bmatrix}\Delta P_i{}^k \\ \Delta Q_i{}^k\end{bmatrix}$$

STEP 9: Re-compute the values for V_i and δ_i as follows;

$$\delta_i{}^{k+1} = \delta_i{}^k + \Delta\delta_i{}^k$$

$$V_i{}^{k+1} = V_i{}^k + \Delta V_i{}^k$$

STEP 10: Stop the Newton Raphson iteration when all the values obtained for ΔP_i and ΔQ_i are less or equal to ε otherwise increase the iteration counter k by 1 and go to Step 4 and continue with the iteration

The IEEE 33 bus system is a standard test bus with generator buses, load buses and interconnected lines. In this paper, Bus 1 in the case study IEEE 33 bus system is selected as the slack bus. An interconnected bus line of the IEEE 33 bus system is shown in Figure 1. The line data and the bus data for the IEEE 33 bus system used for the study are given in Table 1.

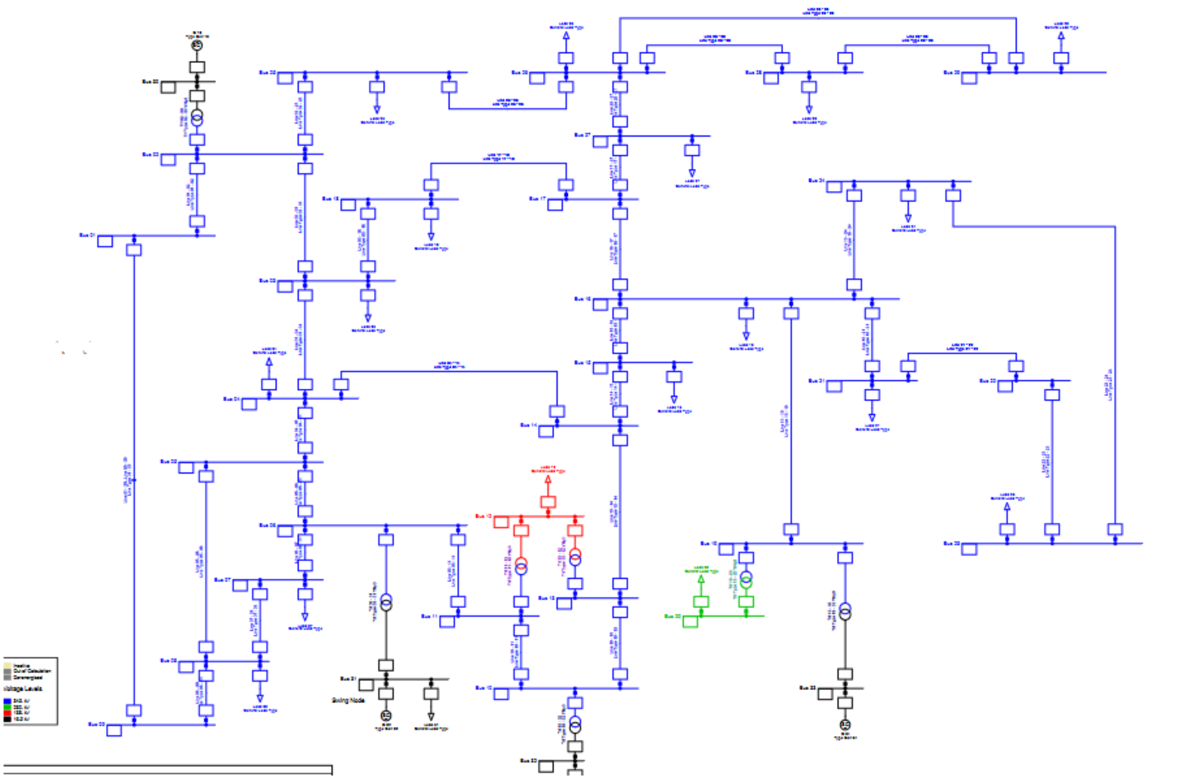

Figure 1: The IEEE 33 bus system extracted from Etap software

Table 1 The IEEE 33 bus system line dataset and bus dataset

The IEEE 33 bus system line dataset

Bus Number	Sending Bus Number	Receiving Bus Number	Line Resistance	Line Reactance
1	1	2	0.0922	0.047
2	2	3	0.493	0.2511
3	3	4	0.366	0.1864
4	4	5	0.3811	0.1941
4	5	6	0.819	0.707
6	6	7	0.1872	0.6188
7	7	8	0.7114	0.2351
8	8	9	1.03	0.74

The IEEE 33 bus system bus dataset

Bus Number	LOAD: Active Power (KW)	LOAD : Reactive Power (KVAR)	Q Injected
1	0	0	0
2	100	60	0
3	90	40	0
4	120	80	0
5	60	30	0
6	60	20	0
7	200	100	0
8	200	100	0

9	9	10	1.044	0.74
10	10	11	0.1966	0.065
11	11	12	0.3744	0.1238
12	12	13	1.468	1.155
13	13	14	0.5416	0.7129
14	14	15	0.591	0.526
15	15	16	0.7463	0.545
16	16	17	1.289	1.721
17	17	18	0.732	0.574
18	2	19	0.164	0.1565
19	19	20	1.5042	1.3554
20	20	21	0.4095	0.4784
21	21	22	0.7089	0.9373
22	3	23	0.4512	0.3083
23	23	24	0.898	0.7091
24	24	25	0.896	0.7011
25	6	26	0.203	0.1034
26	26	27	0.2842	0.1447
27	27	28	1.059	0.9337
28	28	29	0.8042	0.7006
29	29	30	0.5075	0.2585
30	30	31	0.9744	0.963
31	31	32	0.3105	0.3619
32	32	33	0.341	0.5302

9	60	20	0
10	60	20	0
11	45	30	0
12	60	35	0
13	60	35	0
14	120	80	0
15	60	10	0
16	60	20	0
17	60	20	0
18	90	40	0
19	90	40	0
20	90	40	0
21	90	40	0
22	90	40	0
23	90	50	0
24	420	200	0
25	420	200	0
26	60	25	0
27	60	25	0
28	60	20	0
29	120	70	0
30	200	600	0
31	150	70	0
32	210	100	0
33	60	40	0

3. Results and discussion

The focus of this paper is to use MATLAB program to determine the bus voltages and phase angles at each bus for the IEEE 33 bus system. With Newton Raphson method, the solution converged at the 4^{th} iteration. The result obtained from the MATLAB program for the bus voltage and phase angle based on the Newton Raphson load flow method are given in Table 2. Specifically, Figure 2 shows the scatter plot of the bus voltage value for each bus using Newton Raphson method is presented in Figure 2 while Figure 3 shows the bar chart of the bus voltage value for each bus using Newton Raphson method. Based on the bar chart of Figure 3, only four buses (namely, bus 1,2, 19 and 20) have voltages that satisfy the acceptable voltage level of 95% or 0.95 p.u. The rest of the buses have voltage values that are below the acceptable value. Also, Figure 4 shows the scatter plot of the phase angle value for each bus using Newton Raphson method

Table 2: The results of the bus voltage and phase angle based on the Newton Raphson load flow method

Bus No	Voltage (p.u.)	Phase Angle (radians)
1	1.0000	0.0000
2	0.9862	0.0116
3	0.9270	0.0743
4	0.8924	0.1218
5	0.8607	0.1739
6	0.7693	0.2954
7	0.7277	0.3218
8	0.7236	0.3904
9	0.7036	0.4948
10	0.6954	0.5951
11	0.6981	0.6094
12	0.7032	0.6330
13	0.7077	0.7334
14	0.7053	0.7737
15	0.7085	0.8019
16	0.7135	0.8253
17	0.7150	0.8631
18	0.7170	0.8706
19	0.9821	0.0116
20	0.9543	0.0124
21	0.9486	0.0118
22	0.9432	0.0110
23	0.9198	0.0769
24	0.9094	0.0800
25	0.9042	0.0814
26	0.7635	0.3074
27	0.7568	0.3226
28	0.7226	0.3739
29	0.7025	0.4090
30	0.6971	0.4272
31	0.6815	0.4554
32	0.6776	0.4616
33	0.6746	0.4653

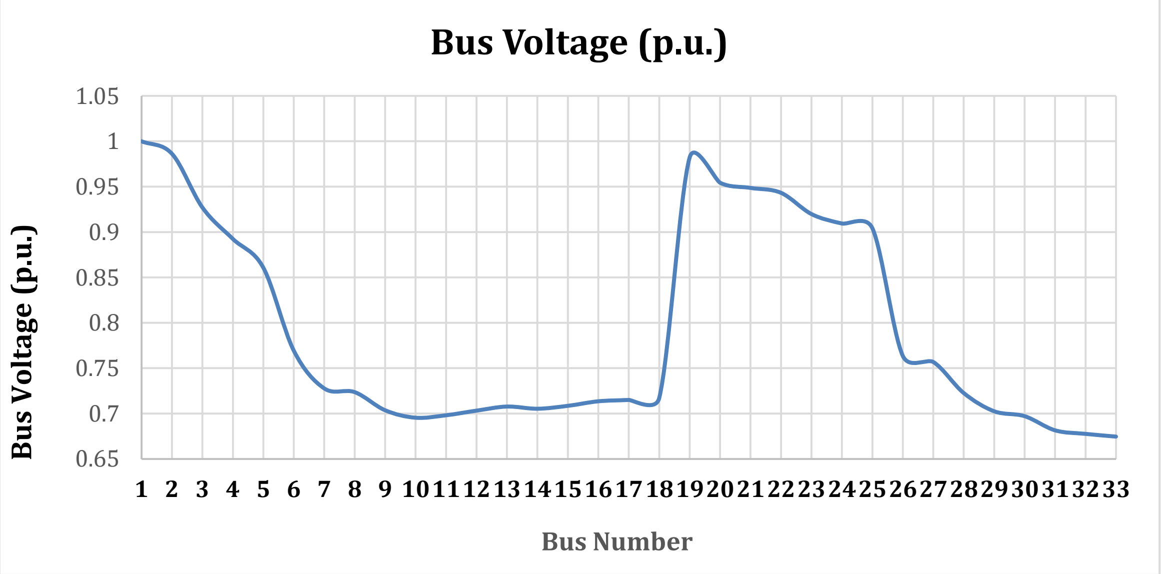

Figure 2: The scatter plot of the bus voltage value for each bus using Newton Raphson Method

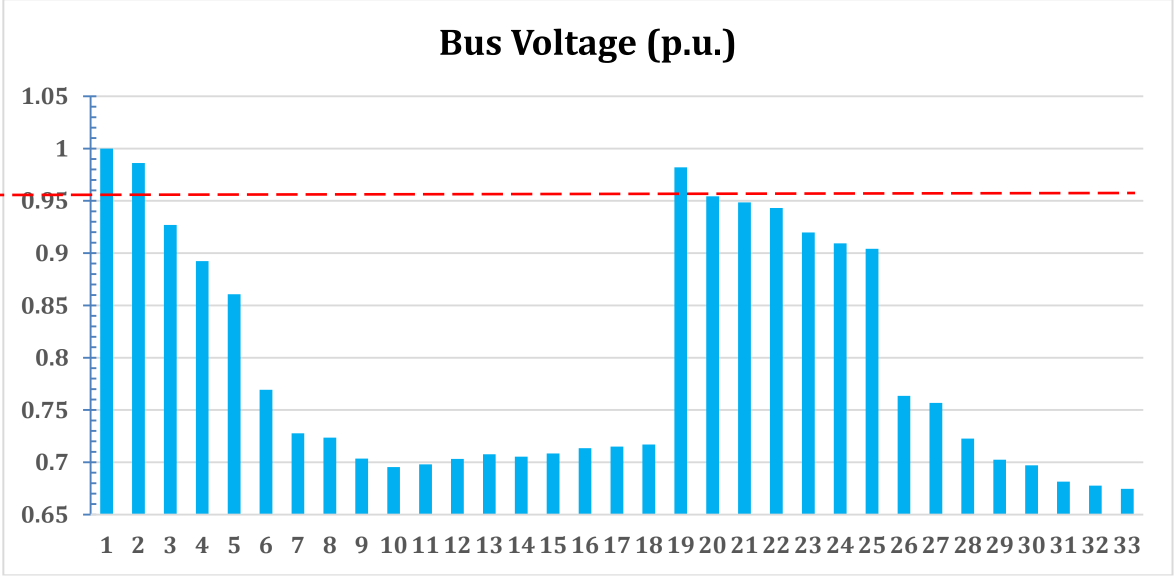

Figure 3: The bar chart of the bus voltage value for each bus using Newton Raphson Method

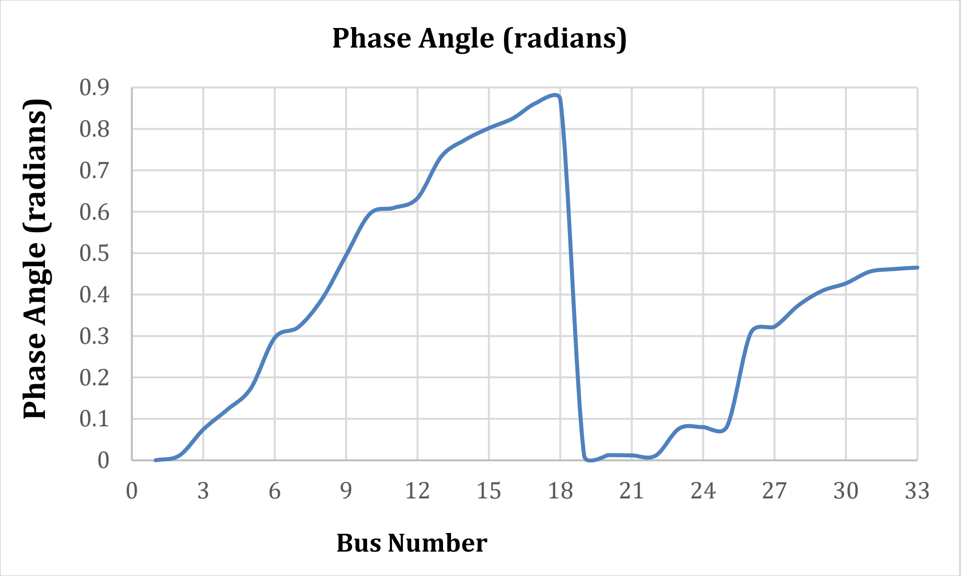

Figure 4: Phase angle of voltage values for each bus using Newton Raphson Method

4. Conclusion

Newton Rapson (NR) method is used to conduct load flow analysis on the IEEE 33 bus system. The NR mathematical models and algorithm are presented and the load flow program was written in MATLAB and then used to simulate the NR load flow analysis using the IEEE 33 line data and bus data. The results show that majority of the bus voltages are below the acceptable range of 0.95 p.u.

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