

Improved load flow formulation for radial distribution networks

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Article Info

Article history:

Received Oct 1, 2018

Revised Dec 10, 2018

Accepted Jan 25, 2019

Keywords:

Load flow

Power loss

Radial distribution network

Real power loss

Voltage profile

ABSTRACT

This paper aims to provide an improved load flow formulation for solving load flow problem in radial distribution networks. The improved algorithm is formulated from the basic Kirchoff's voltage law. The proposed method does not need any matrix multiplication, and the voltage equation is derived to compute the voltage at each node. The proposed method is then tested on 28-bus, IEEE-33 and IEEE-69 systems of radial distribution networks with different resistance to reactance ratio and different condition of loads. The simulation results from the suggested algorithm show that the proposed method has fast convergence capability compared with other existing methods. A very good agreement is achieved.

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1. INTRODUCTION

Load flow study can be considered as an important aspect of power system planning, analysis, operation and control. It is normally used to check whether the voltage profiles are within the limits throughout the network at the design stage [1]. Additionally, the load flow study can also predict the network stability, reliability and the required protection scheme. However, the conventional Newton-Raphson and fast decoupled load flow methods for the transmission systems often encounter convergence problem and cannot be applied for the distribution networks due to high R/X ratio [2]. For the load flow analysis to be acceptable, it should meet the conditions for low storage requirement, high speed, high reliability, accepted versatility and simplicity [3]. Therefore, many researchers have attempted to propose modified versions of conventional power flow related to the distribution networks.

For instance, researchers in [4, 5] proposed load flow solution to calculate the voltage magnitudes but did not mention any procedures to estimate the voltage phase angles. In [6], the authors implemented the load flow solution for radial and meshed distribution networks by using matrix multiplication. Another load flow method using dynamic data matrix for radial distribution systems was provided in [7]. However, the proposed method depends on the system's topology and converged after more than twenty iterations. A novel matrix transformation technique was developed in [8], which directly solves the determinants of branch flows in the radial distribution networks, consequently it makes forward and backward sweeps based on load flow method. Another load flow analysis hybridized with PV nodes and backward/forward sweep was presented in [9]. A novel of load flow algoritrh was proposed by the authors in [10] for calculating the distribution grid systems. Researchers in [11] implemented the traditional load flow method in distribution networks, but the method was not useful for active distribution system networks and the load was modelled

using heuristic method. Another method called multi-agent communication system was proposed by the authors in [12] in order to solve for unbalanced radial distribution networks. In [13], a load flow approach for radial distribution system was developed using different static of loads. Cholesky factorization method was used for the load flow analysis by modelling the loads and wind power as probability functions in [14]. A technique called breadth first search (BFS) method was developed to integrate with backward/forward sweep technique for solving the distribution networks in [15].

However, this paper aims to improve the existing load flow studies aforementioned, to fill the research gaps of longer execution time, high computational burden, complicated coding scheme to identify the branches and nodes by providing a simplified method to evaluate the voltage magnitude and its phase angle, the real and reactive power losses under influence of diferent R/X ratios and different load conditions. The improved load flow formulation is then tested on standard distribution systems, and the simulation results are compared with other existing methods.

2. ASSUMPTIONS

In order to implement the improved load flow formulation, it is assumed that the three-phase systems are balanced and the charging capacitance is neglected

3. PROBLEM FORMULATIONS

A single-line diagram of a balanced three-phase supply in radial distribution system is shown in Figure 1. The notation i represents the node number or bus number. The voltage at bus i is represented as V_i , voltage at bus $(i+1)$ is V_{i+1} , impedance of the line, Z_i , and the load current represent as I_i . The load current can be calculated as (1) where S_i is the complex load at node i .

$$I_i = \left(\frac{S_i}{V_i} \right)^* = \left(\frac{P_i + jQ_i}{V_i} \right)^* \tag{1}$$

The line current can also be estimated as

$$I_{(i,i+1)} = I_{(i+1)} + \sum \text{current emanating from node } i+1 \tag{2}$$

By applying the Kirchoff's voltage law (KVL) at node i , the voltage at node i can be calculated as

$$V_i = V_{i+1} + I_{(i,i+1)} \cdot Z_i \tag{3}$$

Knowing the line current, the real and reactive power losses can be determined as

$$P_{(i,i+1)} = I_{(i,i+1)}^2 \cdot R_i \tag{4}$$

$$Q_{(i,i+1)} = I_{(i,i+1)}^2 \cdot X_i \tag{5}$$

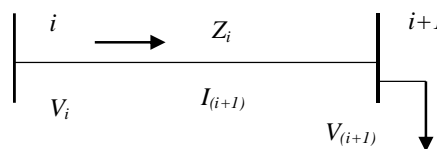


Figure 1. Single-line diagram for balanced power system network.

3.1. Power Flow in the Improved Load Flow Formulation

The voltage magnitudes, phase angles, real and reactive power losses for radial distribution networks can be obtained from the following steps:

Step 1: Read the line and the load data.

Step 2: Initialize the base values for MVA and kV.

Step 3: Calculate the base impedance and convert the line and load parameters into per unit (p.u) value.

Step 4: Construct the incidence matrix [16] to identify the branches and nodes. The positive value of 1 indicate the sending end of the branch i , negative value of 1 will be the receiving end of the branch i , and 0 if there is no connection between the nodes. The incidence matrix for the branch to node is

$$IM = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & 1 \end{bmatrix}$$

Step 5: Construct the node to branch which is the inverse incidence matrix [16].

Step 6: Find the end of each node of the bus system, calculate the total end nodes, lateral and sub-lateral of the bus system, and link them to calculate the current and voltage.

For example, from the sample power system network as shown in Figure 2, the end of the nodes are node 4, 6 and 8. Therefore, the total number of end nodes are 3. The lateral (branch) of the system are 3. The lat[1]=1,2,3,4; lat[2]=2,5,6 and lat[3]=3,7,8.

Step 7: Initialize the bus voltage, $v(i) = 1.0$ for all $i=1,2,3,\dots,n_{max}$, number of iteration=0, and tolerance=0.0001.

Step 8: Calculate the load current using (1) for each nodes and linked them in order to calculate the branch or line current using (2) starting from the last nodes to downstream until the substation node for each branches. This is the application of basic current law, KCL where the current injection is equal to the load current.

Step 9: Calculate the voltage at each node using (3) which is from the calculated branch currents starting from the substation nodes towards to the last nodes for each branches. Calculate the voltage mismatch between the present and previous iterations. If the error is less than 0.0001, then the load flow calculation has converged, otherwise go to **Step 8**.

Step 10: Calculate the real and reactive power losses at each bus using (4) and (5). Modification has been made in order to calculate the power losses using branch currents. Therefore, real and reactive power loss can be easily determined in Step 8 and reduced CPU time.

Step 11: Calculate the total real and reactive power losses of the system, find the minimum voltage and display the results.

Step 12: Stop

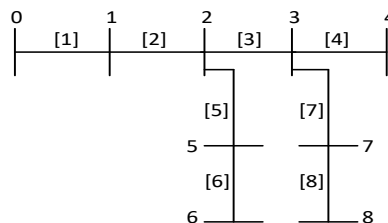


Figure 2. Sample power system network with branches and nodes

4. SIMULATION RESULTS

The proposed method as shown in previous section has been tested on the 28 bus, IEEE 33 and IEEE 69 bus radial distribution systems respectively in MATLAB 2017 and run on Intel's i3 processor with Windows 7 operating system and clock of 1.90GHz. A tolerance of 0.0001 on voltage magnitude is used as a convergence criteria. The proposed algorithm is considered to successfully reach convergence if the voltage mismatch between any two successive iterations is less than or equal to 0.0001 p.u. While implementing the proposed method, it is assumed that: (a) three-phase radial distribution systems are balanced and represented

by their single-line diagrams; (b) charging capacitance is neglected in the distribution voltage level.; (c) the load flow has been compared for constant power load modeling.

The summary of the results for the 28-bus system is shown in Table 1. The base kV and MVA are 11 kV and 100 MVA, respectively. The bus and line data of the system can be found in Appendix. Table 1 gives the line number, the voltage magnitude and its phase angle at the receiving ends. From Table 1, total real and reactive power losses are 68.72 kW and 45.97 kVar, respectively. These are 8.28% and 8.81% of their loads. The minimum voltage is 0.9133 p.u. at bus 26. The load flow results are verified with two previously published papers in [17-18] as given in Table 2. It is observed that the voltage profile has improved with the decreases in power losses. The total real and reactive losses are reduced, and the minimum voltage is improved in the proposed method. From Table 2, it can be noted that the results obtained from the proposed method have closely matched with that of [18].

The second test case is an IEEE-33 bus, 12.66 kV, 100 MVA, 33 nodes and 32 lines for radial distribution system. The line and load data for this system is given in Appendix. At the nominal voltage, the total real and reactive power losses are 3715 kW and 2300 kVar, respectively. The load flow solutions for bus voltage (in p.u) and phase angle (in rad) are tabulated in Table 3. From the results, the real and reactive power losses at bus 18 are 210.0628 kW and 142.5248 kVar or 5.65% and 6.2% of their nominal losses respectively. The minimum voltage occurs at bus 18 with 0.9042 p.u. These results are also compared with other methods for the real and reactive power losses and the minimum voltage at which bus it occurs as illustrated in Table 4. From this comparison, it can also be observed that the magnitudes of the voltage are almost equal. The proposed method has computed for almost the same voltage magnitudes with the convergence rate of 0.0001. Authors in [2, 6, 16, 19, 21-23] obtained the real power losses for the base case were different from the authors in [3, 20]. This happens because the researchers in [2, 6, 16, 19, 21-23] have chosen the values for resistance and reactance at 7th line data as 1.7114 Ω and 1.2351 Ω respectively. Whereas for [3, 20], both resistance and reactance were taken to be 0.7114 Ω and 0.2351 Ω respectively.

Table 1. Voltage and Phase Angles from Simulation Results for 28-bus Radial Distribution Networks

Convergence rate 10 ⁻⁴					
Node	V(p.u)	δ (rad)	Node	V(p.u)	δ (rad)
1	1.0000000	0.0000000	15	0.9432998	0.0152452
2	0.9863163	0.0029824	16	0.9375553	0.0146665
3	0.9666978	0.0074175	17	0.9264808	0.0176244
4	0.9527096	0.0106982	18	0.9255211	0.0181109
5	0.9386695	0.0141202	19	0.9238817	0.0189454
6	0.9282349	0.0167384	20	0.9230383	0.0193759
7	0.9191517	0.0190741	21	0.9224153	0.0196948
8	0.9167180	0.0197059	22	0.9163278	0.0205363
9	0.9164404	0.0197783	23	0.9148220	0.0213206
10	0.9161973	0.0198416	24	0.9136700	0.0219220
11	0.9466007	0.0136370	25	0.9134157	0.0220549
12	0.9448555	0.0144860	26	0.9132536	0.0221399
13	0.9438129	0.0149946	27	0.9162326	0.0199571
14	0.9435370	0.0151294	28	0.9161112	0.0200199

Table 2. Comparison of Load Flow Results for 28-bus Radial Distribution Networks

Methods	Power Losses			Bus no.	Convergence rate	Iteration no.
	Real (kW)	Reactive (kVar)	V _{min(p.u)}			
Proposed Method	68.71761	45.97376	0.9133	26	10 ⁻⁴	4
Peddanna and Kishore [18]	68.84580	46.02310	0.9124	26	-	-
D.Das et., al[17]	68.79110	46.06950	0.9127	26	-	-

The proposed load flow was also tested for the 69-node, 12.66 kV, 100 MVA radial distribution system. The line and load data for this system are available in [5]. The total real and reactive power loads consumed at nominal voltage are 3791.89 kW and 2694.10 kVAr, respectively. The load flow results for bus voltages and phase angles of this system are given in Table 5. From the proposed method, the real and reactive power losses at bus 65 are 224.8721 kW and 102.1535 kVAr or 5.93% and 3.79% of their respective real and reactive loads. The minimum voltage of the system is 0.910152 at bus 65. The proposed algorithm has been verified with other eight existing methods for constant power load as presented in Table 6. The real and reactive power losses, minimum voltage, convergence rate corresponding to the number of iterations are

shown in Table 6. From this table, the results from the proposed load flow technique have agreed very well with those presented in [18].

Table 3. Voltage and phase angle from simulation results for IEEE-33 bus radial distribution networks.

Convergence rate 10^{-4}					
Node	V(p.u)	δ (rad)	Node	V(p.u)	δ (rad)
0	0.000000	0.000000	17	0.904819	-0.01281
1	1.000000	0.000000	18	0.904211	-0.01300
2	0.997021	0.000239	19	0.996493	0.00005
3	0.982924	0.001682	20	0.992919	-0.00113
4	0.975441	0.002845	21	0.992216	-0.00147
5	0.968042	0.004024	22	0.991580	-0.00183
6	0.949627	0.002412	23	0.979339	0.001137
7	0.946158	-0.001680	24	0.972671	-0.000420
8	0.932554	-0.004600	25	0.969348	-0.001190
9	0.926249	-0.006030	26	0.947710	0.003130
10	0.920400	-0.007260	27	0.945164	0.004152
11	0.919530	-0.007160	28	0.933758	0.005794
12	0.918012	-0.00699	29	0.925569	0.007298
13	0.911875	-0.00876	30	0.922043	0.009199
14	0.909616	-0.01021	31	0.917863	0.007794
15	0.908205	-0.01092	32	0.916942	0.007407
16	0.906834	-0.01137	33	0.916657	0.007276

Table 4. Comparison of Load Flow Results for IEEE-33 bus Radial Distribution Networks

Methods	Power Losses		$V_{\min(p.u)}$	Bus no.	Convergence rate	Iteration no.
	Real (kW)	Reactive (kVar)				
Teja et., al[19]	210.9824	143.0219	0.903776	18	10^{-4}	4
Babu B. and Maheswarapu [6]	210.9800	143.0200	0.903776	18	10^{-4}	4
Malik et., al[23]	210.9700	143.1100	0.903000	18	10^{-4}	4
Proposed Method	210.0628	142.5248	0.904211	18	10^{-4}	4
Ramana et., al[2]	209.6800	142.2000	0.905090	18	10^{-4}	2
Hamouda and Zehar [16]	205.1900	139.2300	0.904100	18	10^{-4}	2
Nagaraju et., al[3]	202.6817	135.2370	0.913080	18	10^{-5}	4
Vasquez and Quilumba [7]	211.0000	-	0.903700	18	10^{-3}	23
Ghosh and Sherpa [20]	202.3000	135.0200	0.909924	18	10^{-5}	-
Kumar et., al[22]	210.9716	143.9716	0.903780	18	-	-
Rupa and Ganesh [21]	203.6500	102.6000	0.913600	18	-	-

The proposed algorithm was also tested for different R/X ratios in order to investigate its effect on the voltage profile in the 28-node and IEEE-33 bus test systems as shown in Figure 3 and Figure 4, respectively. As can be observed, the increase of R/X ratio will reduce the voltage magnitude of the system. The load voltage also varies with the different loading conditions by multiplying their real and reactive powers by a constant. The effect of different loads has been implemented for the IEEE-69 bus test system as shown in Figure 4. The p.u values of the voltage decrease with the increase in the load because the increasing branch current which leads to larger voltage drop. However, from nodes 27 to 45, the voltage magnitudes are fairly constant because these nodes are quite close to the source node with small line parameters and the loads are at low level. The proposed technique was also tested on convergence rate for the values of 10^{-1} , 10^{-2} , 10^{-3} , 10^{-4} , 10^{-5} and 10^{-6} . The results are tabulated in Table 7. From Table 7, it can be observed that the tolerance level decreases with the decrease of convergence rate. Table 8 shows the the comparison of relative CPU time with other existing methods for constant power load model. It can be seen that the proposed algorithm gives better CPU time compared to other existing methods, and can be concluded that the proposed method is time efficient for radial distribution system.

Table 5. Voltage and Phase Angle from Simulation Results for IEEE-69 bus Radial Distribution Networks

Node	Convergence rate 10 ⁻⁴				
	V(p.u)	δ (rad)	Node	V(p.u)	δ (rad)
0	0.000000	0.000000	35	0.998946	0.000184
1	1.000000	0.000000	36	0.999918	-0.000050
2	0.999966	-0.000021	37	0.999747	-0.000160
3	0.999932	-0.000041	38	0.999588	-0.000200
4	0.999837	-0.000099	39	0.999542	-0.000220
5	0.999012	-0.000290	40	0.999540	-0.000220
6	0.990115	0.001166	41	0.998843	-0.000410
7	0.980862	0.002712	42	0.998550	-0.000490
8	0.978656	0.003084	43	0.998512	-0.000500
9	0.977528	0.003276	44	0.998503	-0.000500
10	0.972527	0.004823	45	0.998405	-0.000540
11	0.971401	0.005131	46	0.998405	-0.000540
12	0.968236	0.006099	47	0.999787	-0.00013
13	0.965298	0.006957	48	0.998547	-0.00092
14	0.962386	0.007810	49	0.994719	-0.00338
15	0.959503	0.008658	50	0.994177	-0.00373
16	0.958968	0.008816	51	0.978620	0.003090
17	0.958082	0.009077	52	0.978611	0.003093
18	0.958073	0.009079	53	0.974762	0.003779
19	0.957602	0.009235	54	0.971544	0.004366
20	0.957300	0.009335	55	0.967105	0.005185
21	0.956811	0.009497	56	0.962771	0.005992
22	0.956805	0.009499	57	0.940635	0.013943
23	0.956733	0.009524	58	0.929747	0.018002
24	0.956578	0.009578	59	0.925538	0.019621
25	0.956406	0.009631	60	0.920602	0.021691
26	0.956337	0.009655	61	0.913275	0.023264
27	0.956317	0.009662	62	0.912988	0.023326
28	0.999925	-0.000005	63	0.912604	0.023410
29	0.999854	-0.000091	64	0.910721	0.023819
30	0.999732	-0.000054	65	0.910152	0.023943
31	0.999711	-0.000048	66	0.971345	0.005152
32	0.999604	-0.000015	67	0.971344	0.005152
33	0.999348	0.000063	68	0.967907	0.006209
34	0.999013	0.000165	69	0.967906	0.006210

Table 6. Comparison of Load Flow Results for IEEE-69 bus Radial Distribution System

Methods	Power Losses			Bus no.	Convergence rate	Iteration no.
	Real (kW)	Reactive (kVar)	V _{min(p.u)}			
Proposed Method	224.8721	102.1535	0.9102	65	10 ⁻⁴	4
Teja et., al[19]	317.9070	143.8350	0.8754	65	10 ⁻⁴	5
Babu B and Maheswarapu [6]	224.9300	102.1300	0.9038	65	10 ⁻⁴	4
Nagaraju et., al[3]	224.6300	101.9900	0.9092	65	10 ⁻⁵	4
Hamouda and Zehar [12]	218.8400	95.59000	0.9095	65	10 ⁻⁴	4
Ramana et., al[2]	223.3100	101.3800	0.9106	65	10 ⁻⁴	2
Ghosh and Sherpa [20]	225.0000	102.0950	0.9068	65	10 ⁻⁵	-
Kumar et., al[22]	224.8011	102.0954	0.9092	65	-	-
Peddanna and Kishore [18]	224.8799	102.1091	0.9093	65	-	-

Table 7. Summary of Convergence Rate and Tolerance Level of the Proposed Method

Convergence rate	Tolerance Level		
	28-bus	IEEE 33-bus	IEEE 69-bus
10 ⁻¹	0.080537	0.080340	0.082969
10 ⁻²	0.005775	0.005777	0.006993
10 ⁻³	0.000408	0.000392	0.000580
10 ⁻⁴	0.000026	0.000015	0.000042
10 ⁻⁵	0.000001	0.000002	0.000004
10 ⁻⁶	0.000000	0.000000	0.000000

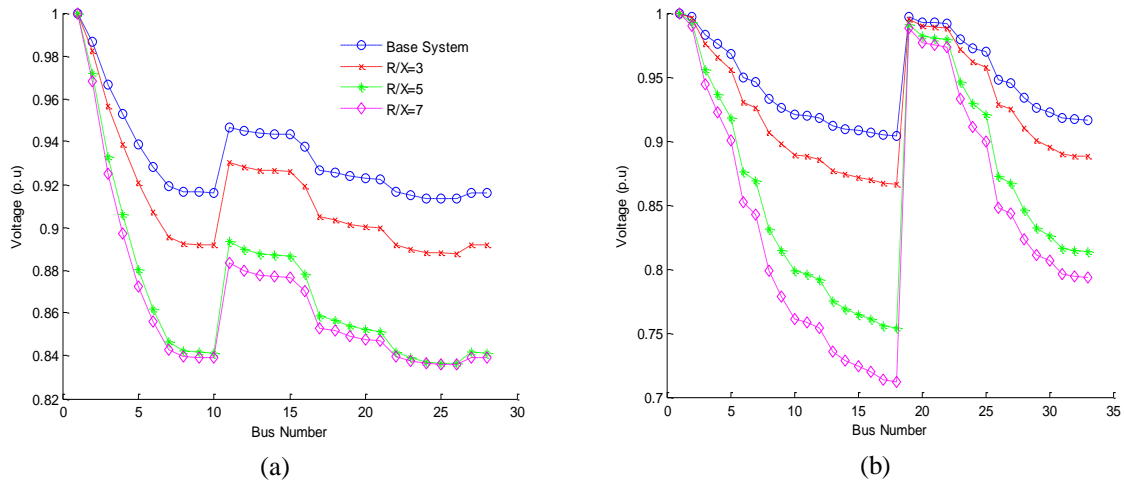


Figure 3. Voltage profile of (a) 28-bus and (b) IEEE-33 bus radial distribution system for different R/X ratio

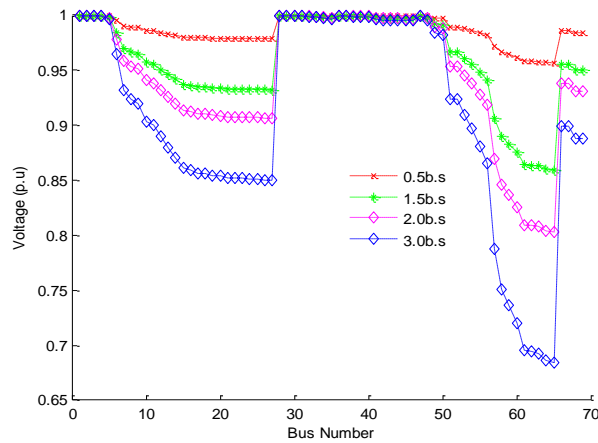


Figure 4. Effect of different loading conditions for IEEE-69 bus test system

Table 8. Comparison of CPU Time and Tolerance Level of the Proposed Method

Distribution Systems	CPU Time(Tolerance Level at convergence rate of 0.1)				
	Proposed Method	Satyanarayana et., al.[24]	Singh & Ghosh [25]	Singh & Ghose [8]	Bhullar& Ghosh[13]
28-bus	0.89(0.080537)	1.43(0.080590)	1.37(0.080593)	1.51(0.080658)	1(0.080540)
IEEE-33	0.95(0.080340)	1.51(0.080375)	1.43(0.080368)	1.57(0.080391)	1(0.080348)
IEEE-69	0.98(0.082969)	1.83(0.083011)	1.71(0.082988)	1.92(0.083029)	1(0.082973)

5. CONCLUSION

In this paper, the improved load flow formulation for radial distribution network has been proposed and tested on the 28 bus, IEEE 33 and IEEE 69 bus radial distribution systems under different load conditions and different R/X ratio. The results have been compared with the existing methods as proposed by previous researchers. From this evaluation and analysis, it is found that the proposed method can confidently be applied for the radial distribution system with good accuracy and fast convergence rate.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge Universiti Sains Malaysia and Universiti Malaysia Pahang for providing technical and financial support in conducting this research and also to thank the reviewers for their comments and recommendations for improving the quality of the paper.

REFERENCES

- [1] A. D. Rana, J. B. Darji, Mosam Pandya, "Backward/Forward Sweep Load Flow Algorithm for Radial Distribution System", *International Journal of Scientific Research and Development*, vol. 2(01), pp. 398-400, 2014.
- [2] T. Ramana, V. Ganesh, S. Sivanagaraju, "Simple and Fast Load Flow Solution for Electrical Power Distribution Systems", *International Journal of Electrical Engineering and Informatics*, vol. 5, pp. 245-255, Sept 2013.
- [3] K. Nagaraju, S. Sivanagaraju, T. Ramana, P. V. Prasad, "A Novel Load Flow Method for Radial Distribution Systems for Realistic Loads", *Electric Power Components and Systems*, vol. 39, pp. 128-141, 2011.
- [4] D. Das, D. P. Kothari, and A. Kalam, "Simple and Efficient Method for Load Flow Solution of Radial Distribution Networks", *Elect. Power Energy Syst*, vol. 17(5), pp. 335-346, 1995.
- [5] R. Ranjan and D. Das, "Simple and Efficient Computer Algorithm to Solve Radial Distribution Networks", *Electric Power Components and Systems*, vol. 31(1), pp. 95-107, 2003.
- [6] Kiran Babu B. and Sydulu Maheswarapu, "An Efficient Power Flow Method for Radial Distribution System Studies under Various Load Models", *Electric Power Components and Systems*, vol. 16, pp. 1-6, 2016.
- [7] Wilson A. Vasquez and Franklin L. Quilumba, "Load Flow Method for Radial Distribution Systems with Distributed Generation using a Dynamic Data Matrix", *Electric Power Components and Systems*, vol. 16, pp. 1-6, 2016.
- [8] S. Singh and T. Ghose, "Improved Radial Load Flow Method", *Electric Power Components and Systems*, vol. 44, pp. 721-727, 2013.
- [9] Yuntao, J.u, Wenchun, W.u, Bomim, Zhang Z. & Hongbin, Sun S., "Loop Analysis Based Continuous Power Flow Algorithm for Distribution Networks", *IET Generation, Transmission and Distribution*, vol.8(7), pp.1284-1292, 2014.
- [10] Eltantawy, A.B. & Salama, M.M.A., "A Novel Zooming Algorithm for Distribution Load Flow Analysis for Smart Grid", *IEEE Transaction of Smart Grids*, vol. 5(4), pp. 1701-1711, 2014.
- [11] Nikmehr, N., and Najafi Ravadanegh, "Heuristic Probabilistic Power Flow Algorithm for Microgrids Operation and Planning", *IET Generation, Transmission and Distribution*, vol.8(11), pp.985-995, 2015.
- [12] Nguyen, C.P. & Flueck, A.J., "A Novel Agent Based Distributed Power Flow Solver for Smart Grids", *IEEE Transaction of Smart Grids*, vol. 6(3), pp. 1261-1270, 2015.
- [13] Suman Bhullar & Smarajit Ghosh, "A Novel Search Technique to Solve Load Flow of Distribution Networks", *Journal of Engineering Research*, vol. 5(4), pp. 60-75, 2017.
- [14] Narayan, K.S & Kumar, A., "Impact of Wind Correlation and Load Correlation on Probabilistic Load Flow for Radial Distribution Systems", *IEEE International Conference on Signal Processing, Informatics, Communication and Energy Systems, Kozhikode(Kerala)*, pp. 1-5, 2015.
- [15] S. Sunisith, K. Meena, "Backward/Forward Sweep Based Distribution Load Flow Method", *International Electrical Engineering Journal*, vol. 5(9), pp. 1539-1544, 2014.
- [16] Abdellatif Hamouda and Khaled Zehar, "Improved Algorithm for Radial Distribution Networks Load Flow Solution", *Electric Power and Energy Systems*, vol. 33, pp. 508-514, 2011.
- [17] D. Das, D. P. Kothari, and H. S. Nagi, "Novel Method for Solving Radial Distribution Networks", *IEEE Proc Gener. Transm. Distrib.*, vol. 141(4), pp. 291-298, 1994.
- [18] Gundugallu Peddana and Y. Siva Rama Kishore, "Power Loss Allocation of Balanced Radial Distribution Systems", *International Journal of Science and Research*, vol. 4(9), pp. 360-366, September 2015.
- [19] B. Ravi Teja, V. V. S. N. Murty, Ashwani Kumar, "An Efficient and Simple Load Flow Approach for Radial and Meshed Distribution Networks", *International Journal of Grid Distributed Computing*, vol. 9(2), pp. 85-201, 2016.
- [20] Smarjit Ghosh and Karma Sonam Sherpa, "An Efficient Method for Load-Flow Solution of Radial Distribution Networks", *World Academy of Science, Engineering and Technology*, vol. 21, pp. 700-708, 2008.
- [21] J. A. Michline Rupa and S. Ganesh, "Power Flow Analysis for Radial Distribution System using Backward/Forward Sweep Method", *International Journal of Electrical and Computing Engineering (IJECE)*, vol. 8(10), pp. 1621-1625, 2014.
- [22] V.Kumar, Shubham Swapnil, R. Ranjan and V. R. Singh, "Improved Algorithm for Load Flow Analysis of Radial Distribution System", *Indian Journal of Science and Technology*, vol. 10(18), pp. 1-7, May 2017.
- [23] Nitin Malik, Shubham Swapnil, Jaimin D.Shah, Vaibhav A. Maheshwari, "Simple Robust Power Flow Method for Radial Distribution Systems", *Journal of Information, Knowledge and Research in Electrical Engineering*, vol. 3(01), pp. 412-417, 2014.
- [24] Satyanarayana, S.Ramana, T.,Sivanagaraju, S., & Rao, G.K., "An Efficient Load Flow Solution for Radial Distribution Network Including Voltage Dependent Load Models", *Electric Power Components and Systems*, vol. 35(5), pp. 539-551, 2007.
- [25] Singh, Kultar Deep & Ghosh, T., "A New Efficient Method for Load Flow Solution for Radial Distribution Networks", *Electrical Review: Engineering and Technology*, pp. 66-73, 2011Eltantawy, A.B. & Salama, M.M.A., "A Novel Zooming Algorithm for Distribution Load Flow Analysis for Smart Grid", *IEEE Transaction of Smart Grids*, vol. 5(4), pp. 1701-1711, 2014.

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APPENDIX A

Table A1: 28-bus radial distribution systems

Branch no.	Sending Bus	Receiving Bus	R (ohms)	X (ohms)	Node No.	PL(kW)	Node No.	PL(kW)
1	1	2	1.197	0.820	1	0.000	15	35.28
2	2	3	1.796	1.231	2	35.28	16	35.28
3	3	4	1.306	0.896	3	14.00	17	8.960
4	4	5	1.851	1.268	4	35.28	18	8.960
5	5	6	1.524	1.044	5	14.00	19	35.28
6	6	7	1.905	1.305	6	35.28	20	35.28
7	7	8	1.197	0.820	7	35.28	21	14.00
8	8	9	0.653	0.447	8	35.28	22	35.28
9	9	10	1.143	0.783	9	14.00	23	8.960
10	4	11	2.823	1.172	10	14.00	24	56.00
11	11	12	1.184	0.491	11	56.00	25	8.960
12	12	13	1.002	0.416	12	35.28	26	35.28
13	13	14	0.455	0.189	13	35.28	27	35.28
14	14	15	0.546	0.227	14	14.00	28	35.28
15	5	16	2.550	1.058				
16	6	17	1.366	0.567				
17	17	18	0.819	0.340				
18	18	19	1.548	0.642				
19	19	20	1.366	0.567				
20	20	21	3.552	1.474				
21	7	22	1.548	0.642				
22	22	23	1.092	0.453				
23	23	24	0.910	0.378				
24	24	25	0.455	0.189				
25	25	26	0.364	0.151				
26	8	27	0.546	0.226				
27	27	28	0.273	0.113				

Power factor of the load is taken as $\cos \phi=0.70$
Reactive power load = $PL \tan \phi$

Table A2: IEEE-33 bus radial distribution systems

Branch no.	Sending Bus	Receiving Bus	R (ohms)	X (ohms)	P _L (kW)	Q _L (kVar)
1	1	2	0.0922	0.0477	100.0	60.00
2	2	3	0.4930	0.2511	90.00	40.00
3	3	4	0.3660	0.1864	120.0	80.00
4	4	5	0.3811	0.1941	60.00	30.00
5	5	6	0.8190	0.7070	60.00	20.00
6	6	7	0.1872	0.6188	200.0	100.0
7	7	8	1.7114	1.2351	200.0	100.0
8	8	9	1.0300	0.7400	60.00	20.00
9	9	10	1.0400	0.7400	60.00	20.00
10	10	11	0.1966	0.0650	45.00	30.00
11	11	12	0.3744	0.1238	60.00	35.00
12	12	13	1.4680	1.1550	60.00	35.00
13	13	14	0.5416	0.7129	120.0	80.00
14	14	15	0.5910	0.6560	60.00	10.00
15	15	16	0.7463	0.5450	60.00	20.00
16	16	17	1.2890	1.7210	60.00	20.00
17	17	18	0.7320	0.5740	90.00	40.00
18	18	19	0.1640	0.1565	90.00	40.00
19	19	20	1.5042	1.3554	90.00	40.00
20	20	21	0.4095	0.4784	90.00	40.00
21	21	22	0.7089	0.9373	90.00	40.00
22	3	23	0.4512	0.3083	90.00	50.00
23	23	24	0.8980	0.7091	420.0	200.0
24	24	25	0.8960	0.7011	420.0	200.0
25	6	26	0.2030	0.1034	60.00	25.00
26	26	27	0.2842	0.1447	60.00	25.00
27	27	28	1.0590	0.9337	60.00	20.00
28	28	29	0.8042	0.7006	120.0	70.00
29	29	30	0.5075	0.2585	200.0	600.0
30	30	31	0.9744	0.9630	150.0	70.00
31	31	32	0.3105	0.3619	210.0	100.0
32	32	33	0.3410	0.5302	60.00	40.00