Simple and Fast Load Flow Solution for Electrical Power Distribution Systems

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Abstract: The proposal of this paper is on a simple and fast distribution load flow solution algorithm. The proposed method fully exploits the radial structure of the network and solves the distribution load flow directly using the single dimension vectors. An effective data structure is proposed to identify lines and number of lines available beyond the particular line. Using this concept, power summations are calculated to obtain the distribution load flow solution. Unlike other traditional methods, the proposed method consider the effective convergence approach which is not only simple and fast but also is efficient from time perspective and needs very less memory for any size of the distribution system compared with the existing methods. The proposed concept was tested on standard distribution system and results are promising and have great potential for applications in the distribution automation.

Keywords: Load flow solution, line path identification, sparse technique, distribution automation, distribution systems

1. Introduction

There are many solution techniques for load flow calculations. However, an acceptable load flow method should meet the requirements [1] such as high speed and low storage requirements, highly reliable, and accepted versatility and simplicity.

In fact, conventional load flow methods, which were developed to solve the transmission networks, encounter convergence problems when applied to distribution networks due to high R/X ratio. In view of the topological specialty of distribution networks, and non-applicability of the transmission networks power flows, researchers has proposed several special load flow techniques for distribution networks [2–8]. The methods [2–8] derive quadratic equations that relate the sending and receiving end voltage magnitudes with a strong convergence characteristic and speed. However, these solution procedures depend on the knowledge of the distribution system structure.

The methods [9-11] have presented power flow problem of distribution systems in terms of sets of recursive equations and analyzed power flow results for various voltage dependent load models. D. Das et al. [12, 13] have presented proposed a simple algebraic recursive expression of voltage magnitude and the proposed algorithm uses the basic principle of the circuit theory. J.Liu et al. [14] have proposed Ratio-Flow method based on forward–backward ladder equation for complex distribution system by using voltage ratio for convergence control. B. Venkatesh and R. Ranjan [15] have shown th ability of automation algorithms to handle these complex tasks that require frequent topology changes in the RDS demands a dynamic topology processor based on a well-defined data structure.

J. H. Teng [16] has proposed a direct approach by using the topological characteristics of the distribution networks to solve the power flow problem. A. Dimitrovski and K. Tomsovic [17] have presented a boundary power flow solution, which considers the uncertainty in nodal powers as boundary values. Jabr [18] has formulated the distribution load flow problem as

Received: December 30th, 2012. Accepted: July 26th, 2013

Conic Programming based Convex Optimization Problem. Hamounda and Zeher [19] have proposed a distribution load flow based on Kirchhoff's laws characterized by radial configuration and laterals. Jamali et al. [20] presented a load-flow technique based on sequential branch numbering scheme to design distribution network by considering committed loads.

Singh, et. al. [21] presented a load flow solution for radial and weakly meshed distribution system formulated as an optimization problem solved by Primal dual Interior point method. The methods [22-23] have proposed an algebraic trigonometric recursive expression of voltage magnitude and the proposed algorithm using the spare technique. The proposed spare technique will fail when bus numbering is not in proper order. Abul Wafa [24] has proposed a based on the two elements sparse S matrix and solve the voltage expression for the receiving end voltage using the composite loads.

The aim paper is to propose a simple and fast load flow method for distribution systems. A method is presented for identifying the line paths beyond a particular line using sparse technique, which will improve the speed of the proposed method. Load flow solution is based on simple iterative method of receiving end voltage of radial distribution system. The convergence of the method is accelerated by a judicious choice of the initial voltages and power losses are taken into consideration from the first iteration. The proposed method is tested on standard distribution systems, and then it is compared with the results of seven existing methods.

2. Formulation of proposed single dimension matrices

A. Line Identification Scheme

Table 1. Formation of pln[ ] matrix

<table>
<tr><th>S.No.[s]</th><th>pln[s]</th><th>Line No.</th></tr>
<tr><td>1</td><td>1</td><td rowspan="8">1</td></tr>
<tr><td>2</td><td>2</td></tr>
<tr><td>3</td><td>3</td></tr>
<tr><td>4</td><td>5</td></tr>
<tr><td>5</td><td>4</td></tr>
<tr><td>6</td><td>7</td></tr>
<tr><td>7</td><td>6</td></tr>
<tr><td>8</td><td>8</td></tr>
<tr><td>9</td><td>2</td><td rowspan="7">2</td></tr>
<tr><td>10</td><td>3</td></tr>
<tr><td>11</td><td>5</td></tr>
<tr><td>12</td><td>4</td></tr>
<tr><td>13</td><td>7</td></tr>
<tr><td>14</td><td>6</td></tr>
<tr><td>15</td><td>8</td></tr>
<tr><td>16</td><td>3</td><td rowspan="4">3</td></tr>
<tr><td>17</td><td>4</td></tr>
<tr><td>18</td><td>7</td></tr>
<tr><td>19</td><td>8</td></tr>
<tr><td>20</td><td>4</td><td>4</td></tr>
<tr><td>21</td><td>5</td><td rowspan="2">5</td></tr>
<tr><td>22</td><td>6</td></tr>
<tr><td>23</td><td>6</td><td>6</td></tr>
<tr><td>24</td><td>7</td><td rowspan="2">7</td></tr>
<tr><td>25</td><td>8</td></tr>
<tr><td>26</td><td>8</td><td>8</td></tr>
</table>

Table 2. Formation of ipf[ ] and ipt[ ] Matrices

Line No.	ipf[i]	ipt[i]
1	1	8
2	9	15
3	16	19
4	20	20
5	21	22
6	23	23
7	24	25
8	26	26

For a multiphase balanced radial distribution system, the system tree is represented as a single line equivalent, where a line between two buses represents only the connectivity between the buses.

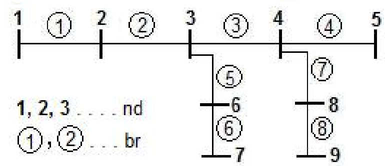

Figure 1. Sample Radial Distribution System

A single dimension vector, namely, path line vector pln[ ] is introduced to store all the lines beyond the path including the path line which is interested. The dimension of the vector is changed based on the tree structure of the radial distribution system. Two other vectors ipath-from, ipf[ ] and ipath-to, ipt[ ] are introduced which acts as points to the pln[ ] vector and whose dimensions are equal to the number of lines available in the radial distribution system. These vectors in turn govern the reservation allocation of memory location of each path line, where ipf[ ] and ipt[ ] hold the data of starting memory allocation and each memory location of path line i in the pln[ ] vector, i = 1, 2, … br. There is no dependence of the of buses numbering order with the substation bus number. The above mentioned branch identification scheme is explained with reference to a sample distribution system of Figure 2. Table 1 and Table 2 shows data stored in pln[ ], ipf[ ] and ipt[ ] vectors of the sample distribution system. Figure 3 shows the flow chart for the formation of pln[ ], ipf[ ] and ipt[ ] vectors.

B. Sparse Technique

In the proposed sparse technique, single dimensional vectors are used instead of two dimensional arrays in Ghosh and Das method [12] for implementation. This can reduce a lot of memory and CPU time as it minimizes the search process in identifying the adjacent nodes and branches beyond a particular branch. With two dimensional arrays, a system with n nodes needs matrix size of n×n. In which most of the elements are zero. This can be avoided by three single dimensional vectors ipf[br], ipt[br] and pln[br(br+1)/2]. The pln[ ] vector size is less than or equal to br(br+1)/2 based on the radial distribution tree structure. The total elements/location of vectors is the 2×br plus less than or equal to 1×br(br+1)/2 and they are very much less than n×n in [12]. Therefore proposed technique reduces the memory requirement and CPU time for large distribution systems.

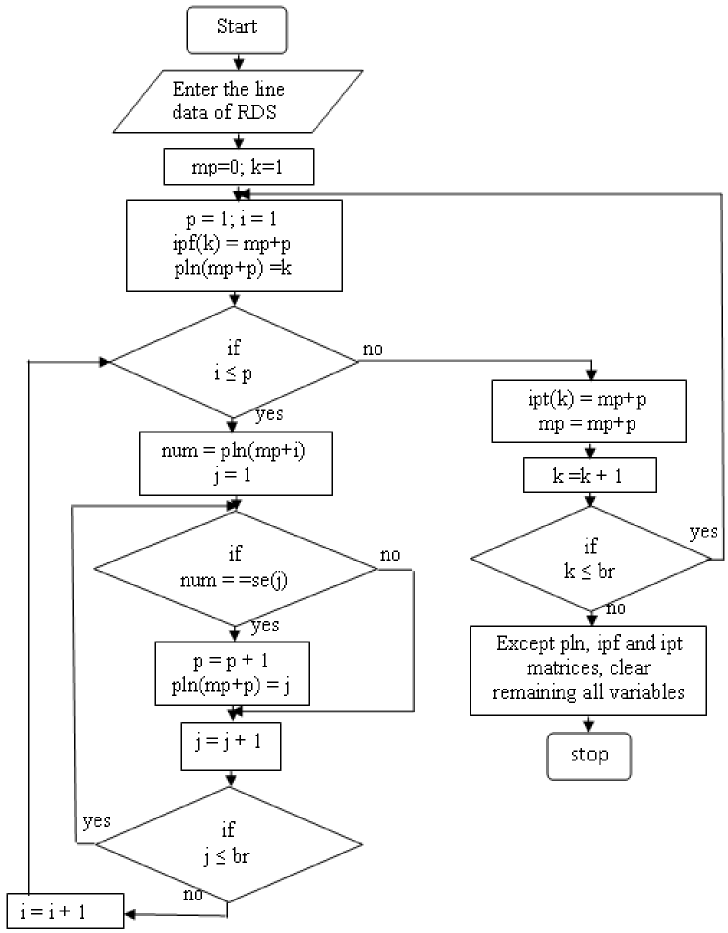

Figure 2. Flowchart for the formation of pln[ ], ipf[ ] and ipt[ ]

C. Advantages of the Scheme

a) There is no dependency of the order of node numbers like other methods [9-23].
b) An end bus can be easily identified.
c) For an branch i, where ipf[i] - ipt[i] = 0, then end bus is re(pln[ipf[i]]) or re(pln[ipt[i]]).
d) Applying the scheme, directly the backwards direction to calculate the power flows in the line and the forward direction to calculate voltages very fast and effective.
e) On application of this scheme, there is reduction of memory usage and CPU time as it minimizes the search process in identifying the adjacent buses and braches of a radial distribution system.

3. Mathematical Formulation

A. Assumptions

It is assumed that the three-phase radial distribution system is balanced and thus can be represented by its one line diagram. The loads are modeled as constant power. Distribution feeders are of medium level voltage then, the shunt capacitance are negligible.

B. Mathematical models

Consider an equivalent circuit model of typical branch between buses p and q of the radial distribution system as shown in Figure 2. In Figure 2, $|V(p)|\angle\delta(p)$ and $|V(q)|\angle\delta(q)$ are the voltage magnitudes and phase angles of two buses p and q respectively and power flowing through the line *pq* is P(pq)+j Q(pq) and P_1(pq)+jQ_1(pq) at sending end and receiving end buses respectively. The substation voltage is assumed to be (1+j0) p.u..

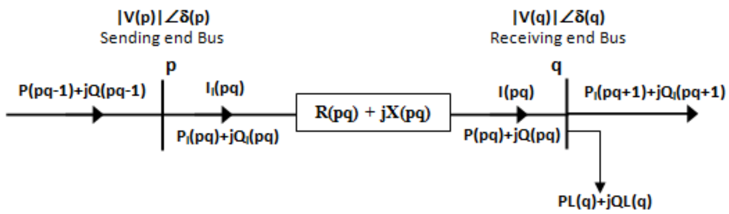

Figure 3. Equivalent circuit model of RDS of a typical branch *pq*

B.1 Branch Power and Current

From the electric equivalent of a feeder branch shown in Figure3, we can write the set of the below power summation equations for branch pq.

$$\begin{aligned}\mathrm{S(pq)} = \mathrm{P(pq)} + \mathrm{jQ(pq)} &= \left(\sum_{k=ipf(pq)}^{ipt(pq)} PL(re(p\ln(k))) + \sum_{k=ipf(pq)+1}^{ipt(pq)} Ploss(p\ln(k))\right) \\ &+ j\left(\sum_{k=ipf(pq)}^{ipt(pq)} QL(re(p\ln(k))) + \sum_{k=ipf(pq)+1}^{ipt(pq)} Qloss(p\ln(k))\right)\end{aligned} \tag{1}$$

$$\mathrm{S_1(pq)} = \mathrm{P_1(pq)} + \mathrm{jQ_1(pq)} = (\mathrm{P(pq)} + \mathrm{Ploss(pq)}) + \mathrm{j}(\mathrm{Q(pq)} + \mathrm{Qloss(pq)}) \tag{2}$$

where

PL(re(pln(k))) and QL(re(pln(k))): active and reactive load power at path line pln(k) of receiving end bus respectively.

Ploss(pln(k)) and Qloss(pln(k)): active and reactive power loss in the path line pln(k) respectively.

P(pq) and Q(pq): active and reactive power at the end of branch *pq*. It is equal to the sum of the active and reactive power of all the loads beyond bus q (bus q included) plus the sum of the active and reactive power losses of the branches beyond bus q (branch *pq* not included) respectively.

P_l(pq) and Q_l(pq): active and reactive power at the beginning of the branch *pq*. It is equal to the sum of the power at the end of branch *pq* plus the active and reactive power loss in this same branch respectively.

Ploss(pq) and Qloss(pq) : active and reactive power loss in the branch *pq* respectively.

If the complex voltage at the bus q,

$$\mathrm{V(q)} = |V(q)|(\cos\delta(q) + j\sin\delta(q)) \tag{3}$$

Than, the current following through the ith branch with respect to receiving end voltage is

$$\mathrm{I(pq)} = \left(\frac{S(pq)}{V(q)}\right)^* = \frac{P(pq) - jQ(pq)}{V(q)^*} \tag{4}$$

and the current following through the ith branch with respect to sending end voltage is

$$\mathrm{I}_1(\mathrm{pq}) = \left(\frac{S_1(pq)}{V(p)}\right)^* = \frac{P_1(pq) - jQ_1(pq)}{V(p)^*} \tag{5}$$

The pq^{th} branch active and reactive power losses are given by

$$\mathrm{Sloss(pq)} = \mathrm{Ploss(pq)} + \mathrm{jQloss(pq)} = (I(pq))^* I(pq)Z(pq) \tag{6}$$

Where
Z(pq): Impendance of the branch *pq* and equal to R(pq)+jX(pq)

B.2 Bus Voltage
For computing the receiving voltage, we canwrite the following complex expression

$$V(q) = V(p) - I_1(pq)Z(pq) \tag{7}$$

4. Flow Chart for Load Flow Calculation

The initial voltage set the higher values compared to final ones, produce lower starting line current and low voltage drop. Thus, for a given line, the voltage of the receiving end bus is far from its actual value. The iterative process takes then, a great number of iterations and therefore a relatively long time to converge. In order to reduce the computing time and increase the convergence speed, a different the voltage calculation methodology proposed. The current

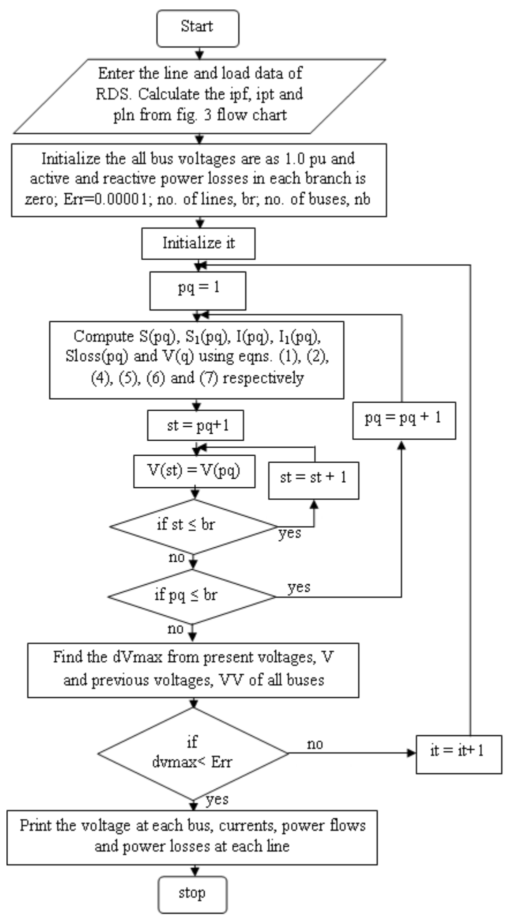

Figure 4. Flowchart for load flow calculation

for a given line is equal to the sum of load required current at the buses to which they belong. Then, in the calculation of the receiving end bus voltage of a given branch, the loads currents are evaluated on the basis of the sending end voltage. In addition, both active and reactive power losses are introduced from the first iteration and calculated also on the basis of the considered line sending end voltage.

The convergence criterion of the proposed method is that if, in successive iterations the maximum difference is voltage magnitude (dVmax) is less than 0.0001 p.u., the solution have then converged. The complete load flow calculation flow chart for radial distribution system is shown in Figure 4.

5. Results and Analysis

To demonstrate the effectiveness of the proposed method, following three examples are selected. The first example is of a 15-bus, 11 kV radial distribution system. The data of the system is available in [9]. The total real and reactive power loads at nominal voltage are 1226.40 kW and 1250.93 kVAr respectively. The real and reactive power line losses are 5.04% and 4.58% of their respective real and reactive loads respectively. The minimum voltage of this system is at bus 12 and voltage regulation is 5.56%. Table 3 gives the line numbers and voltage at receiving end with phase angle, injected power in each branch and losses of the line section between nodes for constant power load model only.

Table 3.The summary of load flow results for 15-bus RDS

Br	p	q	Voltage V_q (p.u)	Angle δ_q (rad)	Injected Powers				Power Losses	
					P_{pq} (kW)	P_{qp} (kW)	Q_{pq} (kVAr)	Q_{qp} (kVAr)	Ploss (kW)	Qloss (kVAr)
1	1	2	0.97128	0.00056	1288.17	1250.48	1308.46	1271.58	37.70	36.88
2	2	3	0.95689	0.00086	724.27	712.99	747.61	726.58	11.28	11.03
3	3	4	0.95117	0.00099	394.81	392.37	402.56	400.17	2.44	2.39
4	4	5	0.95018	0.00120	44.10	44.04	44.99	44.95	0.06	0.04
5	2	6	0.95813	0.00336	358.44	352.67	365.06	361.17	5.77	3.89
6	6	7	0.95591	0.00383	140.00	139.61	142.83	142.56	0.39	0.27
7	6	8	0.95685	0.00363	70.19	70.08	71.55	71.47	0.11	0.08
8	2	9	0.96793	0.00126	116.23	115.76	117.84	117.52	0.47	0.32
9	9	10	0.96686	0.00148	44.10	44.04	44.99	44.95	0.06	0.04
10	3	11	0.95030	0.00228	252.35	250.18	256.89	255.42	2.17	1.47
11	11	12	0.94619	0.00316	114.18	113.58	116.46	116.05	0.60	0.41
12	12	13	0.94488	0.00345	44.10	44.03	44.99	44.94	0.07	0.05
13	4	14	0.94886	0.00148	70.64	70.44	71.72	71.58	0.20	0.14
14	4	15	0.94870	0.00152	140.41	139.97	143.11	142.81	0.44	0.30

The second example is a 33-bus, 12.66 kV radial distribution system. Data for this system is available [14]. The total real and reactive power loads at nominal voltage are 3715kW and 2300 kVAr, respectively. The real and reactive power line losses are 5.64% and 6.18% of their respective real and reactive loads, respectively. The minimum voltage of this system is at bus 18 and voltage regulation is 9.49%. The load flow solution bus voltages and phase angles results for 33-bus RDS has been shown in Table 4. The proposed method was also implemented for various ratios R/X for a tolerance of 10^{-4} p.u., the solution is reached after two iteration for the considered values of R/X. The solution results of minimum voltage and number of iterations are shown in Table 5 for the considered values of R/X. The bus voltages evolution according to R/X is in conformity with the electric circuit laws. For the same line current, low voltage drop is due to reactance.

The third example is a 69-node, 12.66 kV radial distribution network. Data for this system is available [3]. The total real and reactive power loads at nominal voltage are 3791.89 kW and 2694.10 kVAr respectively. The losses are 5.89% and 3.76% of their respective real and reactive loads respectively. The minimum voltage of this system is at bus 65 and voltage regulation is 8.94%. The load flow solution bus voltages and phase angles results for 69-bus RDS has been shown in Table 6. Various load conditions are also considered by multiplying each bus acitive and reactive powers by a constant. For the 69-bus system and for the considered load factors, the number of iterations to reach the convergence is two for a convergence rate of 10^{-4}p.u. The solution results of minimum voltage and number of iterations are shown in Table 7 for the considered values of loading factors. However, we note a constant voltage at some buses regardless the load conditions. This could be explained by the fact that, these buses are close to the source bus, the loads low level and the small values of the branch parameters.

Table 4. Load Flow solution bus voltages and phase angles for 33-bus RDS

Bus No	Voltage in p.u.	Angle in p.u.	Bus No	Voltage in p.u.	Angle in p.u.	Bus No	Voltage in p.u.	Angle in p.u.
1	1.00000	0.00000	12	0.91894	-0.00646	23	0.97960	0.00114
2	0.99702	0.00024	13	0.91282	-0.00808	24	0.97298	-0.00041
3	0.98315	0.00166	14	0.91054	-0.00948	25	0.96967	-0.00117
4	0.97573	0.00281	15	0.90912	-0.01015	26	0.94844	0.00301
5	0.96839	0.00397	16	0.90774	-0.01056	27	0.94589	0.00399
6	0.95032	0.00233	17	0.90570	-0.01193	28	0.93461	0.00544
7	0.94683	-0.00170	18	0.90509	-0.01210	29	0.92647	0.00679
8	0.93341	-0.00437	19	0.99643	0.00004	30	0.92293	0.00863
9	0.92713	-0.00567	20	0.99287	-0.00113	31	0.91880	0.00716
10	0.92132	-0.00679	21	0.99216	-0.00147	32	0.91788	0.00675
11	0.92045	-0.00666	22	0.99153	-0.00183	33	0.91760	0.00662

Table 5. Minimum Voltages and number of iterations for different R/X ratios for 33-bus RDS

Convergence rate is 10^{-4} p.u.		
R/X ratio	Minimum Voltage	Number of Iteration
Base case	0.90509	2
5	0.85625	2
7.5	0.78692	2
10	0.70573	2

Table 6. Load Flow solution bus voltages and phase angles for 69-bus RDS

Bus No	Voltage in p.u.	Angle in p.u.	Bus No	Voltage in p.u.	Angle in p.u.	Bus No	Voltage in p.u.	Angle in p.u.
1	1.00000	0.00000	24	0.95697	0.00860	47	0.99979	-0.00013
2	0.99997	-0.00002	25	0.95681	0.00865	48	0.99855	-0.00092
3	0.99993	-0.00004	26	0.95674	0.00867	49	0.99472	-0.00334
4	0.99984	-0.00010	27	0.95672	0.00868	50	0.99418	-0.00369
5	0.99903	-0.00032	28	0.99993	-0.00005	51	0.97883	0.00243
6	0.99023	0.00087	29	0.99986	-0.00008	52	0.97882	0.00243
7	0.98107	0.00213	30	0.99976	-0.00004	53	0.97498	0.00296
8	0.97887	0.00243	31	0.99975	-0.00003	54	0.97177	0.00341
9	0.97774	0.00258	32	0.99966	0.00001	55	0.96734	0.00404
10	0.97277	0.00406	33	0.99946	0.00011	56	0.96301	0.00465
11	0.97167	0.00439	34	0.99923	0.00024	57	0.94117	0.01156
12	0.96853	0.00530	35	0.99916	0.00026	58	0.93028	0.01508
13	0.96562	0.00611	36	0.99992	-0.00005	59	0.92603	0.01649
14	0.96273	0.00692	37	0.99975	-0.00016	60	0.92104	0.01831
15	0.95987	0.00772	38	0.99959	-0.00021	61	0.91372	0.01951
16	0.95934	0.00787	39	0.99954	-0.00022	62	0.91343	0.01956
17	0.95846	0.00812	40	0.99954	-0.00022	63	0.91304	0.01962
18	0.95845	0.00812	41	0.99884	-0.00041	64	0.91115	0.01993
19	0.95799	0.00827	42	0.99855	-0.00049	65	0.91057	0.02003
20	0.95769	0.00837	43	0.99851	-0.00050	66	0.97161	0.00441
21	0.95721	0.00852	44	0.99850	-0.00050	67	0.97161	0.00441
22	0.95720	0.00852	45	0.99841	-0.00054	68	0.96820	0.00541
23	0.95713	0.00855	46	0.99841	-0.00054	69	0.96820	0.00541

Table 7. Minimum Voltages and number of iterations for different loading factors for 69-bus RDS

Convergence rate is 10^{-4} p.u.		
Loading factor	Minimum Voltage	Iteration number
0.5	0.95695	2
1.0	0.91057	2
1.5	0.86013	2
2.0	0.80454	2
2.5	0.74219	2
3.0	0.67035	2

A. Discussion and observations

The results of proposed method implemented for the different convergence rates and it is observed that the number of iterations is equal to two and threefor the convergence rates 10^{-4}p.u. and 10^{-7}p.u. respectively. The minimum voltage, total real power losses, total reactive power losses of the system, number of iterations corresponding to the convergence rate is shown in Table 8.

Table 8. Summary of example RDS load flow results for different convergence rates

Example RDS	Convergence rate is 10^{-4} p.u.				Convergence rate is 10^{-7} p.u.			
	Vmin in p.u.	Total Ploss in kW	Total Qloss in kVAr	Iteration number	Vmin in p.u.	Total Ploss in kW	Total Qloss in kVAr	Iteration number
15-Bus RDS	0.94488	61.78	57.28	2	0.94488370.	61.78	57.28	3
33-Bus RDS	0.90509	209.68	142.20	2	9050856	209.68	142.20	3
69-Bus RDS	0.91057	223.31	101.38	2	0.9105744	223.31	101.38	3

Table 9. Comparison of speed and number of iteration of proposed method and existing methods with the convergence criteria of 10^{-4}

Proposed method another seven existingmethods	15-bus RDS		33-bus RDS		69-bus RDS	
	CPU time (sec)	Iteration number	CPU time (sec)	Iteration number	CPU time (sec)	Iteration number
Proposed method	0.025	2	0.053	2	0.096	2
Nagaraju et.al. [19]	0.03	3	0.06	3	0.13	3
Satynarayana et.al. [18]	0.03	3	0.06	3	0.13	3
Ghosh and Das [12]	0.04	3	0.09	3	0.16	3
Chaing [5]	0.05	3	0.11	3	0.24	3
Baran and Wu [3]	0.07	3	0.13	3	0.29	3
Renato method [6]	0.08	4	0.14	4	0.33	4
Kersting [2]	0.10	4	0.16	4	0.37	4
AbulWafa [24]	0.11	4	0.14	4	0.16	4

The proposed method is also compared with seven other existing methods for constant power load model. Table 9 gives the CPU time and number of iterations of all the three case studies. From Table 9, it is seen that the proposed method is better than the other seven existing methods. It can be concluded that the proposed method is robust and time efficient for the radial distribution systems and it can be said the proposed method has faster convergence ability than the other seven existing methods. The methods are implemented on Intel – i3, 1 GB-RAM processor.

6. Conclusion

In this paper, a simple and fast load flow solution algorithm for distribution system was proposed, which is basically a power summation method. The proposed scheme of line identification makes the method quite fast. This scheme reduces a lot of memory and CPU time as it minimizes the search process in the radial distribution system. The convergence of the method is accelerated by a judicious choice of the initial voltages and power losses are taken into consideration from the first iteration. Load flow problem under different load conditions and for various ratios R/X has been successfully treated by out method. In order to test results, confirmation of the accuracy of the method is there, whereas the fastness of the both in terms of number of iterations and CPU execution time is evident from the results and finds great potential application in the distribution automation.

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