Indian Journal of Science and Technology, Vol 10(18), DOI: 10.17485/ijst/2017/v10i18/113752, May 2017
ISSN (Print) : 0974-6846
ISSN (Online) : 0974-5645

Improved Algorithm for Load Flow Analysis of Radial Distribution System

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Abstract

Objectives: In this paper an improved algorithm for load flow analysis of Radial Distribution Systems (RDS) is presented. The algorithm incorporates probabilistic variations of line and load data along with composite loads. **Methodology:** The algorithm uses Simple Backward and Forward Sweep based method for solving RDS and has further been modified to solve distribution systems with Distributed Generation (DG). **Findings:** This Improved algorithm for load flow analysis is tested on standard RDS and considerable promising results have been delivered for the system having Distributed Generator for improving the voltage profile and reduce the losses. **Novelty/Improvement:** The results obtained are exemplary that confirms usefulness of the algorithm and can have significant impact on future planning and operation purposes of unbalanced RDS.

Keywords: Distributed Generations, Forward/Backward Sweep Algorithm, Load Flow Algorithm, Power Flow Analysis, Radial Distribution Systems

1. Introduction

Power flow analysis is one of the most important methods to know the parameters. The steady state values of power flow, current, voltage profile and losses of the power systems are also find out with power flow analysis. There are several power flow analysis algorithms already available which are widely used for power transmission systems.[1-4] However, most of these load flow algorithms fails to deliver due to power distribution systems owing to its topology and high Resistance(R)/reactance(X) ratio, which is often referred as ill-conditioned. Hence, famous Netwon Raphson or Fast Decoupled Load Flow algorithms are not found useful to solve Radial Distribution Systems.

In reported article RDS Load Flow (LF) shows that although many load flow algorithms have been proposed in recent years, but these LF methods are not found robust in nature and many of them do not even take into account uncertainties of load and line data.[5-8] Few earlier reported algorithms didn't even consider the composite nature of load.[9,10] Although other reported methods includes composite load model and uncertainties but fail to appreciate importance of DG in RDS.[11,12] Since, the distribution systems being near to consumer, therefore, they plays highly important role and any deviation in the system parameters will directly affect the consumer. Hence, utility engineers always took utmost care in selecting load flow algorithms for planning and operation of RDS. However, considering the high Resistance(R)/reactance(X) ratio of

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RDS, reported losses in distribution systems are as high as 13%. Increased demand of quality electricity followed by environmental considerations forced us to look for and find alternative solutions other than conventional methods like using capacitors and installing additional capacity generating stations. Distributed Generations (DG) in RDS further provide extended benefits to the utility as they can be installed near to the load point, thereby, providing environmentally clean and easy to operate systems.[13,14] Although, DG is found to be vastly useful for improving parameters like voltage profile, reducing losses and increasing systems security; still its mathematical modelling and its incorporation in LF algorithm remains a challenge.

The Load Flow algorithm reported in the papers were Forward/Backward Sweep based methods, where forward sweep was used for voltage calculation while backward sweep is used for branch flow calculation.[15-17] This proposed Load flow algorithm has been modified to overcome all the earlier limitations mentioned above and further incorporates load and line variations, Composite Load model and DG placed in the System.[18] The proposed Algorithm has been tested on 33 node and 69 node IEEE test systems. The results obtained from proposed algorithm are promising which can be used for prospective application in RDS.

2. Mathematical Model

2.1 Radial Distribution Systems

A balanced three phase Radial distribution system represented by single line diagram is shown in Figure 1.

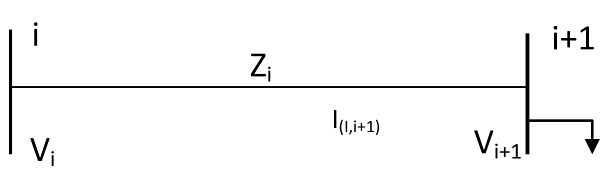

Figure 1. Single line diagram of balanced power system.

Where,

i,i+1... represents number

V_i is Voltage at ith Node

V_{i+1} is Voltage at i+1th Node

Z_i is Impedance of Line i(R_i+ jX_i)

I_i is Load current

$I_{(i,i+1)}$ is current emanating through ith node towards i+1th Node

A_{i+1} is complex Load (P_{i+1}+jQ_{i+1}) at node no i+1

All the voltage, current, complex power and impedance shown above are in vector form.

Load current is calculated as

$$I_i = \left(\frac{A_i}{V_i}\right)^* \tag{1}$$

Applying simple Kirchoff's Law Voltage at ith Node is calculated as below

$$V_i = V_{i+1} + I_{(i,i+1)} * Z_i \tag{2}$$

Line current

$I_{(i,i+1)}$=(Load Current at i+1th Node) I_{i+1} + Σcurrents emanating from node i+1 (3)

Power Loss

$$P_{(i,i+1)} = I^2_{(i,i+1)} {}^*R_i \tag{4}$$

2. 2 Line and Load Variations

Uncertainties reported earlier due to errors in load forecast, errors in the measured value of transformer and in line parameters are modeled by interval arithmetic.[11] This uncertainty in bound form may be expressed as

$$P_i = P_0(1 \pm \delta) \tag{5}$$

$$Q_i = Q_0(1 \pm \delta) \tag{6}$$

Where δ represent the variation in reactive power and real power.

Similarly,the variations in Line parameters like Resistance(R) and Reactance (X) are modeled as

$$R_i = R_0(1 \pm \delta) \tag{7}$$

$$X_i = X_0(1 \pm \delta) \tag{8}$$

2. 3 Load Model

Major algorithms for load flow analysis reported earlier in RDS arena consider load as constant power load. However, this consideration holds good if distribution system either maintains constant voltage or the load is insensitive of the voltage variations. These earlier load flow algorithms works fine in grid connected transmission systems, where regulation of the voltage is modeled at constant power load model. However, in case of distribution systems, earlier load flow algorithms didn't provide satisfactory results. Therefore, in the proposed load flow algorithm composite load model is also included along with the earlier reported uncertainties. In this algorithm loads are modeled either as constant impedance, constant current, constant power, or a combination of all. It is represented as below

$$P = P_o(\gamma V^2 + \beta V^1 + \alpha V^0) \tag{9}$$

$$Q = Q_o(\gamma V^2 + \beta V^1 + \alpha V^0) \tag{10}$$

Where γ, β, α, and are the fractions of constant impedance, constant current and constant power, load. In any case

$$\gamma + \beta + \alpha = 1.0 \tag{11}$$

2. 4 Model of Distributed Generation (DG)

DGs are the small generators having size less than 10 MW and are connected to a substation, a feeder or near to the load points. Ideally, DGs are renewable energy generating stations and are expected to play a very significant role in modern distribution systems for loss minimization, for power quality and for usage of clean energy to protect environment. Hence, it is apparently necessary that all RDS should be equipped to implement DGs in their Load flow algorithm. In the proposed work, DGs has been modeled as negative load with fixed voltage. Furthermore, harmonics injected due to asynchronous DGs has been neglected. It is assumed that DGs can deliver reactive and real power at the same time. However, proposed load flow algorithm can be suitably modified either for delivering real power DG or reactive power DG with ease. Mathematical model for the DG is given below:

$$A_i = P_i + jQ_i - P_D - jQ_D \quad ; \quad |V_i| = 1.0\ p.u \tag{12}$$

Where,

A_i = Complex Load at Node i

P_i, Q_i = Real & Reactive Load connected at Node i

P_D, Q_D = Real & Reactive power injected in to the systems by DG connected at i

$|V_i|$ = Constant voltage at the node due to DG (varies from 1.0 p.u to 1.05 p.u)

3. Improved Backward and Forward Sweep Method

In backward sweep, currents are computed using KCL starting from the farthest node to the source node. In forward sweep, the downstream voltage is calculated starting from source node using KVL. Modified Algorithm is explained as below:

1. After 1st iteration the voltage at the end nodes is assumed 1.0 per unit.
2. 2.1 Compute the node current using equation (1) starting with the end node.
3. 2.2 Starting from the end nodes, KCL is applied to determine the current flowing from node i towards node i+1 using equation (3).

   $I(i,i+1)=I_{i+1}$ + Σcurrents emanating from node i+1
4. 3.1 Voltage at i^{th} node using equation (2) is calculated by using this current.
5. Continue the step till the junction node is reached.
6. At junction node the voltage computed is stored.

$$V_i=V_{i+1}+I_{(i,i+1)*}Z_{(i,i+1)} \tag{13}$$

7. After starting with another end node of the system, voltage and current are computed as in step 2 and 3.
8. Calculate with the most recent voltage at junction node and the current using equation (1).
9. Similarly calculate till the reference node/ Substation node is reached.
10. Compare the calculated magnitude of the rated voltage at node with previous iteration voltage. Stop, if the difference is less than specified values, otherwise start with the forward sweep.
11. Start with the reference node at rated voltage.
12. Calculate the node voltage from reference node to end nodes in forward direction by using equation (2).
13. 10.1Again start backward sweep with updated bus voltage calculated in forward sweep.
14. 10.2 The line losses are calculated after computing node voltages and line currents using standard BW/FW sweep.
15. 10.3 A_{ij}(complex power) from buses i to bus j is computed by using equation (14).

$$A_{ij} = V_i I_{ij}^* \tag{14}$$

4. Test Systems

The earlier reported RDS networks in the research papers were tested to validate the effectiveness and accuracy of the proposed method. However, for the purpose of presentation two test systems commonly used in reported research articles, 33 Node RDS and 69 Node RDS have been considered.

4.1 Test System 1

Thirty three Node Test System is shown in Figure 2. Data of 33 nodes 12.66kV RDS is available in the reported article.[19] The total reactive power losses

Table 1. The load flow results of Base case and IEEE 33 node RDS with Line and Load data variation

	Base Case	Case 1 (Factor)		Case 2		Case 3	
		(1-δ)	(1+δ)	(1-δ)	(1+δ)	(1-δ)	(1+δ)
Total real Power Loss (kW)	210.9716	177.0815	219.8928	186.4016	209.4217	166.9513	232.9232
Total reactive Power Loss (kVAr)	143.1173	121.9048	151.4210	128.3209	144.2104	114.9155	160.4192
Minimum Voltage (p.u)	0.90378	0.9094	0.8990	0.9094	0.8990	0.9143	0.8934
Maximum Voltage deviation	0.09622	0.0906	0.101	0.0906	0.101	0.0857	0.1066

obtained in base case was 143.11kVAr and total real power loss was 210.98kW. The minimum voltage was 0.90378p.u. The proposed algorithm was implemented with load and line data variation and results are tabulated in Table 1.

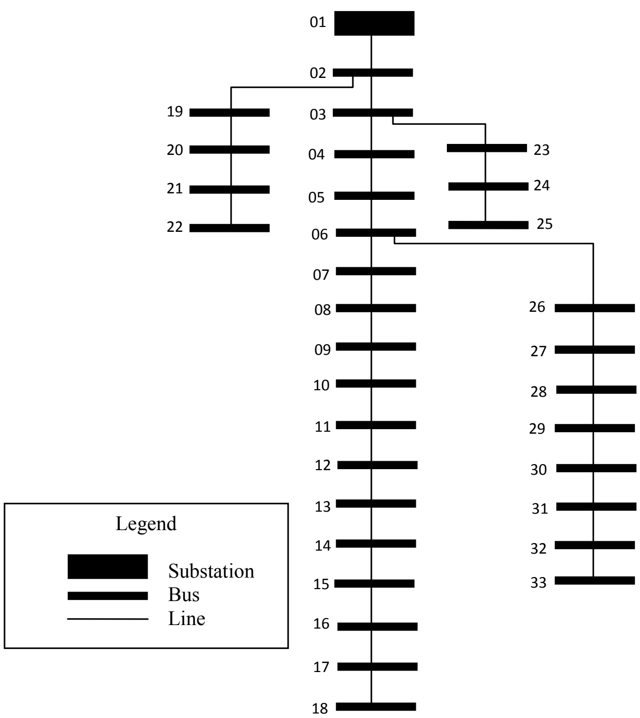

Figure 2. 33 Node RDS

Where,

Case 1: where only Line data varies

Case 2: where only Load data varies

Case 3: where only Line and Load data both varies

The variations in load and line data is represented by δ and considered as 5% in the present case study.

As discussed in Section 2.2.3, Load flow algorithm is also modified to include DG. In the present test System (33 Node) it is assumed that on node 6, a DG of 2MW Capacity with reference Voltage 12.66 kV has been installed. The results of 33node RDS with DG has been tabulated in Table 2. The total reactive loss is 77.9222kVArandtotal real power loss obtained is 105.828 kW. Maximum voltage deviation is 0.0429 and minimum voltage at node 18 is 0.9571p.u.

The effect on voltage profile with DG in comparison to Base Case for 33 node RDS is depicted in Figure 3.

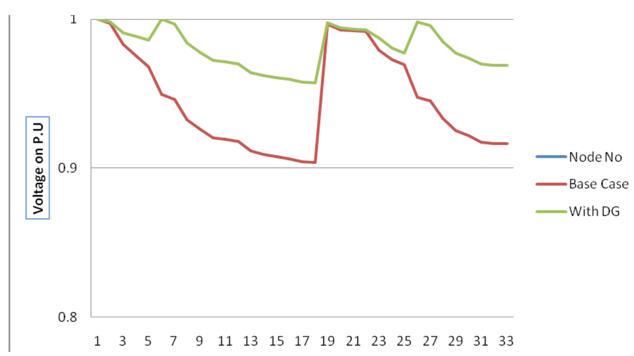

Figure 3. Voltage Profile of 33 Node RDS with DG and Without DG.

4.2 Test System 2

Another test system considered is 69 node where 12.66 kV RDS is available in the reported article and is shown in Figure 4.[20] In base case the reactive power loss obtained was 102.0954kVAr and real power loss found was 224.8011 kW. Minimum voltage was 0.90922p.u. The proposed algorithm

Table 2. Load Flow Result of 33Node RDS with DG installed at Node number 6

Node No	With DG	Without DG	Node No	With DG	Without DG
1	1.0000	1.00000	17	0.9577	0.90440
2	0.9983	0.99701	18	0.9571	0.90378
3	0.9909	0.98288	19	0.9977	0.99649
4	0.9884	0.97537	20	0.9942	0.99291
5	0.9861	0.96795	21	0.9935	0.99220
6	1.0000	0.94947	22	0.9928	0.99157
7	0.9967	0.94595	23	0.9873	0.97930
8	0.9839	0.93229	24	0.9807	0.97263
9	0.9779	0.92596	25	0.9774	0.96930
10	0.9724	0.92010	26	0.9982	0.94754
11	0.9716	0.91923	27	0.9958	0.94498
12	0.9701	0.91772	28	0.9850	0.93353
13	0.9643	0.91154	29	0.9772	0.92532
14	0.9622	0.90925	30	0.9738	0.92176
15	0.9609	0.90783	31	0.9699	0.91760
16	0.9596	0.90644	32	0.9690	0.91668
			33	0.9688	0.91640

was also implemented with load and line data variation and results observed are tabulated in Table 3.

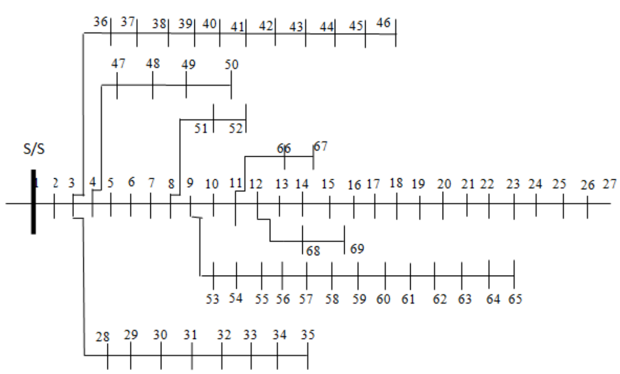

Figure 4. 69 Node RDS.

Where nomenclature used has same meaning as explained in the case 33 Node RDS.

Load flow algorithm with DG is applied in the present test system (i.e.69 Node). DG of 1825kW capacity with Reference Voltage 12.66 kV has been installed at Node 61. The results load flow analysis of 69 node RDS with DG are tabulated in Table 4. The total reactive losses computed are 39.59kVAr and total real power loss found are 81.04 kW and. Maximum voltage deviations is 0.0314 and minimum voltage is 0.9686p.u. at node no. 27

The effect on voltage profile with DG in comparison to Base Case for 33 node RDS is depicted in Figure 5.

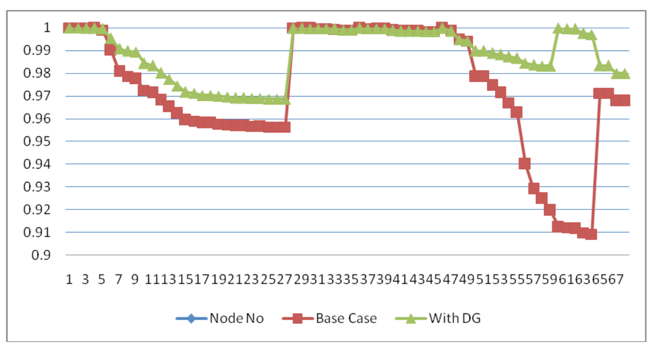

Figure 5. Comparison of Voltage Profile of 69 Node RDS with and Without DG.

5. Conclusion

An improved Load flow Algorithm has been presented which is found easy to implement in RDS. The modified algorithm incorporates the Load and Line uncertainties, composite nature of load and Distributed Generator. The algorithm got

Table 3. Summary of Load Flow results of 69 node RDS for Base case and Line and Load Data Variation

	Base Case	Case 1 (Factor)		Case 2		Case 3	
		(1-δ)	(1+δ)	(1-δ)	**(1+δ)**	**(1-δ)**	**(1+δ)**
Total real Power Loss (kW)	224.8011	200.6603	249.6118	211.2214	237.7255	189.0267	264.6544
Total reactive Power Loss (kVAr)	102.0954	91.0572	113.154	95.8497	107.7657	85.8195	119.9073
Minimum Voltage (p.u)	0.90922	0.9151	0.9053	0.9151	0.9053	0.9196	0.9001
Maximum Voltage deviation	0.09078	0.0849	0.0947	0.0849	0.0947	0.0804	0.0999

Table 4. Result of 69 Node Radial Distribution System with DG installed at Node number 61

Node No	With DG	Without DG	Node No	With DG	Without DG
1	1	1	36	0.9999	0.99992
2	1	0.99997	37	0.9998	0.99975
3	0.9999	0.99993	38	0.9996	0.99959
4	0.9999	0.99984	39	0.9996	0.99954
5	0.9994	0.99902	40	0.9996	0.99954
6	0.9952	0.9901	41	0.9989	0.99884
7	0.9908	0.98082	42	0.9986	0.99855
8	0.9898	0.9786	43	0.9985	0.99851
9	0.9893	0.97747	44	0.9985	0.9985
10	0.9844	0.97247	45	0.9984	0.99841
11	0.9833	0.97135	46	0.9984	0.9984
12	0.9802	0.96818	47	0.9998	0.99979
13	0.9774	0.96526	48	0.9986	0.99854
14	0.9745	0.96236	49	0.9948	0.9947
15	0.9717	0.95949	50	0.9942	0.99416
16	0.9712	0.95896	51	0.9898	0.97857
17	0.9703	0.95808	52	0.9898	0.97856
18	0.9703	0.95807	53	0.9888	0.97468
19	0.9699	0.9576	54	0.9882	0.97144
20	0.9696	0.9573	55	0.9873	0.96697
21	0.9691	0.95682	56	0.9866	0.9626
22	0.9691	0.95681	57	0.9845	0.94013
23	0.969	0.95674	58	0.9836	0.92907
24	0.9689	0.95659	59	0.9832	0.92479
25	0.9687	0.95641	60	0.9832	0.91977
26	0.9686	0.95634	61	1	0.91237
27	0.9686	0.95632	62	0.9997	0.91208
28	0.9999	0.99993	63	0.9994	0.9117
29	0.9999	0.99985	64	0.9976	0.9098
30	0.9997	0.99973	65	0.9971	0.90922
31	0.9997	0.99971	66	0.9833	0.97129
32	0.9996	0.99961	67	0.9833	0.97129
33	0.9994	0.99935	68	0.9799	0.96785
34	0.999	0.99901	69	0.9799	0.96785
35	0.999	0.99895			

tested on many RDS and results obtained are exemplary that confirms usefulness of the algorithm and can have significant impact on future planning and operation purposes of RDS.

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