Backward Forward Sweep Method for Distributed Generation Unit Integration with Radial Distribution Network

Debaparna Sengupta
Dept. of Electrical Engineering,
Techno International New Town,
Kolkata – 700156, India
imdebaparna@gmail.com

Asim Datta
Dept. of Electrical Engineering,
Mizoram University
Aizawl-796004, India
asimdatta2012@gmail.com

***Abstract*—** Due to the inflating demand of renewable energy resources, distributed generations are increasing rapidly. The integration of these distributed generation units with the radial distribution network must be done wisely to secure system stability. Power flow analysis is a mandate for optimum planning of the integrated system. The major disadvantage of radial distribution network is its high resistance to inductive reactance (R/X) ratio. Consequently, conventional methods used for the transmission line load flow computation are not applicable in this scenario. Moreover, the existing power flow analysis methods for radial distribution network are not numerous and need to be explored. The proposed algorithm is a fast, efficient, and derivative free simple method for solving the power flow problem of a grid-connected radial distribution system. It does not require any slack bus unlike the conventional load flow analysis methods used for transmission systems. In this paper, the detailed mathematical formulation of this algorithm along with simulation study on a test bed system is developed and a comparative result analysis of this method along with other previously castoff methods is carried out to verify the effectiveness of the proposed method.

I. INTRODUCTION

Due to the diminishing reserve of conventional energy resources and their unfavorable environmental impacts, renewable energy based distributed generation units and their integration with the existing distribution system are on topmost demand. For steady-state operation of any system, power balancing is the utmost important criterion. The generated power, the total power consumed by the loads and the system losses must be balanced. The mathematical modelling and solution of the system parameters based on the power balance at steady-state conditions is called load flow or power flow analysis [1]. For optimum integration of the distributed generation units with the existing distribution system, power flow analysis is a mandate in planning phase. In the early researches, substantial exertion had been employed for the development of load flow solution algorithms of transmission systems [2]. Defiantly, less attention was given for the development of load flow analysis methods for distribution systems [3–7]. It was observed that the conventional methods utilized for transmission systems like Newton Raphson method etc., were tedious and the results showed divergence when applied to the distribution systems [6]. Additionally, the decoupled load flow method used for transmission systems was frequently unproductive for distribution systems due to high resistance to inductive reactance (R/X) ratio. Few researches were found in the domain of power flow analysis of radial distribution systems. Fast and very fast decoupled methods along with their convergence and rate of convergence were verified [8]. A new load flow technique for distribution system was developed [9]. A line identification scheme along with sparse method was explored for fast load flow solution [10]. Current injection method (CIM) based distribution load flow, primitive impedance- based distribution load flow (PIDLF) and fast-decoupled single matrix model (SMM) distribution load flow methods were briefly discussed and applied on radial distribution systems and their comparative analysis was accomplished [11]. Backward forward sweep method (BFSM) was utilized on different test bed systems, but comparative study was not conducted to establish the effectiveness of the proposed method [12]. Researchers have focused on load flow analysis of uncertain distributed generator integrated distribution systems like wind, photovoltaic or biomass etc.in the recent researches [13-15]. In [13], complex affine arithmetic (AA) has been applied upon Gauss-Seidel method for the solution of the load flow problem. A probabilistic load-flow analysis technique for analysing the impacts of biomass-fuelled gas engine driven electric vehicles on distribution system has been investigated [14]. In [15], a probabilistic harmonic load flow analysis technique based on data clustering has been developed. An improved BFSM (IBFSM) method is introduced and comparative analysis of the results is performed with the various previously proven methods like CIM, PIDLF and SMM. But the comparative analysis does not include the conventional BFSM method [16]. In this paper, the fast, efficient, divergence free simple BFSM algorithm is presented for the power flow analysis of the radial distribution network. There is no need for slack bus contrasting the conventional load flow analysis methods adopted for transmission systems. It directly manipulates the currents flowing through the entire network by using simple network equations. The proposed algorithm is applied on IEEE 15 bus radial distribution network to validate its effectiveness on any radial distribution network. Comparative result analysis of the proposed method along with several previously proven methods including the IBFSM for solution of the power flow problem involving the same test network is performed. The investigation reveals the superiority of the proposed method.

II. MATHEMATICAL MODELLING

Before the development of the proposed BFSM algorithm, a simple mathematical model has been developed.

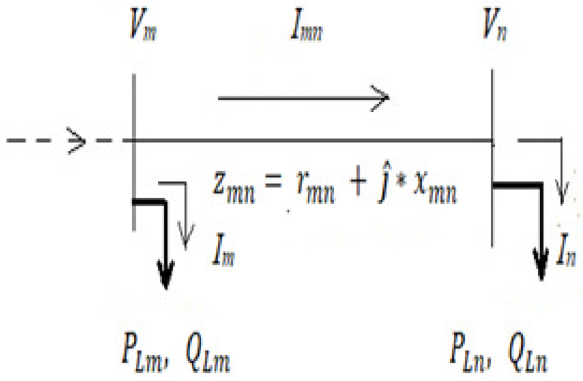

Fig. 1(a) Line connected with end nodes of main feeder or lateral

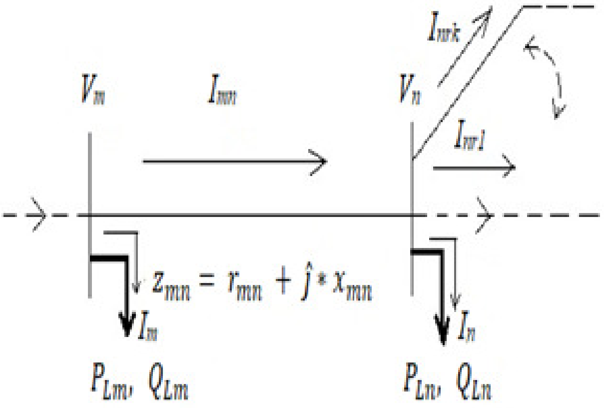

Fig. 1. (b) Line connected in between the intermediate nodes of main feeder or lateral

Fig. 1(a) represents the line connected to the end node of main feeder or lateral. Fig. 1(b) shows the the line connected in between the intermediate nodes of them, where the n^{th} node is further connected with the succeeding node of the main feeder or lateral with/without connection with laterals or sublaterals. V_m, I_m, P_{Lm}, Q_{Lm} and V_n, I_n, P_{Ln}, Q_{Ln} are the node volatge, load current, active and reactive powers of the m^{th} and n^{th} nodes respectively. I_{mn} is the line current flowing in between the m^{th} and n^{th} nodes. z_{mn} is the impedance of this line.

From Fig. 1 (a), $I_{mn} = I_n$ (1)

where, n^{th} node is the end node.

On contrary, from Fig. 1 (b),

$$I_{mn} = I_n + \sum_{r=r_1}^{r_k} I_{nr} \qquad (2)$$

where n is an intermediate node. It is the junction point of the succeeding feeder or lateral node with/without other connecting lateral or sublateral nodes coming out from the n^{th} node. $\sum_{r=r_1}^{r_k} I_{nr}$ is the summation of all currents coming out of the n^{th} node.

III. BACKWARD FORWARD SWEEP METHOD (BFSM)

The proposed algorithm consists of two parts: backward sweep and forward sweep. In backward sweep, currents of the entire network (all line and load currents) are premeditated. After getting all currents, the forward sweep is introduced to calculate all the node voltages of the system. Fig. 2 shows the flow chart of the proposed power flow analysis algorithm.

The detailed steps of implementing this algorithm are given below:

A. Initialization of Parameters

Before starting the proposed method, some arrays must be taken and initialized for running the algorithm. Impedance of a line connected in between nodes m and n is articulated as,

$$z_{mn} = r_{mn} + \hat{\jmath} * x_{mn} \qquad (3)$$

where, $1 \leq m \leq N_B$ and . $1 \leq n \leq N_B$. N_B stands for the total number of system nodes. If there is no physical connection or line in between any two nodes of the system under consideration, the corresponding z_{mn} value will be $(0 + \hat{\jmath} * 0)$ pu. Z matrix holds the line impedance data. z_{mn} is an element of Z matrix.

Two three-dimensional matrices V and I are formed beforehand to hold the voltage and current data generated in successive iterations of the proposed power flow algorithm. 'it' denotes the current iteration number. The range of 'it' is $1 \leq it \leq 'maxitrn'$, where $'maxitrn'$ signifies the maximum iteration number. Initialization of the 0^{th} iteration values of the volatges and currents are accomplished by storing $(1 + \hat{\jmath} * 0)$ and $(0 + \hat{\jmath} * 0)$ pu inside the V and I matrices for all elements.

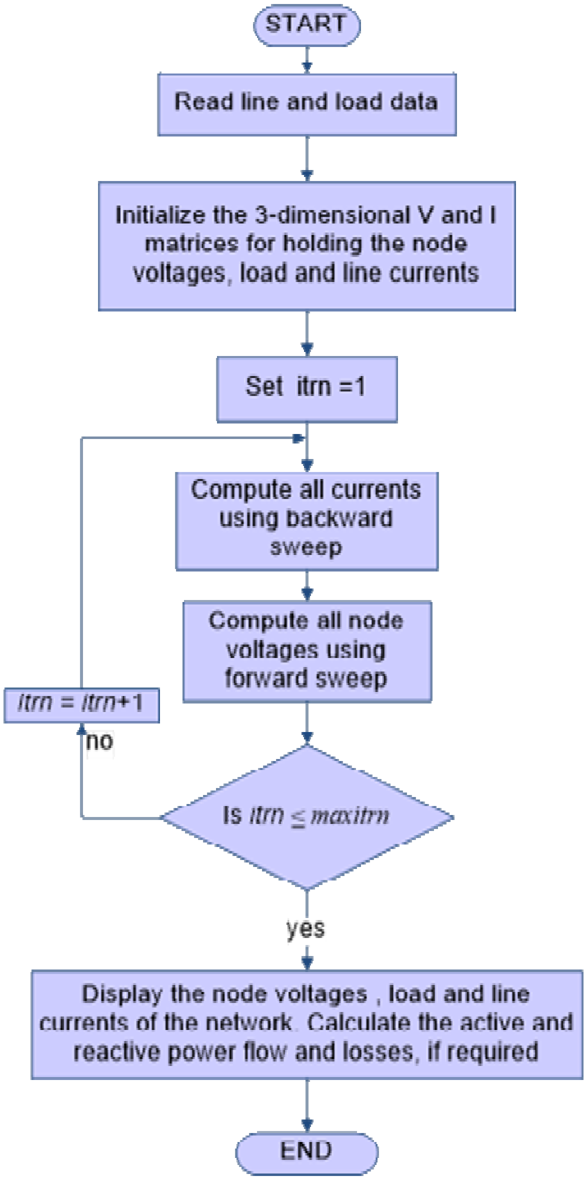

Fig. 2. Flow Chart of Backward Forward Sweep Method

B. *Backward Sweep*

After initialization of the arrays and matrices required for running the proposed algorithm, the backward sweep is started. This step is used to calculate all the line and load currents of the network and the calculation gets started from the end nodes and gradually proceeds towards the starting node.

The syntax used for calculating the n^{th} node's load current is:

for $it = 1{:}maxitrn$

$it = it + 1$

$$I_{(n,n,it)} = \{\frac{(P_{Ln} + j * Q_{Ln})}{V_{(1,n,it-1)}}\}^* \qquad (4)$$

where, $2 \le n \le N_B$

$I_{(n,n,it)}$ presents the load current flowing from the n^{th} node for the ongoing iteration. It is stored inside the n^{th} row and n^{th} column of the (it+1)th third dimension index location of the I matrix. $V_{(1,n,it-1)}$ denotes the n^{th} node voltage of preceding iteration and is stored inside the n^{th} column of the itth third dimension index location of the V matrix. After receiving all load currents of the network, the next step is to find out all the line currents. The line currents of the distribution network are calculated by equation (5).

$$I_{(m,n,it)} = I_{(n,n,it)} + \sum_{r=r_1}^{r_k} I_{(n,r,it)} \qquad (5)$$

$I_{(m,n,it)}$ is the line current flowing in between nodes m and n for the ongoing iteration. It is the m^{th} row, n^{th} column and (it+1)th third dimension index element of the I matrix. r signifies all other nodes connected with the n^{th} node in the forward direction and $r_1 \le r \le r_k$. $\sum_{r=r_1}^{r_k} I_{(n,r,it)}$ is the summation of all the line currents for the lines connected with n^{th} node in forward direction of the distribution network for the ongoing iteration. r_1 to r_k are the discrete values taken by r, depending on the network configuration. All deployed load and line currents are stored inside the I matrix. The elements of the three-dimensional I matrix will be updated if nodes m and n are physically connected within the distribution network. Otherwise, its value will remain as it is [$(0 + \hat{j} * 0)$, initialized value]. The 0th iteration values of the currents are stored inside the first third dimension index location of the I matrix.

C. *Forward Sweep*

After calculating all currents of the network by backward sweep, forward sweep is incorporated for calculating all the node voltages. This process proceeds in the forward direction while calculating the node voltages.

The syntax used for calculating the n^{th} node voltage for the ongoing iteration '*it*' of the power flow algorithm is:

for $it = 1{:}maxitrn$

$it = it + 1$

$$V_{(1,n,it)} = [V_{(1,m,it)} - z_{m,n} * I_{(m,n,it)}] \qquad (6)$$

where, $1 \le m \le N_B - 1$ and $2 \le n \le N_B$

After completion of the forward sweep process, all the network currents and node voltages are known for the ongoing iteration. At that point, the stopping criterion for this iterative algorithm is checked and if it is not satisfied, the next iteration is initiated. After completion of the algorithm, active and reactive power losses of the lines and power flow from the nodes can be calculated as per requirement.

IV. RESULTS AND DISCUSSION

The proposed method is applied on IEEE 15 bus radial distribution system to find out network voltages, currents, active and reactive power losses. The results are compared with that of the previously proven power flow analysis methods.

Table 1. Comparative analysis of the node voltage profile of the proposed method with the other previously proven power flow methods

Node no.	CIM	PIDLF	SMM	IBFSM	Proposed method
1	1	1	1	1	1
2	0.97128	0.96885	0.97031	0.97017	0.9713
3	0.95667	0.95427	0.95571	0.95657	0.9567
4	0.9509	0.94852	0.94995	0.95078	0.9509
5	0.94991	0.94754	0.94896	0.94977	0.9499
6	0.95822	0.95583	0.95726	0.96267	0.9582
7	0.95476	0.95237	0.9538	0.95974	0.9560
8	0.95694	0.95455	0.95599	0.96115	0.9570
9	0.96797	0.96555	0.967	0.96020	0.9680
10	0.96689	0.96448	0.96593	0.95936	0.9669
11	0.94955	0.94775	0.949	0.95202	0.9500
12	0.94582	0.94346	0.94488	0.95006	0.9459
13	0.94451	0.94215	0.94357	0.94842	0.9446
14	0.9486	0.94623	0.94766	0.94926	0.9486
15	0.94844	0.94606	0.94749	0.94775	0.9485

Table 2. Other network parameters of the test network obtained from the proposed power flow method

Line no.	In between nodes	|Line current| in pu	Active power loss in pu	Reactive power loss in pu
1	1 and 2	0.0184	$0.3768 * 10^{-3}$	$0.3685* 10^{-3}$
2	2 and 3	0.0108	$0.1128* 10^{-3}$	$0.1103* 10^{-3}$
3	2 and 6	0.0052	$0.0577* 10^{-3}$	$0.0389* 10^{-3}$
4	2 and 9	0.0017	$0.0047 * 10^{-3}$	$0.0032* 10^{-3}$
5	3 and 4	0.0059	$0.0244* 10^{-3}$	$0.0239* 10^{-3}$
6	3 and 11	0.0038	$0.0217* 10^{-3}$	$0.0146* 10^{-3}$
7	4 and 5	0.0007	$0.0006* 10^{-3}$	$0.0004* 10^{-3}$
8	4 and 14	0.0011	$0.0020* 10^{-3}$	$0.0014* 10^{-3}$
9	4 and 15	0.0021	$0.0044* 10^{-3}$	$0.0030* 10^{-3}$
10	6 and 7	0.0021	$0.0039* 10^{-3}$	$0.0027* 10^{-3}$
11	6 and 8	0.0010	$0.0011* 10^{-3}$	$0.0008* 10^{-3}$
12	9 and 10	0.0007	$0.0006* 10^{-3}$	$0.0004* 10^{-3}$
13	11 and 12	0.0017	$0.0060* 10^{-3}$	$0.0040* 10^{-3}$
14	12 and 13	0.0007	$0.0007* 10^{-3}$	$0.0005* 10^{-3}$

From the results obtained in Table 1, it is observed that the proposed method is giving better results in terms of voltage magnitudes while compared with current injection method (CIM) based distribution load flow, primitive impedance-based distribution load flow (PIDLF) and fast-decoupled single matrix model (SMM) distribution load flow methods [16]. But comparison with the very recently developed IBFSM method [16] reveals that the voltage drooping is less in the main feeder nodes as well as the nodes associated with two lateral branches (nodes 9,10 and 15) in case of the proposed method. For the other two laterals branches, the node voltages are slightly less, though they are in tolerance limits. As the voltage deviations in the main feeder nodes are less compared to the other methods mentioned in [16], it can be urgued that, the proposed method is more suitable than that of the other proven methods in terms of voltage profile of the distribution network. From Table 2, it is observed that the line currents and power losses are also within moderate range. The results establish the superoirity of the proposed method.

V. CONCLUSION

In this proposed work, a power flow analysis algorithm named backward forward sweep method is castoff to resolve the power flow issue in radial distribution systems which is essential for distributed generation integration planning. The proposed method can be readily used in collaboration with any efficient optimization technique for optimum size and location identification of these units within the integrated system. The proposed method follows a fast, efficient, divergence free simple technique. Unlike the conventional load flow analysis methods used for transmission lines and few previously established power flow methods utilized for the distribution systems, it does not necessitate any complicated numbering of branches, complex matrix calculation and solution of differential equations. The proposed load flow method is easy to device. The results obtained from the proposed method are compared with that of the earlier methods and found to be giving superior outcomes.

REFERENCES

[1] V. Vittal, J.D. McCalley, P.M. Anderson, and A.A. Fouad, “Power system control and stability,” John Wiley & Sons, 2019.

[2] B. Stott, “Review of load-flow calculation methods,” in *Proceedings of the IEEE*, vol. 62, no. 7, pp. 916-929, 1974.

[3] R. Berg, E.S. Hawkins, and W.W. Pleines, “Mechanized calculation of unbalanced load flow on radial distribution circuits,” *IEEE Transactions on power apparatus and systems*, vol. 4, pp.415-421, 1967.

[4] W. H. Kersting, “Application of ladder network theory to the solution of three-phase radial load flow problems,” in *IEEE PES winter meeting*, 1976, vol. 76044, no. 8.

[5] J. J. Grainger, and S. H. Lee, “Capacity release by shunt capacitor placement on distribution feeders: a new voltage dependent model,” *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-101, no. 5, pp. 1236-1244, 1982.

[6] D. Shirmohammadi, H.W. Hong, A. Semlyen, G.X. Luo, “A compensation-based power flow method for weakly meshed distribution and transmission networks,” *IEEE Transactions on power systems*, vol. 3, no. 2, pp. 753-762, 1988.

[7] M. Baran and F.F. Wu, “Optimal sizing of capacitors placed on a radial distribution system,” *IEEE Transactions on power Delivery*, vol. 4, no. 1, pp. 735-743, 1989.

[8] H.D. Chiang, “A decoupled load flow method for distribution power networks: algorithms, analysis and convergence study,” *International Journal of Electrical Power & Energy* Systems, vol. 13, no. 3, pp. 130-138 1991.

[9] D. Das, D.P. Kothari, and A. Kalam, “Simple and efficient method for load flow solution of radial distribution networks,” *International Journal of Electrical Power & Energy Systems*, vol. 17, no. 5, pp. 335-346, 1995.

[10] T. Ramana, V. Ganesh, and S. Sivanagaraju, “Simple and fast load flow solution for electrical power distribution systems,” *International Journal on Electrical Engineering and Informatics*, vol. 5, no. 3, pp. 245, 2013.

[11] T. Sathiyanarayanan, and M. Sydulu, “Load flow analysis for radial and mesh connected distribution systems,” *International Journal of Science and Research*, vol. 3, no. 6, 2014.

[12] G. Peddanna, and Y.S.R. Kishore, “Power loss allocation of balanced radial distribution systems,” *International Journal of Science and Research*, vol. 4, pp. 360-366 , 2015.

[13] Y.M. Abebe, M.R. Pasumarthi, and G.N. Mudavath, “ Load flow analysis of uncertain power system through affine arithmetic,” *in Microelectronics, Electromagnetics and Telecommunications*, Springer, New Delhi, 2016, pp. 217-231.

[14] F.J. Ruiz-Rodríguez, J.C. Hernández, and F. Jurado, “Probabilistic load-flow analysis of biomass-fuelled gas engines with electrical vehicles in distribution systems,” *Energies*, vol. 10, no. 10, pp. 1536, 2017.

[15] S. Galvani, S.R. Marjani, J. Morsali, and M.A. Jirdehi, “A new approach for probabilistic harmonic load flow in distribution systems based on data clustering,” *Electric Power Systems Research*, vol. 176, pp. 105977, 2019.

[16] S. Ouali and A. Cherkaoui, “An Improved Backward/Forward Sweep Power Flow Method Based on a New Network Information Organization for Radial Distribution Systems,” *Journal of Electrical and Computer Engineering*, 2020.