An Efficient, Fast And Versatile Power Flow Analysis Method For 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*— The proposed method presents a precise power flow analysis technique for radial distribution systems. The main advantage of this method is the development of straight forward and simple algorithm independent of network configuration. The data insertion is methodical and once the system data is entered in the prescribed order, the algorithm can be written very easily in generalized form and can be applied to any distribution network whether sequential or nonsequential. Other attractive features are fast response and accuracy in results. The proposed method utilizes simple generalized equations to calculate the node voltages and the other parameters of the system. The only vital requirement of the proposed technique is to build the dataset of feeder nodes, lateral(s) and sub lateral(s). The effectiveness of the proposed method is established by comparing the results obtained with the other previously recognized methods.**

Keywords*— *Power flow, main feeder, lateral, sub-lateral, node voltage, power loss

I. INTRODUCTION

Power flow analysis is the technique to find out the node voltages along with different real and reactive power losses of the system. Competent power flow study is a mandate for efficient distribution network maintenance and expansion planning to cope up with the growing electricity demand. The constructional features of the transmission and distribution networks are different. Distribution systems are radial having high R/X ratio. Contrarily, the transmission system is loop structured possessing high X/R ratio. Therefore, the load flow analysis variables and solution methods for the distribution structures are dissimilar from that of transmission counterpart. The distribution networks are often called weakly meshed networks and henceforth, the various conservative methods like the Gauss Seidel (GS) and Newton Raphson (NR) methods are not suitable here.

The problems associated with these conventional techniques are their lack of convergence for the distribution network analysis. Numerous efficient load flow methods for transmission system analysis are accessible from previous researches. But very limited number of methods are testified for load flow analysis of distribution networks. Development of efficient power flow methods for the distribution systems is utmost important as distribution systems is the ultimate linkage between the bulk power transmission system and the end customers [1–3]. The approaches proposed in [4,5] are very complex and sluggish. Kersting and Mendive [6] and Kersting [7] projected a new load flow technique for radial distribution networks by applying the backward and forward sweeps within the network for calculating node voltage magnitudes and network currents. Stevens, Rizy and Purucker [8] exhibited that the backward forward sweep method (BFSM) projected in [6,7] is the fastest but convergency is not assured for all networks under study. Shirmohammadi, Hong, Semlyen and Luo [9] proposed a new technique by applying the well-known Kirchoff's laws

upon the radial distribution network with a well-developed branch numbering scheme. The proposed technique improved the mathematical performance of the computation process with a shortfall of laborious data preparation. Baran and Wu [10] and later Jasmon and Lee [13] developed an iterative load flow solution by the essential representative equations of active and reactive powers as well as node voltages. These proposed procedures enhanced the accuracy in results with a deficit of high processing time. Chiang [11] showcased a comparative study of three diverse procedures raised on the scheme introduced by Baran and Wu [10]. An estimated process for load flow solution was introduced by Goswami and Basu [12] considering each node as the junction point of maximum three branches. A sequential node as well as branch numbering scheme was developed and utilized, but the data preparation was complicated. Das, Nagi. and Kothari [14] anticipated a new load flow solution using a new coding scheme for lateral and sub-lateral nodes to achieve power convergence. This newly developed technique introduced computational complexity for large network configurations. Moreover, the technique can be applied only for sequential numbering scheme. The receiving end node voltages were computed by forward sweep technique assuming zero initial power loss. Rahman and Jasmon [15] projected a new method for the load flow solution of radial distribution systems by developing a fourth order differential voltage equation. The processing time of the solution was high. Ghosh and Das [16] developed a new load flow technique by introducing a new scheme of nodes beyond branches with an intention of node voltage convergence. The initial node voltages were assumed to be 1 pu and amalgamation of charging admittances with the network has improved voltage profile with a reduction in line losses. The key downside of this process was the unnecessary storage of nodes introduced beyond each branch. A new load flow technique has been developed by Jamali, Javdan, Shateri and Ghorbani [17] by adopting the sequential branch numbering scheme for committed loads. Aravindhababu, Ganapathy and Nayar [18] showcased a modest and effective branch-to-node matrix-based power flow (BNPF) scheme which was less appropriate in comparison with the conventional NR method due to complications in matrix formation for the existence of sub laterals. Ouali. and Cherkaoui [19] developed an improved backward forward sweep method for radial distribution system. A comparative study was made with the other previously applied methods to show the effectiveness of the technique. From the literature survey, it can be concluded that the main objectives of the various applied techniques were to reduce the computational complicacy, speed up the response and/or enhance the accuracy of results. But each method has its own pros and cons.

The proposed power flow technique presented in this paper focuses to eliminate all the previously encountered shortfalls while applying different previously proven techniques. It is a versatile method irrespective of the network numbering scheme adopted. The only requirement for the successful implementation of the proposed technique is the insertion of a data set involving various nodes and branches of main feeder along with laterals and sub laterals. The proposed technique calculates power flow of all branches along with all active as well as reactive line losses and node voltages most competently without any requirement of storing the node data situated beyond each branch. The equations used here are simple and straightforward. The data preparation is simple and less time consuming related to the other approaches. The proposed technique is applied on a standard test bus system. The results obtained are compared with that of the other prevailing techniques presented in [19] and found to be superior.

II. Mathematical Modelling and Development of Solution Algorithm:

Before forming the mathematical model of the proposed technique, a three-phase balanced radial distribution network is presumed.

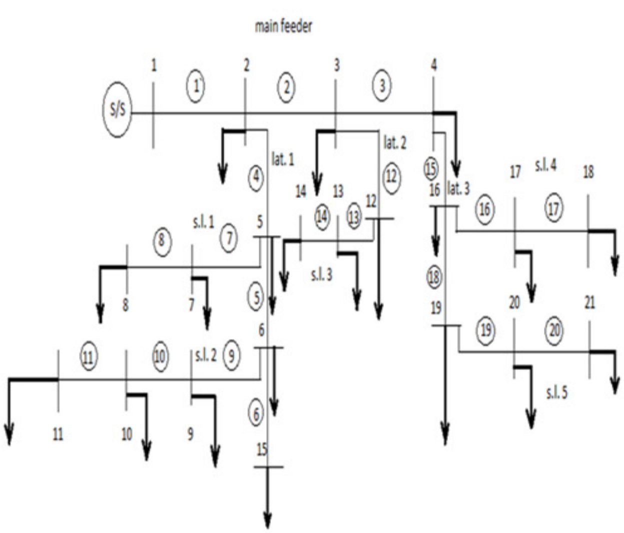

Figure 1. Single line diagram of a radial distribution system with main feeder, laterals and sub-laterals

Figure 1 shows the single-line diagram of a distribution network with main feeder, laterals and sub-laterals with no charging capacitances in effect considering only one phase. A non-sequential numbering scheme is presented here to validate the effectiveness of the proposed technique on any type of numbering scheme. From Figure 1, it is observed that apart from the main feeder, there are three laterals and five sub-laterals. Set of feeder nodes is {1, 2, 3, 4}. Sets of lateral nodes are {2, 5, 6, 15}, {3, 12} and {4, 16, 19} correspondingly. Similarly {5, 7, 8}, {6, 9, 10, 11}, {12, 13, 14}, {16, 17, 18} and {19, 20, 21} are the sets of sub-lateral nodes. The set of branch numbers of main feeder is {1, 2, 3}. Following the same footsteps, the sets of branch numbers of the three laterals are {4, 5, 6}, {12} and {15, 18}. Similarly, the sets of branch numbers of the five sub-laterals are {7, 8}, {9, 10, 11}, {13, 14}, {16, 17} and {19, 20}.

A. *Formation of the array for storing the total node numbers of each feeder, laterals and sub-laterals:*

Number of feeders, laterals and sub-laterals are denoted by '*A*','*B*' and '*C*'. From Figure 1, $A = 1$, $B = 3$ and $C = 5$. The total number of feeders, laterals and sub-laterals is presented by '*TN*'.

$$TN - A + B + C \tag{1}$$

Here, '*TN*' value is 9.

The total numbers of nodes of feeders, all laterals and sub-laterals are stored in a one-dimensional array '*N*'. The number of columns of this array is '*TN*'. Henceforth, the total number of columns of '*N*' array for the network represented in Figure 1 is 9. Therefore, $N(1) = 4$, $N(2) = 4$, $N(3) = 2$, $N(4) = 3$, $N(5) = 3$, $N(6) = 4$, $N(7) = 3$, $N(8) = 3$ and $N(9) = 3$.

B. *Formation of node and branch data sets:*

For creating the data set of nodes and branches involving the feeder, laterals and sub-laterals; two matrices 'FN' and 'FB' are formed: one for storing the node data and another for storing the branch data. Concerning the first indices of these two matrices, feeder is represented by 1, laterals by (2, 3, 4) and sub laterals by (5, 6, 7, 8, 9). The second indices denote the order of the nodes or branches in a specific feeder, lateral or sub-lateral already indicated by the first indices. At first feeder data is set aside, then comes the turn of laterals and sub laterals. The formation of the 'FN' and 'FB' matrices are presented below:

The elements of the 'FN' matrix (two dimensional) are:

$FN(1,1) = 1$, $FN(1,2) = 2$, $FN(1,3) = 3$ and $FN(1,4) = 4$ {presenting main feeder node data}

$FN(2,1) = 2$, $FN(2,2) = 5$, $FN(2,3) = 6$ and $FN(2,4) = 15$ {presenting lateral 1 node data}

$FN(3,1) = 3$ and $FN(3,2) = 12$ {presenting lateral 2 node data}

$FN(4,1) = 4$, $FN(4,2) = 16$ and $FN(4,3) = 19$ {presenting lateral 3 node data}

$FN(5,1) = 5$, $FN(5,2) = 7$ and $FN(5,3) = 8$ {presenting sub-lateral 1 node data}

$FN(6,1) = 6$, $FN(6,2) = 9$, $FN(6,3) = 10$ and $FN(6,4) = 11$ {presenting sub-lateral 2 node data}

$FN(7,1) = 12$, $FN(7,2) = 13$ and $FN(7,3) = 14$ {presenting sub-lateral 3 node data}
$FN(8,1) = 16$, $FN(8,2) = 17$ and $FN(8,3) = 18$ {presenting sub-lateral 4 node data}
$FN(9,1) = 19$, $FN(9,2) = 20$ and $FN(9,3) = 21$ {presenting sub-lateral 5 node data}

Consequently, the elements of the 'FB' matrix (two dimensional) are:

$FB(1,1) = 1$, $FB(1,2) = 2$ and $FB(1,3) = 3$ {presenting main feeder branch data}
$FB(2,1) = 4$, $FB(2,2) = 5$ and $FB(2,3) = 6$ {presenting lateral 1 branch data}
$FB(3,1) = 12$ {presenting lateral 2 branch data}
$FB(4,1) = 15$ and $FB(4,2) = 18$ {presenting lateral 3 branch data}
$FB(5,1) = 7$ and $FB(5,2) = 8$ {presenting sub-lateral 1 branch data}
$FB(6,1) = 9$, $FB(6,2) = 10$ and $FB(6,3) = 11$ {presenting sub-lateral 2 branch data}
$FB(7,1) = 13$ and $FB(7,2) = 14$ {presenting sub-lateral 3 branch data}
$FB(8,1) = 16$ and $FB(8,2) = 17$ {presenting sub-lateral 4 branch data}
$FB(9,1) = 19$ and $FB(9,2) = 20$ {presenting sub-lateral 5 branch data}

In general, the elements of the 'FN' matrix are represented by '*FN (i, j)*', where $i = 1,2,\ldots,TN$ and $j = 1,2,\ldots,N(i)$. The elements of the 'FB' matrix are represented by '*FB (i, j)*', where $i = 1,2,\ldots,TN$ and $j = 1,2,\ldots,N(i) - 1$.

C. Formation of arrays for storing the common nodes of laterals and sub-laterals:

An array named 'mm' is formed for storing the common nodes of laterals and sub-laterals. These common nodes are the first elements of the rows representing the sub-lateral data of the previously formed 'FN' matrix. A second array named 'mn' is premeditated for storing the associated sublateral numbers. The syntax used for storing the information into the 'mm' and 'mn' arrays are:

$j = 0$
for $i = TN : (TN - C + 1)$
$j = j + 1$
$mm(j) = FN(i,1)$
$mn(j) = i$
$i = i - 1$
end

D. Storing information for the common nodes of main feeder and laterals:

The same arrays used in sub section II D are utilized for storing information about the common nodes of main feeder and laterals. These common nodes are the first elements of the rows representing the lateral data of the previously formed 'FN' matrix. 'mm' array stores the common nodes of feeder and laterals whereas 'mn' stores information about the associated lateral numbers. The syntax used for storing the information into the 'mm' and 'mn' arrays are:

for $i = (TN - C) : (TN - C - B + 1)$
$j = j + 1$
$mm(j) = FN(i,1)$
$mn(j) = i$
$i = i - 1$
end

E. Storing the load active and reactive powers; line resistance, reactance and impedance data:

For storing the load active and reactive powers drawn from the system nodes, 'P_L' and 'Q_L' matrices are formed. $P_L[FN(i,j)]$ and $Q_L[FN(i,j)]$ represent the elements of these two matrices. Similarly, line resistance, reactance and impedance data are stored inside the newly formed 'R', 'X' and 'Z' matrices. $R[FB(i,j)]$, $X[FB(i,j)]$ and $Z[FB(i,j)]$ display the elements of these three matrices.

F. Formation and initialization of V and I matrices:

For calculating the active and reactive line losses of the network, the initial values of the node voltages and line currents are to be stored inside voltage and current matrices formed. The initial values of all the elements $V[FN(i,j)]$ of the V matrix are set to $(1 + \hat{j} * 0)$ pu whereas all the elements $I[FB(i,j)]$ of I matrix are taken as $(0 + \hat{j} * 0)$. The dimensional ranges of $V[FN(i,j)]$ elements are $i = 1,2,\ldots,TN$ and $j = 1,2,\ldots,N(i)$. The I matrix elements $I[FB(i,j)]$ are represented for $i = 1,2,\ldots,TN$ and $j = 1,2,\ldots,N(i) - 1$.

G. Calculating and storing the values of active and reactive line losses of the network at initial condition as well as different iterations:

$LP[FB(i,j)]$ and $LQ[FB(i,j)]$ matrices are formed to store the values of calculated active and reactive power line losses. The step by step procedure for calculating the active and reactive line losses of the network are presented by these following equations:

$$|I[FB(i,j)]| = \frac{|V[FN(i,j)]| - |V[FN(i,j+1)]|}{|Z[FB(i,j)]|}$$
(2)

$$LP[FB(i,j)] = |I[FB(i,j)]|^2 * R[FB(i,j)]$$
(3)

$$LQ[FB(i,j)] = |I[FB(i,j)]|^2 * X[FB(i,j)]$$
(4)

where, $i = 1,2,\ldots,TN$ and $j = 1,2,\ldots,N(i) - 1$

After finding out the active and reactive power line losses, the elements of the node voltage matrix is preserved for further use into 'V_1' matrix. $V_1[FN(i,j)]$ is presenting the element of 'V_1'.

$$V_1[FN(i,j)] = V[FN(i,j)] \quad (5)$$

H. Calculating the active and reactive power flows through the lines of the network at initial condition as well as different iterations:

For calculating the active and reactive power flows from the sub-lateral nodes, the following syntax is used:

for $i = TN : (TN - C + 1)$
for $j = (N(i) - 1) : 1$
if $j == N(i) - 1$

$$P_S[FB(i,j)] = P_L[FN(i,j+1)] + LP[FB(i,j)]$$
(6)

$$Q_S[FB(i,j)] = Q_L[FN(i,j+1)] + LQ[FB(i,j)]$$
(7)

else

$$P_S[FB(i,j)] = P_L[FN(i,j+1)] + LP[FB(i,j)] + P_S[FB(i,j+1)] \quad (8)$$

$$Q_S[FB(i,j)] = Q_L[FN(i,j+1)] + LQ[FB(i,j)] + Q_S[FB(i,j+1)] \quad (9)$$

end

$j = j - 1$

end

$i = i - 1$

end

For finding out the active and reactive power flows from the lateral and feeder nodes, the following syntax is castoff:

For $i = (TN - C){:}1$

for $j = (N(i) - 1) : 1$

for $k = 1{:}(TN - 1)$

if $FN(i,j+1) == mm(k)$

if $j + 1 == N(i)$

$$P_S[FB(i,j)] = P_L[FN(i,j+1)] + LP[FB(i,j)] + P_S[FB(mn(k),1)] \quad (10)$$

$$Q_S[FB(i,j)] = Q_L[FN(i,j+1)] + LQ[FB(i,j)] + Q_S[FB(mn(k),1)] \quad (11)$$

else

$$P_S[FB(i,j)] = P_L[FN(i,j+1)] + LP[FB(i,j)] + P_S[FB(mn(k),1)] + P_S[FB(i,j+1)] \quad (12)$$

$$Q_S[FB(i,j)] = Q_L[FN(i,j+1)] + LQ[FB(i,j)] + Q_S[FB(mn(k),1)] + Q_S[FB(i,j+1)] \quad (13)$$

These active and reactive power flows are stored inside the 'P_S' and 'Q_S' matrices formed. $P_S[FB(i,j)]$ and $Q_S[FB(i,j)]$ represent the elements of these two matrices.

I. Calculation of the node voltages, node voltage errors, maximum node voltage error at different iterations and checking for the optimum voltage error as well as maximum iteration criteria:

For the first iteration, after initializing the voltage and current matrices and calculating the initial values of the active and reactive line losses as well as active and reactive power flows of the lines following subsections II F , II G and II H ; the iteration value is set to 1 i.e.

$IT = 1$

For other iterations, the '*IT'* value for the current iteration will be automatically set to '*IT* + 1' in the previous iteration. Henceforth, the steps depicted in subsections II G and II H are followed for retaining the previous iteration values of node voltages in V_1 matrix and calculating the active and reactive line losses as well as active and reactive power flows of the lines in current iteration.

The node voltages and associated voltage errors, the following equations are used:

$$|V[FN(i,j+1)]| = |V[FN(i,j)]| - \frac{\sqrt{(P_S[FB(i,j)])^2 + (Q_S[FB(i,j)])^2}}{|V[FN(i,j)]|} * |Z[FB(i,j)]| \quad (14)$$

$$|\Delta V[FN(i,j)]| = |V_1[FN(i,j)]| - |V[FN(i,j)]| \quad (15)$$

where, $i = 1,2,\ldots,TN$ and $j = 1,2,\ldots,N(i) - 1$. V_1 matrix retains the initial node voltage values and V matrix holds the first iteration values of the node voltages for $IT = 1$. For other iterations, V_1 and V hold the previous and succeeding iteration node voltage values respectively.

Then the maximum node voltage error is calculated by using the syntax:

$$\Delta V_{max} = \max(|\Delta V[FN(i,j)]|) \quad (16)$$

After obtaining the maximum network voltage error, the next step is to verify whether the optimum voltage error criterion is met or not.

If $\Delta V_{max} \leq 0.00001$, then the optimum voltage error criterion is met. The iteration process terminates and the node voltages, the line losses and power flows obtained are the optimum results corresponding to the optimum voltage error criterion.

If the optimum voltage error criterion is not satisfied, then '*IT*' should be set to '(*IT* + 1)' i.e.

$IT = IT + 1$

At that moment inspection of maximum iteration criterion is accomplished.

If $IT \leq IT_{max}$, then the next iteration begins, and the control goes to sub-section II G and subsequently to sub-sections II H and II I, where preservation of node voltages achieved from previous iteration is accomplished; calculation and retention of the active and reactive line losses, active and reactive line power flows, node voltages, node voltage errors and maximum node voltage error in current iteration are calculated and the optimum voltage error as well as maximum iteration criteria are checked. If the maximum iteration criterion is met, then the process stops without any convergence i.e. convergence is not achieved.

III. RESULTS AND DISCUSSION:

For validation of the proposed technique, IEEE 15 bus radial distribution system is taken into consideration. The intention behind this selection, is to perform a comparative study in between the proposed technique and a very recently published new technique along with the other previously established techniques [19]. The node voltages obtained from the various formerly proven power flow analysis methods are compared with that of the proposed method.

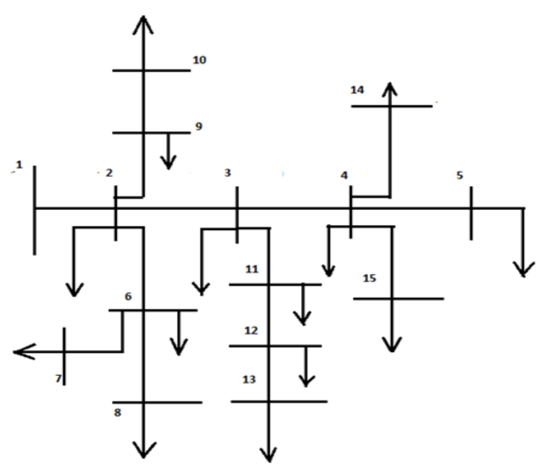

Figure 2. Single line diagram of IEEE 15 bus system.

Figure 2 shows the single line diagram of the IEEE 15 bus radial distribution network.

Table 1. Comparative analysis of different power flow methods with the proposed method

Node no.	PIDLF	SMM	CIM	IBFSM	Proposed method
1	1	1	1	1	1
2	0.96885	0.97031	0.97128	0.97017	0.9713
3	0.95427	0.95571	0.95667	0.95657	0.9567
4	0.94852	0.94995	0.9509	0.95078	0.9509
5	0.94754	0.94896	0.94991	0.94977	0.94993
6	0.95583	0.95726	0.95822	0.96267	0.9587
7	0.95237	0.9538	0.95476	0.95974	0.9550
8	0.95455	0.95599	0.95694	0.96115	0.9572
9	0.96555	0.967	0.96797	0.96020	0.9672
10	0.96448	0.96593	0.96689	0.95936	0.9658
11	0.94775	0.949	0.94955	0.95202	0.9520
12	0.94346	0.94488	0.94582	0.95006	0.9496
13	0.94215	0.94357	0.94451	0.94842	0.9473
14	0.94623	0.94766	0.9486	0.94926	0.9491
15	0.94606	0.94749	0.94844	0.94775	0.9481

Table 1 showcases the comparative study in between the node voltages obtained by the proposed method and other earlier established methods mentioned in [19].

From the result analysis, it is observed that in between the earlier methods current injections method (CIM) is giving better results compared to the primitive impedance-oriented distribution load flow (PIDLF) and fast-decoupled single matrix model (SMM) distribution network load flow methods. The improved backward forward sweep method (IBFSM) used in [19] is showing better results from the previously proven best CIM method in case of three lateral branch nodes, but the node voltages are less in main feeder nodes and the other two lateral nodes. The proposed method is giving superior results in case of main feeder node voltages compared to the CIM and IBFSM methods. For the lateral nodes, the proposed method is giving better results for three lateral branches and slightly less node voltages in case of the other two lateral branches while compared with CIM method. Comparison with the IBFSM method reveals that the proposed method is giving better results for two lateral branches and slightly depraved results in case of the other three lateral branches. As the main feeder node voltage errors are less, it can be argued that the proposed method is an effective one which can be adopted for the power flow analysis of radial distribution systems having any network numbering scheme.

IV. CONCLUSION:

In this paper, a newly developed versatile load flow analysis technique is applied for load flow analysis of a radial distribution system. The proposed method is independent of sequential and nonsequential network numbering schemes. The algorithm developed here is a simple, differential equation free, matrix free algorithm which uses simple algebraic equations for calculating different system parameters. Consequently, the computational time is less. The proposed technique is easy to implement as only system data is needed to be entered in a sequential manner and the rest of the job is taken care of by the simple algorithm developed. The proposed technique is a fast, efficient, versatile one giving overall better results compared to the other previously established techniques.

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