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Improved algorithm for radial distribution networks load flow solution

Abdellatif Hamouda [a,*], Khaled Zehar [b]

[a] Department of Mechanics, QU.E.R.E Laboratory, University Ferhat Abbas, 19000 Setif, Algeria
[b] Department of Electrical Engineering, QU.E.R.E Laboratory, University Ferhat Abbas, 19000 Setif, Algeria

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ABSTRACT

The main aim of this paper is to present an improved method to solve load flow problem in balanced radial distribution systems with laterals. The method is efficient and easy to implement. Based on electric circuit laws, this method is iterative and allows the evaluation of both, voltage (rms) values and phase-angles. The phase-angles although of small values become necessary in the reactive energy optimisation problem. To solve the load flow in lines with laterals, a simple technique of determining nodes beyond each branch is given. Speed convergence was increased by an appropriate choice of initial voltages. The method requires a small number of iterations and less computational time. It has been used successfully in several line examples. The obtained results for voltage magnitudes and deviation-angles are found to be very close to those of previous works.

1. Introduction

Increase in electric energy demand has forced the power utility companies to pay closer attention to distribution networks analysis. Usually, distribution feeders have a high R/X ratio and radial configuration which renders such systems ill-conditioned. Thus conventional method such as Newton–Raphson [1], fast decoupled load flow [2] and their modified versions [3–5] are unsuitable for solving load flow problem in more cases and may even fail to converge.

Several non-Newton efficient algorithms based on backward and forward sweeps are reported in literature [6–12]. Haque [6] has developed a method for radial and mesh networks. In the latter, loops are opened and dummy bus is added in the loop break point. Power flow through the branch that makes the loop is simulated by injection of the same power in the dummy bus. The method uses the backward and forward sweeps with nodes initial voltage assumed to be equal to that of the source bus which is taken as reference. No algorithm to automatically determine the nodes after each branch is given. Ghosh and Das [7] also have used backward and forward sweeps with nodes initial voltage set equal to 1 in per-unit (p.u). In the solution methodology, [7] gives an algorithm for identifying the nodes beyond the branches. This method involves the evaluation of algebraic expressions and only permits the calculation of the nodes voltage rms values. Nanda et al. [8] have solved the load flow problem by going up and down the line. As initial voltage, they assume a value of 1 p.u only at the end buses of the line (main feeder and laterals end buses). Nanda et al. convergence criterion is based on the voltage at the supply node. If the difference between the source voltage, calculated and specified, is within a certain tolerance, the solution is reached. Aravindhababu et al. [9] have proposed an iterative method in which the nodes voltage are assumed to be equal to the source voltage i.e., 1 p.u. They first, form the branch-to-node matrix to then calculate the branch currents and the nodes voltage. As convergence criterion, they have proposed the voltage difference of two successive iterations. Mekhamer et al. [10] have used the equations developed by Baran and Wu for each node of the feeder but with different procedures. In this method, the load flow problem is solved by considering the lateral loads as concentrated ones on the main feeder. Once the voltage of the main feeder calculated, the first node voltage of each lateral is set equal to the voltage of the same node of the main feeder. The nodes voltages of the laterals are then calculated using Baran and Wu equations. Their convergence criterion is based on active and reactive power fed through the terminal nodes of laterals and main feeder. Afsari et al. [11] also have used the Baran and Wu equations but, they initially estimate the terminal nodes voltage which they use as initial values in the backward sweep instead of flat start values of 1 p.u. Any lateral is assumed to be replaced by the total lateral load on the main feeder. The method gives both voltage rms values and phase-angles. Ranjan et al. [12] have presented a method based on the load flow algorithm developed by Das which they have modified to incorporate composite load models. Based on the backward and forward sweeps, the method assumes nodes initial

* Corresponding author. Tel.: +213 36925134.
E-mail address: a_hamouda1@yahoo.fr (A. Hamouda).

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voltage of 1 p.u. Ranjan and Das [13] used the basic principals of circuit theory and have developed an algorithm for determining the nodes after each branch. However, only the node voltage magnitudes are given on the basis of algebraic equations. As a convergence criterion, the authors have proposed the difference between the active and the reactive power at the sub-station end of two successive iterations. If this difference is less than 0.1 kW for the active power and 0.1 kVAr for the reactive power, the solution is reached. Nevertheless, almost all of these methods assume an initial voltage of 1 p.u and determination of the nodes after branches method when it exists [7,12,13,15], it is not easy to implement.

In the present paper, an efficient method for solving the load flow problem in radial distribution feeders with laterals is developed. A fast and easy to understand algorithm for determining nodes after branches is given as well as a procedure to accelerate the speed of convergence. Another plus of the method lies in the fact that in addition of evaluating the voltage rms values, it gives the phase-angles. The latter become necessary if the load flow solution is used in capacitors sizing problem. Indeed, the goal of the capacitor banks placement is the power factor and voltage improvement as well as power losses reduction. Tests are carried out on several feeders with laterals, for different load conditions and R/X ratios. The results obtained by the proposed method have been compared with those of other methods [12–17].

2. Node determination after branch

A simple numbering scheme, not required for the proposed load flow solution is used. It is applied to the example feeder given in Fig. 1. Starting with the source node as bus number 0, we number the nodes of the main feeder. The node just ahead of the source node is labelled node 1 and so on until the end-node of the main feeder (node 4). Thereafter, the nodes of the main feeder are explored for laterals. The lateral that branches out from the bus nearest to the source bus is chosen and its buses are numbered following the end-node of the main feeder (from 5 to 6 as shown in Fig. 1). Similarly, the bus numbers of the next lateral (lateral out from node 3 in Fig. 1) are numbered following the end-node of the previous lateral (7), (8) and so on until all the laterals nodes are numbered. For the branches, we give each one the same number of its receiving node. The feeder connectivity of the line example given by Fig. 1 is shown in Table 1.

The method used to determine the nodes after each branch is based on [15] but presented in a simple and easy to understand way. We first construct the branch-to-node incidence matrix IM wherein, the rows numbers identify the branches and the columns numbers, identify the nodes. The generic elements $IM(i, j)$ are assumed to have the values whose significations are given below.

$$IM(i,j) = \begin{cases} -1 \text{ if } j \text{ is the receiving end of branch } i \\ +1 \text{ if } j \text{ is the sending end of branch } i \\ 0 \quad \text{otherwise} \end{cases}$$

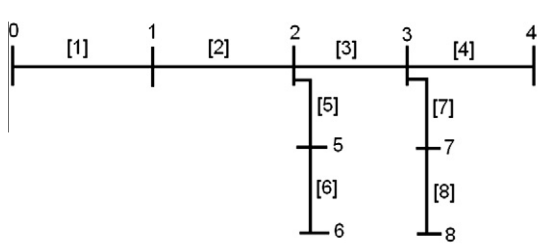

Fig. 1. Nodes and branches numbering schemes.

For the feeder of Fig. 1, the branch-to-node incidence matrix is:

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

The inverse of the branch-to-node incidence matrix gives the node-to-branch incidence matrix G. In the latter, the rows numbers are the nodes identifiers and the columns numbers identify the branches. For the feeder of Fig. 1, the node-to-branch incidence matrix G is:

$$G = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 & 0 & 1 & 0 \\ 1 & 1 & 1 & 0 & 0 & 0 & 1 & 1 \end{pmatrix}$$

For the branch 1 (column 1), the nodes which belong to it are the rows numbers corresponding to the non-zero values of the considered column i.e.: $1, 2, \ldots, 8$. For the third branch (column 3), the non-zero elements correspond to the rows number 3, 4, 7 and 8. This means that after branch 3 we count nodes 3, 4, 7 and 8.

From the node-to branch incidence matrix G, we form the matrix BR. The rows numbers of the latter are the branch numbers. For each branch "i", the non null values $BR(i, j)$, for j varying from 1 to $M(i)$, are the nodes belonging to the considered branch. $M(i)$ is the total number of the nodes after the branch "i", it allows us to avoid calculation for the $BR(i, j)$ equal to zero and thus a saving in the computational time. An $M(i)$ equal to one, means that the branch (or the node) is a terminal branch (or node). Unlike the matrix G, the matrix BR is structured in such a way that, its non-zero elements appears first in each row. No null elements come between two non-zero ones. This has the advantage of not making any test for identifying the non-zero elements of BR.

For the line example of Fig. 1, we obtain:

$$BR = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 \\ 2 & 3 & 4 & 5 & 6 & 7 & 8 & 0 \\ 3 & 4 & 7 & 8 & 0 & 0 & 0 & 0 \\ 4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 5 & 6 & 0 & 0 & 0 & 0 & 0 & 0 \\ 6 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 7 & 8 & 0 & 0 & 0 & 0 & 0 & 0 \\ 8 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

The matrix BR given above shows that for the example feeder of Fig. 1, below the branch number 3 (row 3) we find the nodes 3, 4, 7 and 8. The total number of nodes located below this branch is $M(3) = 4$. Thus, the active power fed through the receiving-end of the branch 3 will be determined by:

$$P_3 = \sum_{k=BR(3,M(3))}^{BR(3,1)} P_{\text{load}_k} + \sum_{k=BR(3;M(3))}^{BR(3,2)} \text{ploss}_k$$