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A fast and efficient load flow technique for unbalanced distribution system

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A R T I C L E I N F O

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A B S T R A C T

This paper presents a fast and efficient load flow technique for unbalanced distribution system. The proposed load flow technique is derived by promulgating the concept of conventional backward forward sweep (BFS) technique of power flow study for distribution system. The proposed technique employs a novel load-impedance matrix (LIM) to calculate the bus voltages in a single step unlike the conventional BFS approach which involves two separate steps (backward sweep and forward sweep) to perform the same and this improvement is claimed as the novelty of this work. This distinctive feature makes the proposed algorithm faster in operation. Nodal voltages, at any iteration, may be calculated, directly, from the values obtained in the previous iteration by utilizing LIM. A simple concept of set theory is adopted here to construct the LIM. Special treatments are also included in this method to analyze weakly meshed systems. The proposed technique is flexible enough to accommodate any sort of changes in the existing network topology through LIM. It is tested on different three-phase balanced and unbalanced radial distribution systems as well as weakly meshed networks for load flow study. A separate case study is also presented to check the validity of the proposed load flow technique for various transformer connections. The obtained results demonstrate the effectiveness of the proposed technique. Furthermore, performance comparison reveals that the proposed algorithm is, computationally, faster and robust than the conventional power flow techniques reported in the recent state-of-the-art literatures.

Introduction

Load flow (LF) study is one of the most important tools for power system operation and planning. The power flow study is, mainly, carried out to obtain the magnitude and the phase angle of the voltage at each load bus and the real and the reactive power flow through each line. Dunstan [1] was the first researcher to solve LF problem by utilizing a digital approach and, finally, this digital approach was, successfully, formulated by Ward and Hale in [2]. Most of these earlier techniques have utilized admittance matrix and Gauss–Seidel iterative method to get the LF solutions. The performances of these techniques have been improved further in [3,4]. Subsequently, Newton Raphson (NR) [5], decoupled [6] and fast decoupled [7] methods were developed to analyze the power system networks. Though NR method takes comparatively more time than the others for each iteration, it is found that NR method exhibits faster convergence characteristics.

These developed methods are very much efficient in transmission and sub-transmission lines but most of them fail, grossly, in case of distribution system due to the presence of the following differences between the distribution and the transmission system.

(a) Unlike the transmission system (which is tightly meshed), distribution system is, generally, radial in nature and sometimes weakly meshed in structure.
(b) R/X ratio is higher in case of distribution system.
(c) Unlike transmission system, the loadings in the phases are not same or, in other words, the system is unbalanced.
(d) Mutual impedances between the phases cannot be avoided as transposition in distribution system is done very rarely.

In view of the above, it is very much clear to the power system researchers that the distribution system has to be handled in a different way. And, as a consequence of continuous research efforts initiated by the previous researchers for many years, numerous LF techniques are now available in the literature to analyze the distribution system. These reported methods can be, broadly, classified into two categories. The methods, belonging to the first

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category, are formulated by incorporating necessary modifications in NR, Gauss Seidal and other existing methods [8–12] of the LF techniques, belonging to the second category, are based on backward forward sweep (BFS) concept [13–35]. The second category can be also divided into two sub-categories. In the first sub-category, BFS concept is implemented by utilizing basic KCL–KVL equations [13–30] and the approaches under the second sub-category are formulated by utilizing bi-quadratic equations [31–35]. Zhang and Chen [8] have developed a LF technique for distribution system which is based on Newton method. Specialty of this method is that Jacobian is to be computed just once but the converging speed of this approach is lower. This problem of lower convergence speed has been overcome by Da Costa et al. in [9]. They have modified NR power flow formulation based on the current injection method which exhibits higher converging speed. In the distribution LF techniques, mentioned in [13–30], KCL and KVL have been employed to get the LF solution in backward-forward process. In [13], Shirmohammadi et al. have formulated a compensation-based LF method to analyze the radial as well as the weakly meshed distribution and transmission system by utilizing multiport compensation technique. The radial part is solved here in two steps. In the first step, branch currents are calculated and nodal voltages are updated in the second step with these calculated values of branch currents. This method was applied in unbalanced real-time distribution system in [14]. The same approach, with some modifications, has been used in [15–18] to solve the balanced and the unbalanced radial distribution system (RDS). In [15], the radial part is solved by calculating the branch currents in backward sweep and nodal voltages are updated in the forward path. LF method, described in [16], has been formulated in a slightly different way. The branch currents, in this approach, have been calculated by utilizing the receiving node voltage and flow of power has been calculated in backward sweep instead of simply applying KCL to the load current. The same concept has been utilized in [17]. In [18], the impact of various types of loads has been analyzed and maximum voltage mismatch has been considered as the termination criteria in the successive iterations. An extension of the popular BFS approach may be found in [19–20] where loop based analysis is adopted to formulate the distribution system LF (DSLF) study. A new backward sweep method, to analyze radial as well as weakly meshed distribution system, has been reported in [21]. This method is named as backward due to the involvement of some unique equations. Another robust LF solution (LFS) technique has been reported in [22] to analyze heavily meshed distribution system. A new load stepping technique has been introduced here to deal with the convergence problem at higher degree of loading. A novel and fast LF algorithm is reported in [23] to analyze multi-phase RDS. This technique utilizes branch voltages as state variables and employs NR algorithm to get the LF solutions. A direct approach to analyze the radial as well as the weakly meshed system may be found in [24]. This technique is based upon two matrices, namely, branch current to bus voltage matrix and bus injection to branch current matrix. While executing this algorithm, these two matrices are formed first and are multiplied to get the LFS directly in the later stage. A new DSLF technique, based on branch impedance matrix (Z_{BR}), has been presented in [25]. In this developed method, the basic concept of graph theory has been utilized to construct the branch path incident matrix and, finally, Z_{BR} algorithm is employed to get the LFSs for three-phase unbalanced RDS. Another efficient DSLF approach has been reported in [26] that exploits the essence of radial structure of distribution systems. This approach carries out backward forward iterative steps by utilizing a radial configuration matrix. A generalized single-equation based LF technique may be found in [27], which is applicable for unbalanced distribution system. The formulation of this technique is based on the impedance matrix and the nodal current injections. The modeling of various system components (such as voltage regulator and transformer) have been also presented in this work. Another improved LFS technique for RDS has been reported by Singh and Ghose in [28]. A special matrix transformation scheme is introduced in this work to calculate the branch current directly and, as a consequence of this direct calculation, the overall algorithm has become faster. An efficient technique has been presented by Kocar et al. in [29] to obtain LFS of three-phase unbalanced distribution network. A modified augmented nodal analysis has been introduced in this LF formulation. Most recently, a novel zooming algorithm is reported in [30] to analyze the radial distribution system. This algorithm is capable to provide LFS for a specific area of interest in the distribution system.

LF techniques, reported in [31–35], are formulated by utilizing bi-quadratic equations. These techniques relate the receiving node voltage and the branch LF with the sending node voltage. In [31], Cespedes has presented a new LF technique in which branch currents are calculated in the backward sweep and nodal voltages are updated in the forward path. Haque [32] has formulated a LF method which is based on bi-quadratic equation and the impacts of voltage dependent loads have been considered in this work. This method has been extended in [33] to solve the radial as well as the weakly meshed network and, with further modifications, more than one generator has been considered in [34]. In [35], Eminoglu and Hocaoglu have presented a LF technique that utilizes a bi-quadratic equation to calculate nodal voltages in forward sweep and uses a voltage ratio to adjust the nodal voltage. The impact of voltage dependent loads on convergence speed has been also included in [35] and maximum nodal voltage mismatch has been considered as convergence criteria.

It is revealed from the literature survey that most of the reported DSLF techniques are, predominantly, based on BFS concept. In this light, a fast and efficient LF technique (based on BFS concept) is presented in this paper. The proposed technique of the present work uses a unique matrix formulation to carry out the load flow analysis. Utilizing this novel matrix formulation of the present work, the bus voltages of the distribution test feeder may be calculated in a single step unlike the conventional BFS approach which uses two separate steps (backward sweep and forward sweep) to calculate the bus voltages and this proposed improvement is the claimed novelty of this work. As this proposed matrix may be constructed using the values of load demands and the impedances of the branches of the test feeder, it is named as load-impedance matrix (LIM). It is worth to note that the proposed load flow technique is derived by promulgating the concept of BFS approach, however, this technique cannot be categorized as BFS approach as it is single step analytical method. This single step operation (using LIM) makes the proposed algorithm faster in execution. A simple concept of set theory is employed to construct the LIM. Special treatments for weakly meshed systems are also included in this work. It is tested on several test systems (*viz*. 28- and 69-bus balanced RDS, 10- and 15-bus unbalanced RDS, IEEE 123-bus system, IEEE 37-bus system and 33-bus weakly meshed system) and the obtained results demonstrate the effectiveness of the proposed approach while comparing those with the existing methodologies. A separate case study is also presented to check the validity of the proposed load flow technique for various connections of the distribution transformers. Furthermore, it is going to reveal that the proposed algorithm is, computationally, faster and robust than the conventional BFS technique, available in the literature.

The rest of the paper is organized as follows. The next section models the three-phase line. LF problem is formulated in Section 'LF problem formulation'. Section 'Modifications in LIM' focuses on the modifications done in LIM. Obtained results are presented and