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Line independency-based network modelling for backward/forward load flow analysis of electrical power distribution systems

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Abstract: In this paper a straightforward method for line independency-based modelling of electrical power distribution systems is proposed. The proposed method can determine the backward and forward sweeping routes of distribution systems for calculating line currents and bus voltages. To do that, the method identifies the independent lines in consecutive steps. An independent line is a line in the distribution system whose current does not depend on the current of other lines in the system. The proposed line independency-based network modelling is required to be performed only once and prior to the load flow analysis. The output of the proposed method, which is suitable for backward/forward load flow analysis, includes matrices which determine the steps, the order of lines, and the start and end points in the system for hierarchical calculation of currents and voltages. In this paper, the forward/backward approach is used as the load-flow algorithm since it is suitable for radial distribution systems with unbalanced loads. The proposed methodology is applied on two IEEE distribution systems and the results show its efficiency in load flow analysis.

Key words: Distribution system, backward/forward load flow, network modelling, independent lines

1. Introduction

The evolution of distribution systems toward smart grids has attracted a lot of attention due to the advantages of smart grids compared to conventional distribution systems. Smart grids are capable of increasing the flexibility and reliability of distribution systems, optimize the utilization of equipment and also make use of alternative clean and sustainable energy sources in distribution systems[1].

The implementation of smart grid technologies requires the integration of systems controlling the network components with communications infrastructure and also with sensors and smart metering devices. However, to achieve this integration, utilities need the rapid and accurate load flow analysis for distribution systems. In a smart grid, the results of load flow analysis are then used for monitoring and controlling components of the distribution system.

So far, many methods have been presented to solve the load flow problem in distribution systems. An effective method for load flow analysis of distribution systems should be able to solve the problem for networks with thousands of buses and different voltage levels even in meshed or radial topology. Generally, in the literature the load flow approaches can be classified into four categories, the Gauss–Seidel-based methods, Newton–Raphson-based methods, direct methods, and forward/backward sweeping-based methods.

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The Gauss–Seidel method, placed in the first category, was one of the first methods presented to solve the load flow problem for three-phase unbalanced distribution systems [2, 3]. However, this method may not converge for radial distribution or weakly meshed systems, or for systems with high R/X ratio. The studies in the second category solve the load flow problem using an iterative-based approach called the Newton–Raphson method [4]. However, the shortcoming of these methods is that they cannot converge for distribution systems with unbalanced weak radial structure [5, 6]. Authors in [7, 8] presented a methodology similar to the Newton–Raphson method to solve the load flow problem which is also called as current injection method. In this method, the Newton–Raphson approach is used for solving the equations of three-phase current injections, which has made it more complex than other methods. However, this method is effective for systems with strongly meshed and with a lot of control devices.

The third category includes methods that use a direction approach for performing power flow analysis of distribution systems. For example, in [9], a load flow algorithm for unbalanced distribution systems was presented, which includes the formation of two matrices namely bus-injection to branch-current (BIBC) matrix and branch-current to bus-voltage (BCBV) matrix. In this algorithm, the distribution load flow (DLF) matrix is obtained by multiplying these two matrices. A similar method is also proposed in [10] for balanced distribution systems. In [11], an algorithm for radial systems with weakly meshed structure has been developed in which the BIBC and BCBV matrices have been improved. In [12], a new load flow method is presented for smart grid, which is based on the methodology presented in [11]. In this method, to reduce the number of buses and in turn the load flow solution time, a technique is presented in which instead of considering complete distribution system, the load flow is performed only on the part of system determined by user.

The fourth category of methods for solving the load flow problem in distribution systems includes methods that use forward and backward sweeping (FBS) of the system and are based on Kirchhoff's laws [13–15] or make use of biquadratic equations [16–20]. In the backward sweeping of the distribution system the currents of lines are calculated starting from the far line to the line which is connected to the root bus. Inversely, in forward sweeping the voltage of buses are calculated started from the bus connected to the root bus to the end buses. Although the FBS method is used for solving radial or weakly meshed systems [14], it suffers from problems in meshed systems or systems with control devices. Therefore, solutions for overcoming these weaknesses have been suggested and have resulted in improvements in the FBS algorithm [21–25]. A load current injection-based load flow technique is presented in [26], in which a single load current to bus voltage matrix is used to perform both the backward and the forward sweeps of power flow calculation in a single step. The issue of solving power flow problem for islanded AC microgrids is also considered in [27]. To do that, the authors have reformulated the load flow problem such that the system frequency is one of the system's unknown variables which are typical for an islanded network justifying further the absence of a slack bus. In [28], a matrix transformation technique is used, which directly solves the determination of branch flows in radial distribution networks. Therefore, it makes FBS-based load flow method more effective and fast.

In this paper, a new method for modelling distribution systems is proposed. The proposed method can be used for power flow analysis algorithms, which use the backward and forward sweepings for calculating line currents and voltages of buses. In fact, by using this method it will be possible to automatically determine the routes for backward and forward sweeping of the distribution system required for calculating currents and voltages, respectively. To do that, the proposed method uses the concept of independent lines to sort the lines of the system in consecutive steps. The proposed method for network modelling is very fast. Moreover, the method is independent of the load flow algorithm and therefore it is needed to be performed once and in advanced to the load flow algorithm.

The rest of the paper is organized as follows. In Section 2, a brief description of load flow method used in this paper is provided. In Section 3, the proposed network modelling algorithm is presented. Section 4 is dedicated to demonstrate the validation of the proposed methodology, and finally conclusions are provided in Section 5.

2. Load flow analysis theory

In this paper, the method presented by Shirmohammadi et al. [13] is used for load flow analysis. In this method, which is called the FBS method, current and voltage phasors are calculated by backward and forward sweeping of the network. By direct use of KCL, the current of line L at iteration k can be obtained as follows.

$$I_L^K = I_{LD}^K + \sum_{j=1}^{N_L^{LD}} I_j^K, L = 1, 2, ..., N_L^T, \tag{1}$$

where I_L^K and I_{LD}^K are the currents of line L and the current of the load connected to the end bus of line L, respectively. N_L^T and N_L^{LD} are the total number of lines in the system and the number of lines emanating from the end bus of line L, respectively. In fact, (1) shows that the current of each line is the sum of all currents of lines emanated from the end bus and the current of the load connected to the end bus of the line. Note that for a line in the distribution system the end bus is the one that is farthest from the root bus of the system. Load current of each bus can easily be calculated using the voltage values obtained at iteration k − 1, according to (2):

$$I_{LD,i}^K = (\frac{S_i}{V_i^{K-1}})^* - Y_i V_i^{K-1}. \tag{2}$$

In (2), $I_{LD,i}^K$ is the current of load at bus i, S_i and V_i are the power injection and voltage of bus i, and Y_i is the sum of all shunt admittances connected to bus i.

After calculating line currents using backward sweeping of the system, bus voltages can be obtained using (3):

$$V_{L1}^K = V_{L2}^K - Z_L I_L^K. \tag{3}$$

According to (1), for the calculation of the current of each line, the lines emanating from this line is needed. On the other hand, the line currents are interrelated to each other in a hierarchical manner. Hence, to calculate the line currents and bus voltages, one should know these relationships to determine the start and end points for the backward and forward sweeping of the system. Therefore, it is necessary to use a straightforward algorithm for sorting the lines and buses in ascending and descending orders to be used in load flow analysis. In the next section, an algorithm will be proposed to model the distribution networks, which uses the dependency of line currents.

3. Line independency-based network modelling algorithm

In this paper, IEEE 13 bus system [29] shown in Figure 1 is used for the illustration of the proposed line independency-based network modelling (LINM) algorithm. The basis of the proposed LINM algorithm is the hierarchical calculation of line currents. To do that, the algorithm calculates the current phasor of independent lines and then virtually removes these lines in each consecutive step, until no further independent line can be found in the system. An independent line is a line in the distribution system whose current does not depend on the current of other lines in the system. In fact, these lines are the lines that no line is connected to their end bus. For example, in Figure 1, lines $L_1 - L_6$ are the independent lines.

The process of hierarchical calculation of the line currents for the IEEE 13-bus system is shown in Figures 2a–2d. As shown in these figures, the currents of all lines are calculated in four steps. In each step, the independent lines, whose currents are to be calculated, are determined with thick lines and an arrow in Figures 2a–2d. Furthermore, those lines whose currents are calculated in previous steps are drawn with dash lines. For example, in the second step shown in Figure 2b, lines $L_7 - L_{10}$ are the independent lines, whose currents are to be calculated in this step, whereas the currents of lines $L_1 - L_6$ have been calculated in step 1.

In fact, the lines that are virtually removed at every step are related to those lines that have been removed in their previous step. Therefore, this fact can be the basis for the backward process of calculating line currents, and the forward process of calculating voltages of buses. This means that by calculating the current of lines removed in the first step, the current of the independent lines determined in the second step can be obtained and in the same way the current of other lines is calculated in the third and fourth steps. Moreover, given the voltage of the source bus and starting from the fourth step, it is possible to calculate the voltage phasor of other buses in a forward manner using (3).

In the proposed method, in order to model the steps shown in Figures 2a–2d, segment data (SD) matrix is used. SD matrix of the example system shown in Figure 1 is given in (4):

$$\mathbf{SD} = \begin{pmatrix} 632 & 645 & 500 & 603 \\ 632 & 633 & 500 & 602 \\ 633 & 634 & 0 & T \\ 645 & 646 & 300 & 603 \\ 650 & 632 & 2000 & 601 \\ 684 & 652 & 800 & 607 \\ 632 & 671 & 2000 & 601 \\ 671 & 684 & 300 & 604 \\ 671 & 680 & 1000 & 601 \\ 671 & 692 & 0 & S \\ 684 & 611 & 300 & 605 \\ 692 & 675 & 500 & 606 \end{pmatrix}. \tag{4}$$

In (4), the first and second columns include the "from buses" and "to buses" of each line, respectively. Furthermore, the third and fourth columns correspond to the length of each line and their configuration of the phases respectively. Therefore, SD is a matrix with dimensions $NL \times 4$ where NL is the number of lines in the system.

The SD matrix is the basis for the proposed line independency-based network modelling algorithm. In this algorithm the SD matrix is taken as the input for finding the independent lines. The algorithm searches for independent lines by evaluating all network lines (rows of SD matrix) individually. To do that, the algorithm starts with the first line of SD matrix and searches in the first column to find if there is any line that its "from bus" is the same as the "to bus" (or end bus) of the first row. If so, the first line, which corresponds to the first row, is not an independent line and must remain in the SD matrix. Otherwise, this line is an independent one (in terms of the forward sweeping for line currents calculation) and is moved to the new matrix called independent segment data (ISD). In each step, this procedure is repeated for all rows of SD matrix. For

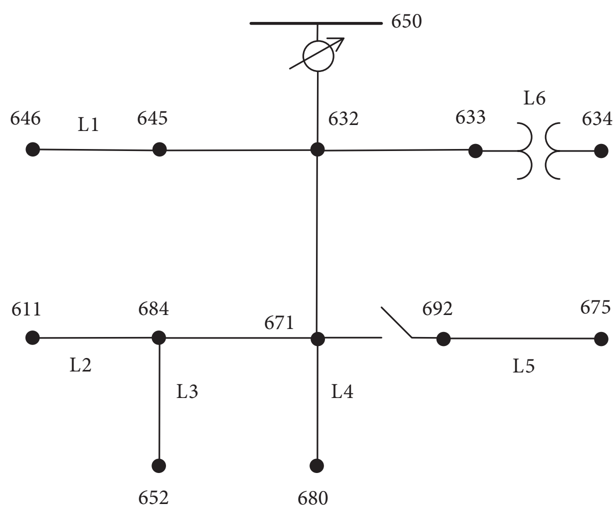


Figure 1. Line diagram of IEEE 13-bus system.

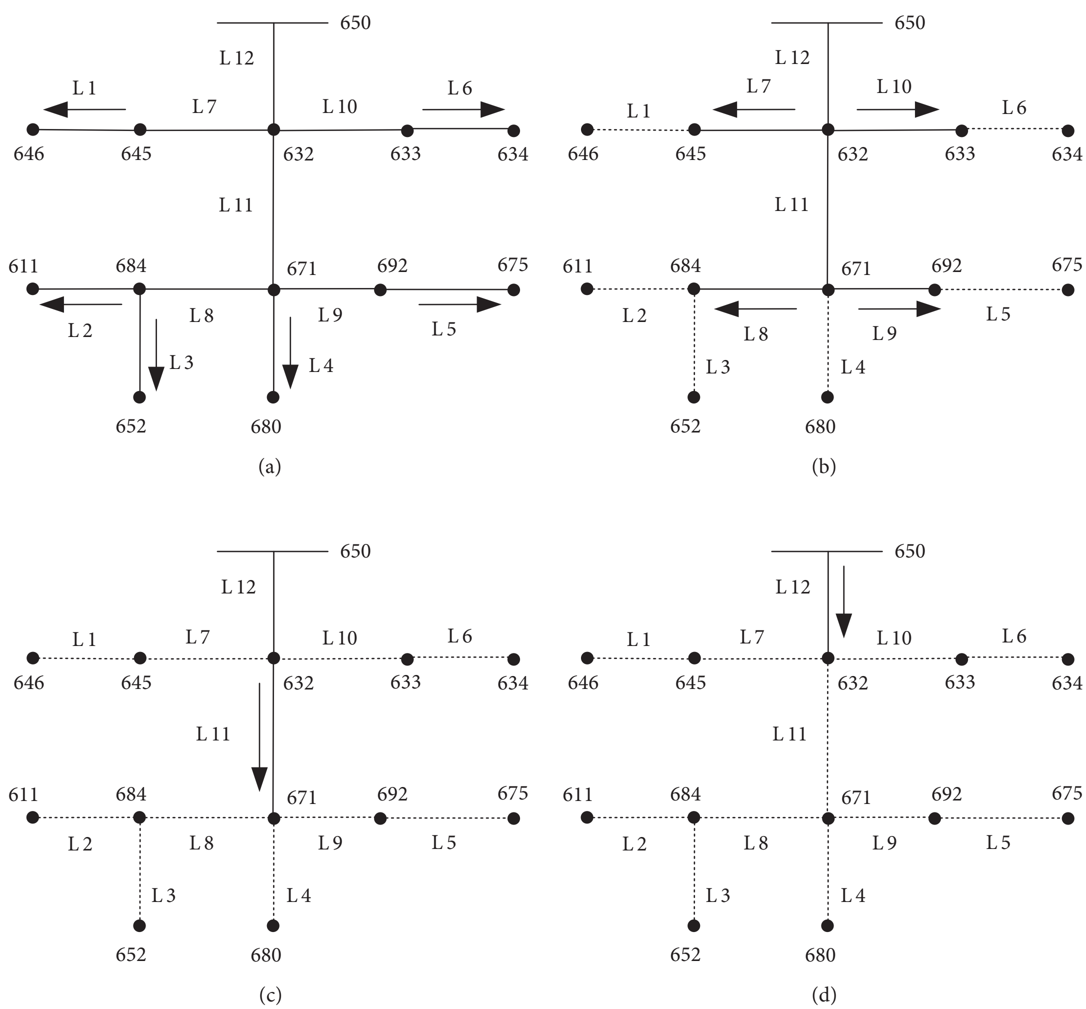


Figure 2. The process of identification of independent lines for the IEEE 13-bus system; (a) step 1, (b) step 2, (c) step 3, and (d) step 4.

example, considering the SD matrix in (4), the ISD matrix and the reduced SD matrix obtained after the first step of LINM algorithm, are as follows.

$$\mathbf{SD(reduced)} = \begin{pmatrix} 632 & 645 & 500 & 603 \\ 632 & 633 & 500 & 602 \\ 650 & 632 & 2000 & 601 \\ 632 & 671 & 2000 & 601 \\ 671 & 684 & 300 & 604 \\ 671 & 692 & 0 & S \end{pmatrix} \tag{5}$$

$$\mathbf{ISD} = \begin{pmatrix} 633 & 634 & 0 & T \\ 645 & 646 & 300 & 603 \\ 684 & 652 & 800 & 607 \\ 671 & 680 & 1000 & 601 \\ 684 & 611 & 300 & 605 \\ 692 & 675 & 500 & 606 \end{pmatrix} \tag{6}$$

By continuing the above process for the new SD matrix in consecutive steps, finally all lines are moved to the ISD matrix. However, it should be noted that in each step, the rows corresponding to the new identified independent lines have to be added at the bottom of the previous ISD matrix. The final ISD matrix of the example system in (4), which is obtained after four steps of the LINM algorithm, is as follows:

$$\mathbf{ISD} = \begin{pmatrix} 633 & 634 & 0 & T \\ 645 & 646 & 300 & 603 \\ 684 & 652 & 800 & 607 \\ 671 & 680 & 1000 & 601 \\ 684 & 611 & 300 & 605 \\ 692 & 675 & 500 & 606 \\ 632 & 645 & 500 & 603 \\ 632 & 633 & 500 & 602 \\ 671 & 684 & 300 & 604 \\ 671 & 692 & 0 & S \\ 632 & 671 & 2000 & 601 \\ 650 & 632 & 2000 & 601 \end{pmatrix} \tag{7}$$

As it is clear from the ISD matrix in (7), lines are sorted in a way that they are interrelated to each other in terms of their current values from top to bottom, and also in terms of voltage relationships from bottom to top. Therefore, this matrix can be used as the basis for the forward/backward load flow algorithm.

After completing the formation of ISD matrix, the dependency matrix has to be constructed. Dependency matrix is a matrix with dimensions $NL \times NL$ in which the sum of elements in each row indicates the number of lines that are connected to the end bus of the corresponding line in ISD matrix. In dependency matrix, the element D (i,j) is equal to one if the jth line in ISD is connected to the end bus of ith line; otherwise, this element will be zero. For the ISD matrix in (7) corresponds to the example IEEE 13-bus system, the dependency matrix will be obtained as follows. Note that the row and column labels in (8) correspond to the branch labels in

Figures 2a–2d.

$$\mathbf{D} = \begin{array}{c} \\ L_6 \\ L_1 \\ L_3 \\ L_4 \\ L_2 \\ L_5 \\ L_7 \\ L_{10} \\ L_8 \\ L_9 \\ L_{11} \\ L_{12} \end{array} \begin{array}{c} \begin{array}{cccccccccccc} L_6 & L_1 & L_3 & L_4 & L_2 & L_5 & L_7 & L_{10} & L_8 & L_9 & L_{11} & L_{12} \end{array} \\ \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 1 & 0 \end{pmatrix} \end{array} \tag{8}$$

Dependency matrix is used to store the hierarchical relation of lines of the system, which is then used for backward and forward sweeping of lines to calculate line currents and bus voltages. This means that to calculate the current of ith line, it is required to calculate the currents of lines determined by unity values in the ith row of dependency matrix. Therefore, by constructing dependency matrix, the current of ith line is obtained by using (9):

$$I_{Line}(i) = I_{Load}(i) + \sum_{j=1}^{i-1} D(i,j) \times I_{Line}(j), \tag{9}$$

where $I_{Line}(i)$ and $I_{Load}(i)$ are the currents of ith line and the load connected at the end of ith line, respectively. D(i,j) is also the element of dependency matrix in row i and column j. Using (9), first, the currents of first 6 lines, which correspond to the first 6 rows of the ISD matrix in (7), are calculated. These 6 lines are those that were identified as independent lines in the first step of the algorithm shown in Figure 2a. Then the current of next 4 lines are calculated. In the third step, the current of line L11, and in the final step the current of line L12 is calculated.

The flowchart of the proposed LINM algorithm is illustrated in Figure 3. The ISD matrix along with the dependency matrix determines the sequence of lines in the process of backward and forward sweeping for calculating the line currents and bus voltages. In the load flow algorithm, in order to calculate the line currents using the bus voltages calculated in the last iteration, the algorithm starts with the first row of dependency matrix and then moves to the bottom of the matrix. On the other hand, for calculating the bus voltages using the line currents calculated in the last iteration, the algorithm will start with the last row of ISD matrix and then moves to the top of matrix. Therefore, the main load flow algorithm makes use of the order of rows of ISD and dependency matrices as well as the information provided in each row of them to solve the load flow problem faster.

The flowchart of the FBS algorithm for load flow analysis using the ISD matrix is shown in Figure 4. It can be seen that the process of line independency-based network modelling (grey block in Figure 4) is independent of the load flow algorithm and is calculated once and in advance. After setting the initial values for the voltages of buses, the currents of lines are calculated by backward sweeping of the distribution system starting from the

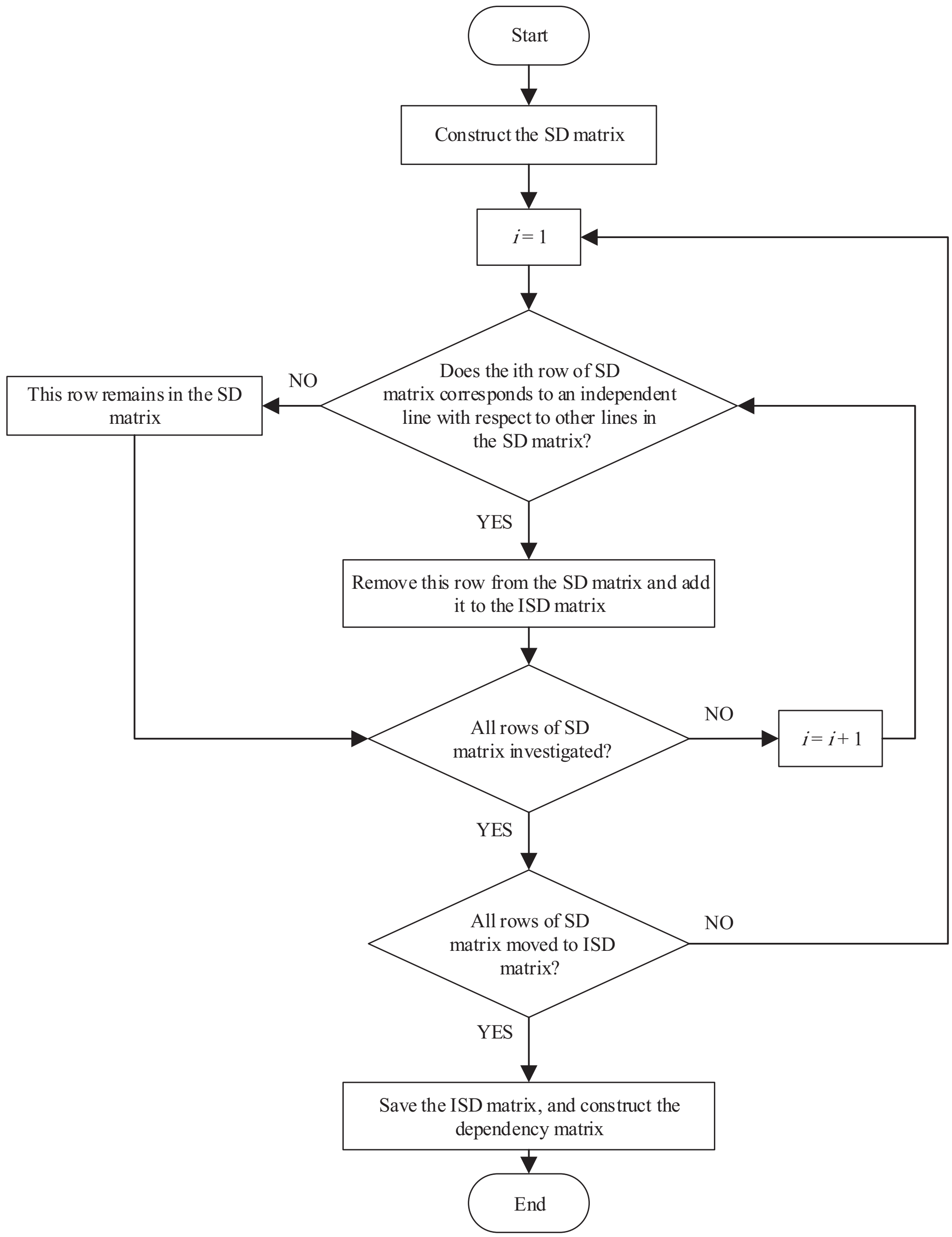


Figure 3. The flowchart of proposed line independency-based network modeling algorithm.

end lines of the system to the line connected to the root bus (or in other words it starts from the first row to the end row of dependency matrix). To calculate the current of line i, (9) will be used, which needs the values of first till (i - 1)th elements from the ith row of dependency matrix. When all line currents are calculated, in contrast to the backward sweeping, the forward sweeping is initiated to calculate the voltage of buses. At this level, the information in ISD matrix related to the configuration of phases of lines will be used for calculating voltages. The algorithm will stop when the difference between the voltage values of all buses calculated in two consecutive iterations becomes less than a predefined threshold. Note that the elements in ISD and dependency matrices do not change during the load flow analysis process shown in Figure 4, and the only updating happens for the currents of lines and voltage of buses until the algorithm is stopped. The voltage difference of each bus is obtained as follows:

$$\Delta V_j^K = V_j^K - V_j^{K-1}, j = 1, 2, ..., N_B. \tag{10}$$

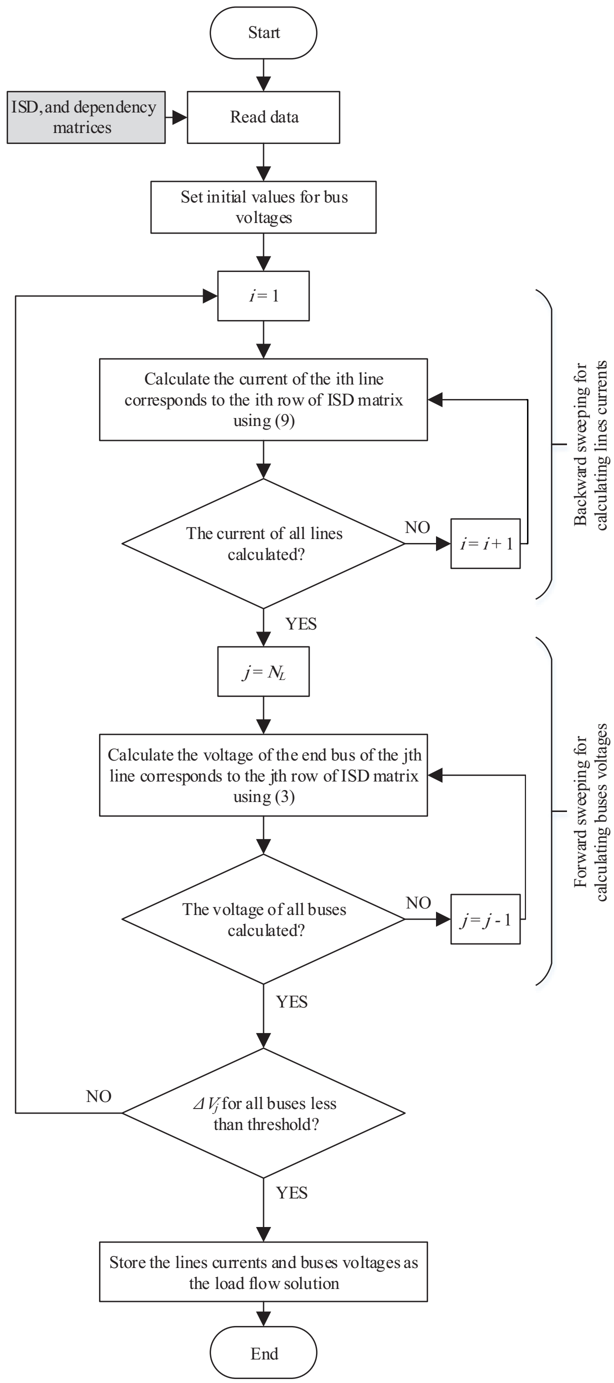


Figure 4. Load flow algorithm using the ISD matrix.

4. Simulation and results

In this paper, the accuracy of the proposed methodology is evaluated by applying it on the IEEE 37-bus and IEEE 123-bus distribution systems. The details of these systems, which are shown in Figures 5 and 6, are provided in Table 1. Note that the end lines in the fourth column of Table 1 correspond to the lines the currents of which are to be calculated in the first step of the proposed algorithm. It should also be noted that all simulations are performed by programming in MATLAB environment and on a laptop with Intel Core i5 CPU and 4GB RAM.

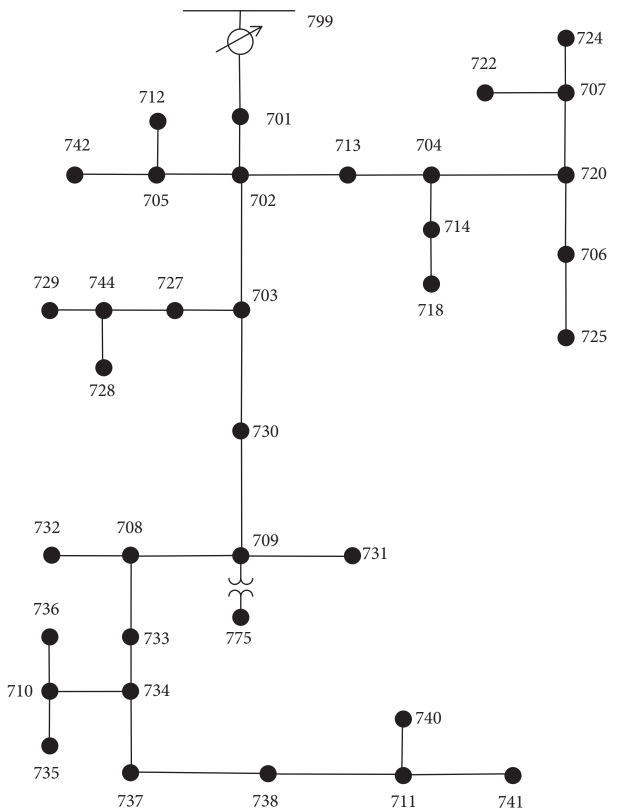


Figure 5. Line diagram of IEEE 37-bus distribution system.

Table 1. Details of test systems.

System	No. of buses	No. of lines	No. of end lines
37-bus	37	36	15
123-bus	123	122	41

The results of applying the proposed methodology for modelling the test distribution systems are detailed in Table 2. As can be seen, the IEEE 37-bus and the IEEE 123-bus systems are modelled in 12 and 22 steps, respectively. This table shows the number of lines identified as the independent lines in each step (No. of lines calculated in the table). Furthermore, all the lines calculated in a specific step have to be virtually removed in the next step. Therefore, the number of calculated lines in a step and the number of virtually removed lines in the next step are the same.

Table 2. Details of applying the proposed method.

Step No.	IEEE 37-bus		IEEE 123-bus	
	No. of lines removed	No. of lines calculated	No. of lines removed	No. of lines calculated
1	-	15	-	41
2	15	7	41	22
3	7	3	22	15
4	3	2	15	8
5	2	2	8	6
6	2	1	6	5
7	1	1	5	4
8	1	1	4	3
9	1	1	3	3
10	1	1	3	2
11	1	1	2	2
12	1	1	2	1
13	-	-	1	1
14	-	-	1	1
15	-	-	1	1
16	-	-	1	1
17	-	-	1	1
18	-	-	1	1
19	-	-	1	1
20	-	-	1	1
21	-	-	1	1
22	-	-	1	1

Table 3. The order of lines obtained by the proposed method for IEEE 37-bus system.

Step	Lines (total)
1	{705-742}, {705-712}, {706-725}, {707-724}, {707-722}, {708-732}, {709-731}, {710-735}, {710-736}, {711-741}, {711-740}, {714-718}, {744-728}, {744-729}, {709-775}
2	{702-705}, {704-714}, {720-707}, {720-706}, {727-744}, {734-710}, {738-711}
3	{703-727}, {704-720}, {737-738}
4	{713-704}, {734-737}
5	{702-713}, {733-734}
6	{708-733}
7	{709-708}
8	{730-709}
9	{703-730}
10	{702-703}
11	{701-702}
12	{799-701}

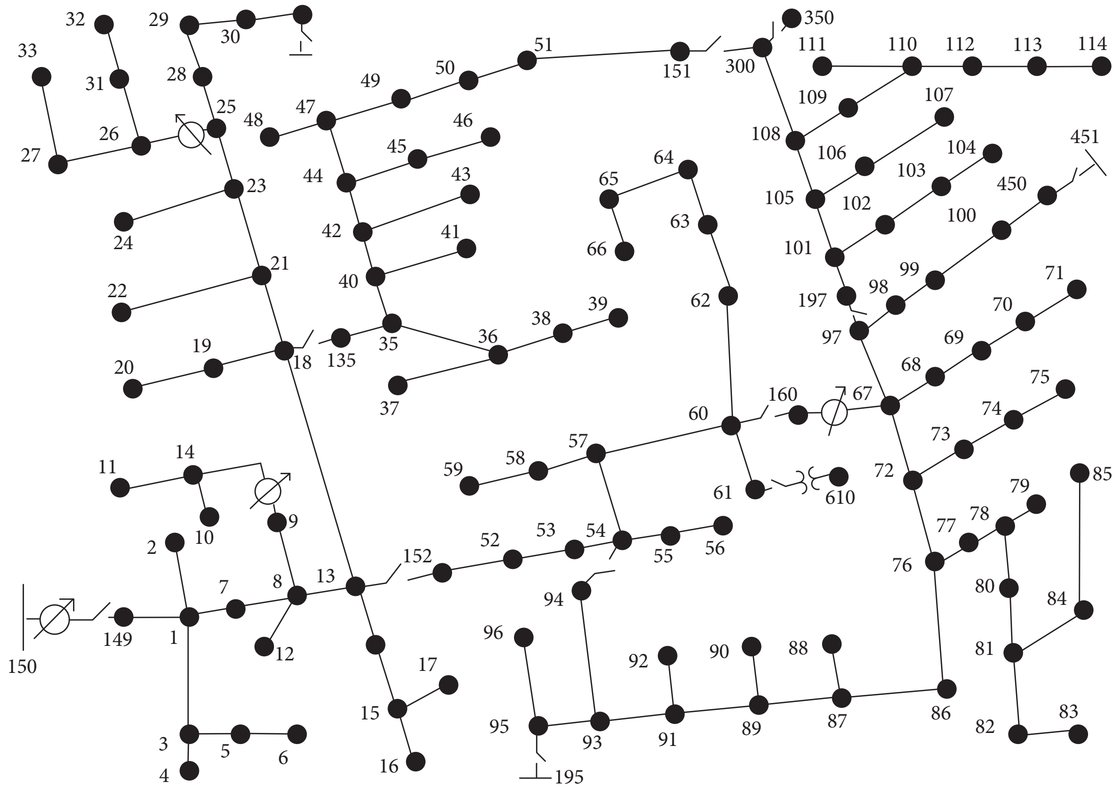


Figure 6. Line diagram of IEEE 123-bus distribution system.

Tables 3 and 4 show the order of lines obtained by the proposed method for IEEE 37-bus and IEEE 123-bus systems, respectively. Note that the ISD matrices corresponding to these test systems are not shown in this section due to their high dimensions. Instead, Tables 3 and 4 are used here. In both tables, lines are sorted from top to down in the second column and from left to right in each row. These orders of lines are to be used for calculating line currents in the backward sweeping of the system. In order to calculate the voltages of buses, one should use the order inversely. As it can be seen, for IEEE 37-bus system, first the current of line between buses 705 and 742 should be calculated. The second line whose current is to be calculated is the line connecting buses 705 and 712. Finally, the line connecting the root bus (bus 799) to bus 701 is calculated. After all line currents are calculated, the process of calculating bus voltages is initiated by forward sweeping of the system starting from the bus nearest to the root node (the last row of Tables 3 and 4). The first bus whose voltage has to be calculated is the end bus of the line, which is placed at the end of order obtained by the proposed method. For the IEEE 37-bus system, first the voltage of bus 701 should be calculated. Then, given the impedance and configuration of line connecting buses 701 and 702, knowing the voltage of bus 701 and the line current, the voltage of bus 702 is calculated. This process continues till the voltages of all buses are calculated. Here, the last bus will be bus 742 which is the end bus of the first line in the order.

In this paper, the forward/backward load flow algorithm shown in Figure 4 is also applied on the test distribution systems. Figures 7 and 8 show the results of load flow on the 37-bus and 123-bus (for ta set of selected nodes) systems, respectively. Also, the voltage values obtained in consecutive iterations for the selected nodes of IEEE 37-bus and IEEE 123-bus systems are shown in Figures 9a and 9b respectively. This figure show that voltage values have been converged in 3 iterations which means that the overall algorithm is very fast.

Table 4. The order of lines obtained by the proposed method for IEEE 123-bus system.

Step	Lines (total)
1	{1-2},{3-4},{5-6},{8-12},{14-11},{14-10},{15-16},{15-17},{19-20},{21-22},{23-24},{27-33}, {30-250},{31-32},{36-37},{38-39},{40-41},{42-43},{45-46},{47-48},{51-151},{55-56},{58-59}, {60-61},{65-66},{70-71},{74-75},{78-79},{82-83},{84-85},{87-88},{89-90},{91-92},{93-94},{95-96}, {100-450},{103-104},{106-107},{108-300},{110-111},{113-114}
2	{3-5},{9-14},{18-19},{26-27},{26-31},{29-30},{34-15},{36-38},{44-45},{50-51},{54-55},{57-58}, {64-65},{69-70},{73-74},{81-82},{81-84},{93-95},{99-100},{102-103},{105-106},{112-113}
3	{1-3},{8-9},{13-34},{25-26},{28-29},{35-36},{49-50},{63-64},{68-69},{72-73},{80-81},{91-93}, {98-99},{101-102},{110-112}
4	{25-28},{47-49},{62-63},{67-68},{78-80},{89-91},{97-98},{109-110}
5	{23-25},{44-47},{60-62},{77-78},{87-89},{108-109}
6	{21-23},{42-44},{76-77},{86-87},{105-108}
7	{18-21},{40-42},{76-86},{101-105}
8	{35-40},{72-76},{197-101}
9	{67-72},{135-35},{97-197}
10	{67-97},{18-135}
11	{13-18},{160-67}
12	{60-160}
13	{57-60}
14	{54-57}
15	{53-54}
16	{52-53}
17	{152-52}
18	{13-152}
19	{8-13}
20	{7-8}
21	{1-7}
22	{149-1}

Table 5. Results of load flow analysis in terms of solving time.

Test system	DLF solution time (ms)			
	Proposed method	Reference [11]	Reference [14]	Reference [30]
IEEE 37-bus	2.16	2.29	4.79	5.98
IEEE 123-bus	6.31	22.20	25.19	219.26

The solving time of load flow algorithm used in this paper and the results obtained by [11], [14], and [30] are provided in Tables 5 for comparison. Note that the solving times in this table includes the associated load flow algorithm and its requirements. For example, for the proposed method, the solving time obtained for IEEE 37-bus system includes the overall time spent for obtaining ISD and dependency matrices and then calculating

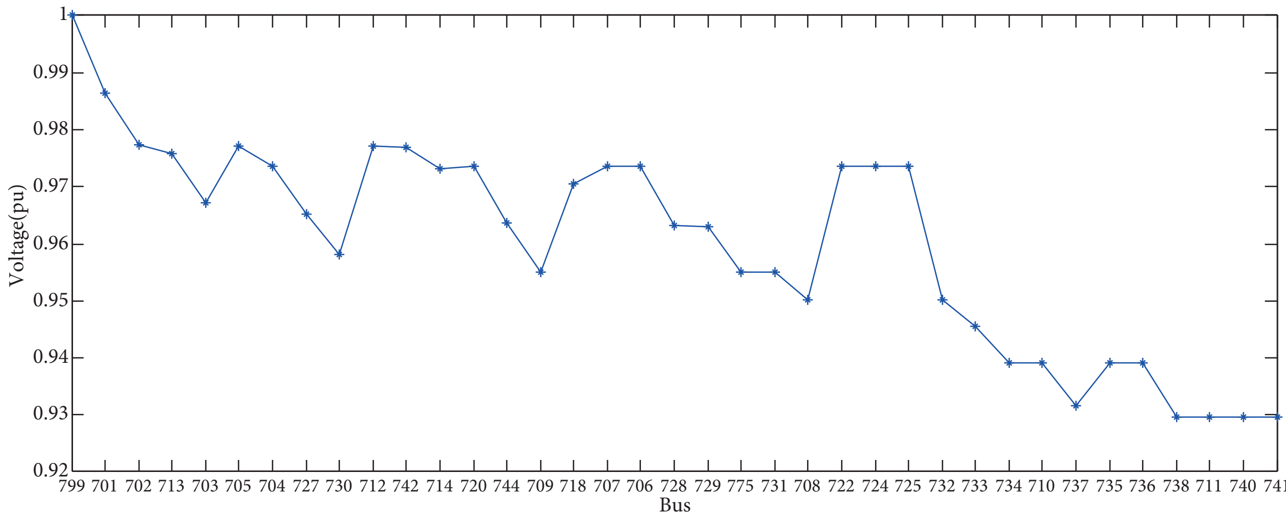


Figure 7. Load flow results of IEEE 37-bus system.

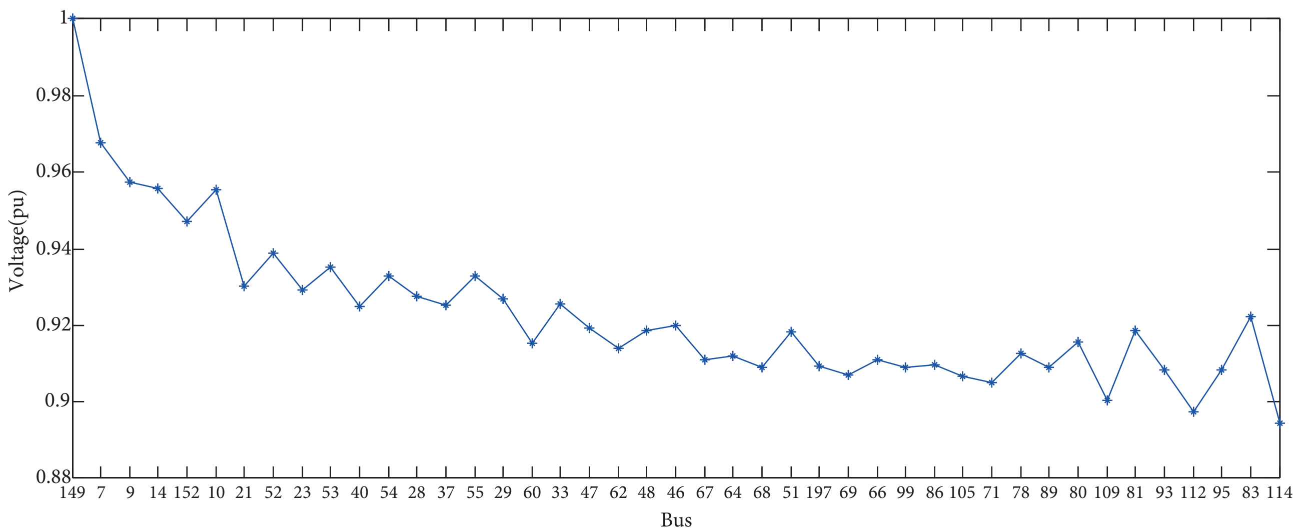
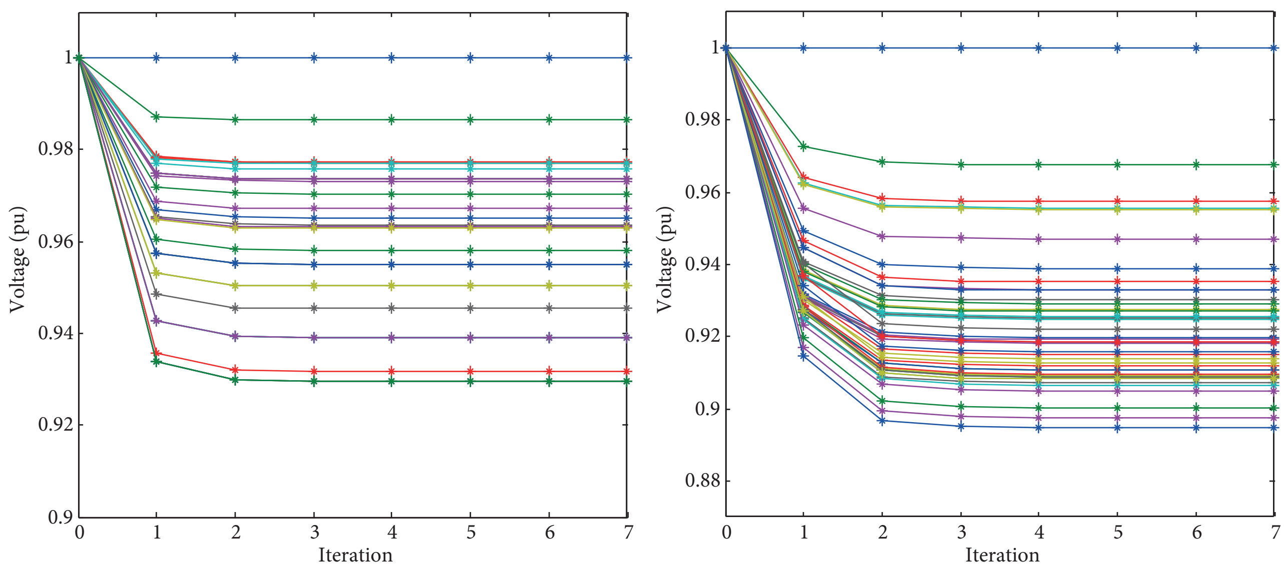


Figure 8. Load flow results of IEEE 123-bus system.

the voltages of buses as the results of load flow analysis. As it can be seen in Tables 5, with increasing the number of buses in the distribution system, DLF solving time obtained by the methods proposed in [11], [14], and [30] increase drastically, while the load flow algorithm used in this paper could solve the load flow problem in a considerably lower time period. For example, the proposed method decreases DLF solution time for IEEE 123- bus system by 71.57% with respect to the method presented in [11].

5. Conclusion

In this paper, a methodology for line independency-based modelling of distribution systems was proposed. The method is used to determine the backward and forward sweeping routes for calculating the line currents and voltages of buses in the load flow analysis of a radial power distribution system. The line independency-



(a) (b)

Figure 9. Voltage values obtained in consecutive iterations (a) IEEE 37-bus system, (b) IEEE 123-bus system

based network modelling method has to be performed only once and prior to the load flow algorithm due to its independency from the load flow algorithm. It was concluded that the proposed method can sort the distribution system's lines and provide a matrix, which can be the basis for backward and forward sweeping of the system. On the other hand, the method proposed for line independency-based modelling is defined in a way that it can expedite the overall load flow analysis and therefore is more appropriate for programming the load flow analysis. This was shown in Results where the calculation time of the proposed method was compared with those of other methods, and it was concluded that the proposed method has the highest speed.

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