DIRECT POWER FLOW METHOD FOR BALANCED AND UNBALANCED RADIAL DISTRIBUTION SYSTEMS WITH MULTI REFERENCE BUSES

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ABSTRACT
This paper presents a direct power flow method for radial distribution systems that include different system components. When step voltage regulators are installed on strategic buses along the distribution feeders, the system will have multi reference buses. Using graph theory, a modified branch path incident matrix of multi reference buses is built and used with the current injection technique to derive a direct mathematical expression. This expression can be used to solve the load flow problem for radial distribution system with multi reference buses. The test results of IEEE 13 and 34 bus unbalanced test feeders indicate that the proposed method is efficient, robust, and accurate.

KEY WORDS
Graph theory, power flow analysis, power distribution, step voltage regulator.

1. Introduction

Power flow analysis is an important tool for planning, designing, operation and control of power systems. Some applications, especially in the field of distribution automation and control need fast and accurate power flow solutions. In these applications, it is imperative that the power flow analysis is solved as efficiently and quickly as possible to provide solutions in real time to the operator in the control center.

Many methods for solving the power flow problem have been developed [1], such as Gauss-Siedel, Newton-Raphson and its decoupled versions. However, these algorithms have been formulated for transmission systems. Due to some inherent features of the distribution systems that are different from the transmission systems, their applications in the distribution systems usually does not provide good results and very often the solution diverges [2]. Several methods have been developed to overcome the difficulties of the distribution power flow problem [3-15]. These methods can be divided into three categories. The first category is the methods that are based on some modifications of the conventional methods. In [3-5], the Gauss implicit Z-Bus method is used to solve the three phase power flow problem. In this method, full or fractional factorization of Y-bus matrix is used. Thus, a large computation time is required. In [6-7], a new formulation of the Newton-Raphson power flow method has been proposed based on the system admittance, current injection and iteration scheme similar to its conventional method. The major drawback of these methods is the Jacobian matrix requirement which needs to be partially recalculated for each iteration. In [8], a fast decoupled power flow method has been proposed. This method orders the laterals instead of buses into layers, thus reducing the problem size to the number of laterals. However, it may add some difficulties if the network topology is changed regularly, which is common in distribution systems. The second category is based on forward/backward sweeping methods [9-13]. The solution is solved by using two steps. The branch currents are first computed (backward sweep) and the bus voltages are updated in the second step (forward sweep).

The third category is the direct load flow methods. These methods are based on the special feature of the distribution system to drive a direct mathematical expression between the bus voltage and the bus current. Therefore, the time-consuming procedures, such as matrix decomposition and forward/backward substitution as in other methods, are not necessary. In [14-15], two developed matrices, the bus current to branch current matrix and bus voltage to branch current matrix, and a simple matrix multiplication are used to solve load flow problem. One of the main disadvantages of this method is that the shunt capacitance currents of the distribution lines are neglected, which makes the results inaccurate. Moreover, the two matrices are built by a direct observation method. Therefore, it is difficult to extend the algorithm.

The methods mentioned in [1-15], however, did not include the modeling of step voltage regulator (SVR), except [13]. In [13], the algorithm uses the bus incidence matrix to derive a relationship between bus current and branch current. This matrix is built without taking into account the effect of SVR turn ratio. Therefore, the algorithm of [13] can include the modeling of the substation voltage regulator but it is not capable of handling the in-line SVR model.

In this paper, a direct power flow method for balanced and unbalanced radial distribution system is presented. The proposed method incorporates the modeling of the different system components. New formulation of SVR model is proposed. The modeling of the SVR produces multi reference buses in the distribution system. Using graph theory, a modified
branch path incident matrix of multi reference buses is built, rather than using the traditional matrix of single reference bus, and used with the current injection technique to solve the power flow problem. The proposed method can also work with distribution system with distributed generators (DG). However, the inclusion of DG is not addressed in this paper. The IEEE-13 and IEEE-34 bus unbalanced test systems [16] are used to test and verify the performance of the proposed method.

2. Distribution System Modeling

2.1 Line Section Model

The model of distribution overhead and underground line section is shown in Figure 1. Using Carson method and Kron’s reduction technique, the series impedance can be expressed by a 3×3 impedance matrix as shown in Eq. (1) [17].

\[
Z_{abc} = \begin{bmatrix}
    z_{aa} & z_{ab} & z_{ac} \\
    z_{ba} & z_{bb} & z_{bc} \\
    z_{ca} & z_{cb} & z_{cc}
\end{bmatrix}
\] (1)

For the line section in Figure 1, the relation between bus voltages and branch currents can be given as shown in Eq. (2). The shunt capacitive current in each bus can be calculated using Eq. (3).

\[
\begin{bmatrix}
    V_{j-a} \\
    V_{j-b} \\
    V_{j-c}
\end{bmatrix} = \begin{bmatrix}
    V_{i-a} \\
    V_{i-b} \\
    V_{i-c}
\end{bmatrix} - \begin{bmatrix}
    z_{aa-n} & z_{ab-n} & z_{ac-n} \\
    z_{ba-n} & z_{bb-n} & z_{bc-n} \\
    z_{ca-n} & z_{cb-n} & z_{cc-n}
\end{bmatrix} \begin{bmatrix}
    I_{ij-a} \\
    I_{ij-b} \\
    I_{ij-c}
\end{bmatrix}
\] (2)

\[
\begin{bmatrix}
    I_{sh-a} \\
    I_{sh-b} \\
    I_{sh-c}
\end{bmatrix} = \frac{1}{2} \begin{bmatrix}
    Y_{aa} & Y_{ab} & Y_{ac} \\
    Y_{ba} & Y_{bb} & Y_{bc} \\
    Y_{ca} & Y_{cb} & Y_{cc}
\end{bmatrix} \begin{bmatrix}
    V_{a} \\
    V_{b} \\
    V_{c}
\end{bmatrix}
\] (3)

2.2 Distributed Load Model

Distributed loads can be represented by two lumped loads [17]. Two thirds of the total load is connected at one-fourth length of the line from the sending end. One third of the total load is connected at the receiving node.

2.3 Transformer Model

A three phase transformer can be modeled as an equivalent leakage impedance matrix and the core loss block, as shown in Figure 2 [18].

\[
\begin{array}{c}
V_P \\
I_P \\
Z_{leakage} \\
I_S \\
V_S
\end{array}
\]

Figure 2. Three-phase transformer model

Where, \(Z_{leakage}\) represents transformer leakage impedance, \(Y_m\) represents the core losses, \(V_P\) represents primary voltage and \(V_S\) represents secondary voltage.

2.4 Shunt Capacitor Model

Shunt capacitors bank are modeled as constant impedances loads with wye or delta connection.

2.5 Load Model

In power systems, the loads can be one, two or three phase loads with wye or delta connection. These loads can be modeled either as constant power, constant current or constant impedance depending on their characteristics. The common characteristics of the exponential load models are given as:

\[
S = (P_0 + jQ_0) \times \left(\frac{V}{V_0}\right)^{nl}
\] (4)

Where \(nl\) is the load constant, \(P_0\) and \(Q_0\) represent the specified active and reactive powers at rated voltage \(V_0\) and \(V\) is the actual voltage magnitude. The value of the load constant can cause specific load types such as 0: constant power, 1: constant current, and 2: constant impedance.

2.6 Step Voltage Regulator Model

One of the common devices that are used to supply voltage within ANSI standards to every customer on a distribution feeder is the Step Voltage Regulator (SVR). SVR is an autotransformer in which the voltage or phase angle of the regulated circuit is controlled in steps by
means of taps without interrupting the load. Tap changing is controlled by the Line Drop Compensator (LDC).

LDC is the control circuit that is used to model the voltage drop of the distribution line from the regulator to the load center. The typical input voltage and current of this circuit are 120V and 5A respectively. Figure 3 shows a simplified sketch of the compensator circuit [17]. In Figure 3, \( R' \) and \( X' \) represent the equivalent resistance and reactance from the regulator to the load center calibrated in volts and \( Z_{line} \) is the unbalanced line impedance including the self and mutual equivalent impedance for the three phases.

\[
\begin{bmatrix}
V_{P-abc} \\
I_{P-abc} \\
S
\end{bmatrix} = \begin{bmatrix}
1 & 0 & 0 \\
0 & a_{R-b} & 0 \\
0 & 0 & a_{R-c}
\end{bmatrix} \begin{bmatrix}
V_{P-abc} \\
I_{P-abc} \\
S_{abc}
\end{bmatrix}
\]

Figure 3. Line drop compensator circuit

Three single-phase regulators can be connected externally in wye, delta, and open delta to form a three-phase regulator [17]. The general three-phase model is shown in Figure 4 [19].

\[
\begin{bmatrix}
P \\
I_{P-abc} \\
S \\
V_{P-abc} \\
I_{S-abc} \\
V_{S-abc}
\end{bmatrix}
\]

Figure 4. General three phase voltage regulator model

The step voltage regulators can be connected in a type-A or type-B connection according to the ANSI/IEEE C57.15-1986 standard. The general equations for three type-A regulators connected in wye form are [17]:

\[
\begin{bmatrix}
V_{S-an} \\
V_{S-bn} \\
V_{S-cn}
\end{bmatrix} = \begin{bmatrix}
a_{R-a} & 0 & 0 \\
0 & a_{R-b} & 0 \\
0 & 0 & a_{R-c}
\end{bmatrix} \begin{bmatrix}
V_{P-an} \\
V_{P-bn} \\
V_{P-cn}
\end{bmatrix}
\]

\[
\begin{bmatrix}
I_{P-an} \\
I_{P-bn} \\
I_{P-cn}
\end{bmatrix} = \begin{bmatrix}
a_{R-a} & 0 & 0 \\
0 & a_{R-b} & 0 \\
0 & 0 & a_{R-c}
\end{bmatrix} \begin{bmatrix}
I_{S-an} \\
I_{S-bn} \\
I_{S-cn}
\end{bmatrix}
\]

Where \( a_{R-a} \), \( a_{R-b} \) and \( a_{R-c} \) are the effective turn ratios for the three single phase regulators. These turn ratios relate the voltages and currents between the subsystem downstream and upstream of the SVR. Therefore, the system model can be divided into two subsystems as shown in Figure 5.

The substation bus is the reference voltage bus for the subsystem upstream of the SVR, whereas, the dependent voltage source is the reference bus for the subsystem downstream of the SVR.

\[
I_{P-abc} = a_{R-abc} \times I_{S-abc} \\
V_{P-abc} = a_{R-abc} \times V_{P-abc}
\]

Figure 5. The proposed representation of SVR

3. Problem Formulation

The proposed method is based on graph theory in conjunction with standard power flow formulation. Using graph theory, a modified branch-path incident matrix (MBP) for multi reference buses is built. An equivalent current injection based model for distribution system is used. MBP and the current injection model are merged in order to form a direct general expression to determine the voltage drop from each bus to its reference bus taking into account the effects of SVR.

3.1 Modified Branch-Path Incident Matrix Proposed for Multi Reference Buses

The special feature of most distribution networks is the radial configuration. Therefore, it can be constructed as a tree of graph. When the tree is defined, a unique path can be traced from any bus in the radial distribution system to its reference bus and the orientation is always from the reference bus to each bus. The proposed MBP for multi reference buses is used to describe these paths. Any element \( (MBP_{ij}) \) in the MBP is unity when the \( i^{th} \) branch is in the path from the reference of \( j^{th} \) bus to the \( j^{th} \) bus and equals to zero when the \( i^{th} \) branch is not in the path from the reference of the \( i^{th} \) bus to the \( j^{th} \) bus.

The MBP can be built for a radial distribution system which has one reference bus (substation bus) or one independent reference bus and multi dependent reference buses. By using the specified criterion for the MBP, the MBP for a single reference bus in a radial distribution system shown in Figure 6, can be represented by Eq. (7).

\[
(MBP) = \begin{bmatrix}
1 & 1 & 1 & 1 \\
0 & 1 & 1 & 1 \\
0 & 0 & 1 & 1 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

For the multi reference buses system shown in Figure 7, the system consists of one independent reference
bus (substation bus) for buses 1 and 2, and a dependent reference bus (bus-2) for buses 3 and 4. The MBP for this system can be written as:

$$[M_{BP}] = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 \\ 0 & 0 & 1 & 1 \end{bmatrix}$$

(8)

Figure 6. A sample radial distribution system with one reference bus

Figure 7. A sample radial distribution system including two reference buses

It is important to note that the numbering of the buses in the first and second subsystems should not overlap as shown in Figure 7. Therefore, if the system has a lateral feeder, any existing buses of this lateral feeder should be numbered immediately after the number of the feeding feeder. This numbering scheme is very simple and has been implemented in the algorithm proposed in this paper.

The algorithm can easily be expanded to multi-phase balanced and unbalanced radial distribution systems. For example, if the branch section between bus-i and bus-j is a three-phase line section, then the value of 1 in the MBP will become a 3x3 unity matrix.

3.2 Current Injection Model

The loads and the shunt elements of each bus in radial distribution systems can be represented as current injection. The current injection is calculated using the estimated bus voltage and should be updated for every iteration. At the $k^{th}$ iteration, the equivalent current injection $I_{i}^{(k)}$, at bus- $i$ is calculated as:

$$[I_{i}]^{(k)} = [I_{L,i}]^{(k)} + [I_{sh,i}]^{(k)}$$

(9)

Where $[I_{L,i}]$ and $[I_{sh,i}]$ are the three phase load current and shunt elements current at bus- $i$ respectively. In the case of three phase loads connected in star, the load current injections at the $i^{th}$ bus can be given by:

$$[I_{L,i}]^{(k)} = \begin{bmatrix} S_{L,a,i} \cdot \left(\frac{V_{a,i}^{(k-1)}}{V_{a,i}^{k-1}}\right)^{m} & V_{a,i}^{k-1} \\ V_{a,0}^{k-1} & -S_{L,a,i} \cdot \left(\frac{V_{a,i}^{(k-1)}}{V_{a,i}^{k-1}}\right)^{m} \\ V_{c,i}^{k-1} & V_{c,0}^{k-1} & -S_{L,c,i} \cdot \left(\frac{V_{c,i}^{(k-1)}}{V_{c,i}^{k-1}}\right)^{m} \end{bmatrix}$$

(10)

The load current injections at the $i^{th}$ bus for three phase loads connected in delta can be expressed by:

$$[I_{L,i}] = \begin{bmatrix} S_{L,ab,i} \cdot \left(\frac{V_{ab,i}^{(k-1)}}{V_{ab,i}^{k-1}}\right)^{m} & V_{ab,i}^{(k-1)} \\ V_{ab,0}^{k-1} & -S_{L,ab,i} \cdot \left(\frac{V_{ab,i}^{(k-1)}}{V_{ab,i}^{k-1}}\right)^{m} & V_{bc,i}^{(k-1)} \\ V_{bc,0}^{k-1} & -S_{L,bc,i} \cdot \left(\frac{V_{bc,i}^{(k-1)}}{V_{bc,i}^{k-1}}\right)^{m} \end{bmatrix}$$

(11)

The shunt elements current at bus- $i$ can be expressed by:

$$[I_{sh,i}]^{(k)} = [Y_{sh,i}] \cdot [V_{i}]^{(k-1)}$$

(12)

Where $S_{L,i}$ is the load power that are connected at bus- $i$, $nl$ is the load constant, $V_{i}$ is the three phase voltage at bus- $i$, $V_{0}$ is the system nominal voltages, and $Y_{sh,i}$ is the shunt capacitive admittance at bus- $i$.

3.3 Derivation of the Proposed Method

The voltage drop from any bus to its reference bus in the radial distribution system can be obtained using the MBP, the primitive impedance matrix, and the current injection model.

A general radial distribution system represented by a one-line diagram shown in Figure 8 is used to illustrate the derivation of the proposed method. The system has ($n$) branches and ($n+1$) buses with step-voltage regulator at bus-$m$. The reference bus for buses (1 to $m$) is the substation bus, whereas, the reference bus for all the buses downstream to bus- $m$ is the secondary voltage of step-voltage regulator which is represented by the dummy bus- $m'$.  

The primitive branch performance equation for each branch in the system is:

$$v_{ij} = z_{ij}I_{b,ij}$$

(13)

The primitive branch performance for the whole system can be represented by:
Where \(v\) is the voltage across each branch in the primitive system, \([z]\) is the primitive impedance matrix, and \([I_b]\) is the branches currents. Multiplying Eq. (14) by \([MBP]\) yields:

\[
\begin{bmatrix}
MBP^\dagger
\end{bmatrix}[v] = [MBP^\dagger][z][I_b]
\]

(15)

\([MBP^\dagger][v]\) gives the sum of all voltage drop \([DV]\) between each bus and its reference bus, or it can be written as:

\[
[DV] = [MBP^\dagger][v]
\]

(16)

Substituting Eq. (15) into Eq. (16) gives:

\[
[DV] = [MBP^\dagger][z][I_b]
\]

(17)

The bus current matrix can be formulated by using the current injection model taking into account the effects of SVR in the radial distribution system. Each bus in the given system has two current components; the load current and the shunt element current, except bus-\(m\) which has three components; the load current, the shunt element current and the current supplied to the buses downstream bus-\(m\) as shown in Eq. (18).

\[
I_{bus-i} = \begin{bmatrix}
I_{L-i} + I_{sh-i} \\
I_{L-i} + I_{sh-i} + a_R \sum_{j=m+1}^{n} I_{L-j} + I_{sh-j} \\
I_{L-n} + I_{sh-n} \\
I_{L-n} + I_{sh-n} + a_R \sum_{j=m+1}^{n} I_{L-j} + I_{sh-j}
\end{bmatrix}, \quad i = 1, 2, \ldots, n \quad \& \quad i \neq m
\]

(18)

Where \(a_R\) is the effective turns ratio of the SVR and \((m+1)\) represents the number of the first bus in the second subsystem.

The power in primitive and in interconnected network must be equal. Hence, it can be written as

\[
[I_{bus}^\dagger][DV] = [I_{bus}^\dagger][v]
\]

(19)

Substituting Eq. (16) in Eq. (19) results in:

\[
[I_{bus}^\dagger][MBP^\dagger][v] = [I_{bus}^\dagger][v]
\]

Simplifying Eq. (20) yields:

\[
[I_{bus}^\dagger][MBP] = [I_{bus}^\dagger][v]
\]

(21)

Substituting Eq. (21) into Eq. (17) gives Eq. (22):

\[
[DV] = [Z_{bus-eq}][I_{bus}]
\]

(22)

and

\[
[Z_{bus-eq}] = [MBP^\dagger][z][MBP]
\]

(23)

Where \([Z_{bus-eq}]\) represents the equivalent bus impedance matrix for the multi-reference buses distribution system. Equation (22) represents a direct general mathematical expression that is used to find the voltage drop from each bus to its reference bus with taking into account the effects of SVR.

The voltage at each bus of radial distribution system with multi reference bus is calculated as:

\[
\begin{bmatrix}
V_{bus-1} \\
\vdots \\
V_{bus-m} \\
V_{bus-m+1} \\
\vdots \\
V_{bus-n}
\end{bmatrix} = \begin{bmatrix}
V_{ref1} \\
\vdots \\
V_{ref1} \\
V_{ref2} \\
\vdots \\
V_{ref2}
\end{bmatrix} - \begin{bmatrix}
DV_1 \\
\vdots \\
DV_m \\
DV_{m+1} \\
\vdots \\
DV_n
\end{bmatrix}
\]

(24)

Where, \(V_{ref1}\) is the voltage of the first reference bus and its voltage is equal to the substation voltage, \(V_{ref2}\) is the voltage of the second reference bus, and its voltage is calculated as:

\[
V_{ref2} = V_{m'} = V_{ref1} - DV_m
\]

(25)

Where \(V_{m}\) is the voltage of bus-\(m\), \(DV_m\) is the voltage drop between bus-\(m\) and the substation bus which is calculated from Eq. (22). The solution of distribution load flow problem can be obtained by solving Eq. (18), Eq. (22), Eq. (24), and Eq. (25) iteratively.
3.4 Proposed Algorithm

The proposed algorithm can be summarized in the following steps:

1. Read the system data.
2. Build the MBP of the distribution system with multi voltage references buses.
3. Use Eq. (23) to calculate the equivalent system impedance matrix.
4. Assume a flat profile for the initial voltages at all buses and unity effective turn ratios \( a_R \).
5. Use Eq. (18) to calculate the bus current matrix taking into account the effects of the SVR model.
6. Use Eq. (22) to calculate the voltage drop between each bus and its reference bus.
7. Calculate the voltage of the dependent reference buses based on Eq. (25).
8. Update bus voltages.
9. Return to step 5 until the convergence tolerance is achieved according to Eq. (26).

\[
\left| V_{bus-i}^{(K+1)} - V_{bus-i}^{(K)} \right| \leq \varepsilon
\]  

(26)

Where \( \varepsilon \) is the voltage tolerance.

10. Calculate the number of required taps based on LCD and the effective turn ratios \( a_R \) (for more details refer to [17]).
11. Keep on returning to step 5 until the taps changing is settled.

Figure (9) shows the flowchart of the proposed algorithm.

4. Case Studies and Results

In this paper, the proposed power flow algorithm for balanced and unbalanced radial distribution systems containing SVR has been implemented by using MATLAB. IEEE 13 and 34 bus unbalanced radial distribution test feeders [16] were used to verify the performance of the proposed power flow algorithm and to evaluate the capability of the algorithm to handle the proposed modeling of the SVR.

The above two test feeders contain overhead and underground lines with a variety of phasing, unbalanced spot and distributed loads with different load modeling and types, in–line transformers, shunt capacitors, and SVR with LCD control technique. Moreover, the IEEE 13 bus test feeder is small but provides a good test for most of the special features of the radial distribution system. This feeder is highly loaded and has one substation step voltage regulator consisting of three single phase units connected in wye. In another side, the IEEE 34 bus test feeder is an actual feeder located in Arizona. It is very long and has two in – line step voltage regulators to maintain a good voltage profile.

4.1 Case 1: IEEE 13 Bus Test Feeder

From an initial voltage of 1.0 per unit, four iterations were required to converge to a tolerance of 0.0001 per unit. This includes the simulation of the LCD circuit which is used to adjust the tap position of the SVR based on the given data in [16]. It has been found that those taps are 10, 8, and 11 for phase a, b, and c, respectively. These results comply with those of IEEE. A comparison between the load flow results of the proposed algorithm and the IEEE results are presented in Table 1. This table shows that the voltage magnitudes and angles resulted from the proposed algorithm are close to the IEEE results.
To verify the accuracy and convergence of the proposed algorithm, the results of [13] are used for comparison. Table 2 shows the deviation of the bus voltage magnitudes and angles obtained by using the proposed algorithm and the algorithm in [13], with respect to IEEE results. The comparison of results show that the maximum deviation of bus voltage magnitudes and angles obtained within four iterations by using the proposed algorithm are 0.0004 p.u. and 0.05° respectively. However, after five iterations, the deviation resulted from the algorithm of [13] are 0.0019 p.u. and 0.08°.

4.2 Case 2: IEEE 34 Bus Test Feeder

In this section, the IEEE 34 bus test feeder is used to validate the proposed algorithm. For a tolerance of 0.0001 p.u., the solution is reached after six iterations. Using LDC, the number of required taps and effective turn ratios for the two SVRs are calculated. Table 3 shows the calculated taps and effective turn ratios for the regulators of IEEE 34 bus test feeder.
lated taps and effective turn ratios for the two SVRs. In Table 3, all the tap results of the proposed algorithm comply with those of IEEE except the taps of the two regulators connected in phase-a at locations 514-850 and 852-832. IEEE algorithm considers the tap value of 12.03 of the regulator connected at location 514-850 as 12, whereas, the proposed algorithm considers 12.03 as 13 similar to [17]. The tap setting at location 852-832 is different from the IEEE due to the effect of the upstream tap difference at 814-850. Table 4 shows the bus voltage magnitudes and phase angles obtained from the proposed algorithm.

By comparing the results of the bus voltage magnitudes and phase angles with those of IEEE results, it has been found that the maximum deviation of bus voltage magnitudes and angles are 0.0062 p.u. and 0.0198° for phase A, 0.0001 p.u. and 0.0022° for phase B, and 0.0001 p.u. and 0.05° for phase C.

5. Conclusion

In this paper, a direct distribution load flow method for balanced and unbalanced radial distribution systems has been proposed. The new formulation exploits the topological characteristics of a distribution system to obtain a direct load flow formulation method for multi reference buses distribution systems using the graph theory. From the graph theory, the proposed modified branch path incident matrix for multi reference buses is built and used with the current injection technique to solve the load flow problem.

From the conventional primitive data that are used by most utilities, different system components are modeled and easily addressed such as overhead and underground lines, transformers, loads, shunt capacitors, and SVRs with LDC control technique.
The time-consuming procedures, such as matrix decomposition and forward/backward substitution as in other methods, do not exist in the proposed method. The method has been tested using two test systems; IEEE 13 and IEEE 34 bus unbalanced test systems. Test results show that the proposed method has robust convergence, high performance, and the capability to handle the proposed modeling of the SVR. The proposed method offers the feasibility of its usage for real time applications.

References