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An Optimal and Distributed Method for Voltage Control in Electrical Distribution Systems

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Abstract: *A load flow solution for three phase unbalanced radial distribution feeder ungrounded wye delta transformer connection using MATLAB software is proposed in this paper. Different steps have been presented for the analysis of the feeder. First, the ladder iterative technique using generalized matrices for the unbalanced distribution feeder. Second, it has proposed testing and evaluating of three phase wye delta transformers with ungrounded connection, an IEEE 4 Node test system. Finally, the proposed method for voltage control is tested on IEEE 4 Node test system within the limits and the results will be obtained by MATLAB Software.*

Keyword: *load flow; unbalanced distribution feeder; ungrounded wye delta transformer; ladder iterative technique.*

1. INTRODUCTION

The major mechanisms of an electric power system are Generation, interconnected transmission system, bulk power substation, sub transmission network, distribution substation. In the previous half of the twentieth century the operation of the generation and transmission system offered many challenges to involved engineers and researchers. Power plants became larger and the Transmission lines are converged the land forming huge interconnected networks. The operation of these large interconnected networks required the improvement of new analysis and operational techniques. For the movement, the distribution systems continued to deliver power to the ultimate user's meter with little or no analysis. In certain cases, the distribution substation is fed directly from a high voltage transmission line, in which case there is likely no sub transmission system. Distribution voltages are typically medium voltage, between 2.4 kV and 33 kV depending on the practices of the local utility and the size of the area served. Even though there are many works dealing with step Voltage Regulator (SVR) in power flow studies [1] not deals with general models and results for all possible configurations. Several voltage control possibilities can be achieved by coordinating the small generators and storage units installed near customers and the well-known Switched Capacitors and Step Voltage Regulators [2]. The authors in [3] proposed a corresponding to mitigate the voltage rise caused for high penetration levels of Photovoltaic systems control of energy storage systems with SVRs.

In [4], based on decentralized and distributed voltage control, the authors propose a robust and effective approach to deal with voltage increase issues by coordinating DGs and customers' energy storage units. There have been some trials and studies [5-7] that show OLTC (on load tap changer) fitted LV (low voltage) distribution transformers proved to be effective at regulating voltage with high saturation of DG. Newton Raphson method is also used for solving the nonlinear equation [8] to determine stepped switching angles for cascade multilevel inverters. The authors in [9-11] showed that the inverter-based DG has superior facility for unequal voltage disturbances and mitigation for fast load voltage regulation. In [12, 13] various system equipment models for distribution power flow were presented. Other recommended methods are including such as SCs (shunt capacitor), OLTC (on load tap changer [14-16] and Heuristic Algorithmic approach for reactive power optimization [17].

Currently, there are different technologies for voltage regulators in commercial devices [18]. In [19], re-

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active power absorption based on the rate of modify of the PV panel output was suggested. In[20],studies have shown that the battery energy storage devices have been effective in reducing the transients from large scale PV plants due to cloud movement, related to our approach [21,22] discuss adding a very small resistance term to the model to handle a similar network disconnection issue due to the presence of ideal transformers. Hence it is not deemed effective for modeling transformers. In [23] the three phase's current injection method (TCIM) based on the power flow algorithm with capabilities to solve for three phase systems was presented. Some efficient LF (load flow) techniques are reported in [24-27] to analyze active distribution system. These reported algorithms are capable enough to candle PV nodes efficiently. Furthermore, undesirable transient currents in capacitors, transformers, motors [28-30]. The large number of nodes and lines make the impedance matrix hard to implement [31]. The main contribution of this paper is to find the final voltages at the load point whether check inside the specified limits. To use generalized matrices for an unbalanced distribution feeder to implement the ladder iterative technique. The 4-node test system for testing and evolution of three phase transformer connections.

2. PROBLEM FORMULATION

The modified Carson's equations will be used to compute the primitive self and mutual impedances of overhead and underground lines. Only two approximations are made in deriving the modified Carson's equations

$$\hat{Z}_{ii} = r_i + 0.09530 + j0.12134\left(\ln\frac{1}{GMR_i} + 7.93402\right)\Omega/mile \quad (1)$$

$$\hat{Z}_{ij} = 0.09530 + j0.12134\left(\ln\frac{1}{D_{ij}} + 7.93402\right)\Omega/mile \quad (2)$$

$$\hat{Z}_{in} = 0.09530 + j0.12134\left(\ln\frac{1}{D_{in}} + 7.93402\right)\Omega/mile \quad (3)$$

Where

$$D_{ij} = GMD_{ij} = \sqrt[3]{D_{ab}.D_{bc}.D_{ca}}\ ft$$

$$D_{in} = GMD_{in} = \sqrt[3]{D_{an}.D_{bn}.D_{cn}}\ ft$$

$\hat{Z}_{ii}$ -Self impedance of conductor i in Ω/mile

$\hat{Z}_{ij}$ - Mutual impedance between Conductors i and j in Ω/mile

r_i - Resistance of conductor i in Ω/mile

D_{ij} - GMD between phases

D_{in} - GMD between phases and neutral

2.1 The Test System

In transformer model the system to be used is shown in Fig 1 below. The line segment on the source side [ZeqS] and the load side [ZeqL] of the transformer bank utilize the pole spacing's as shown in Figure 2.

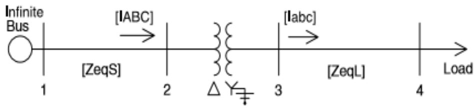

Fig. 1 Transformer Model Test System

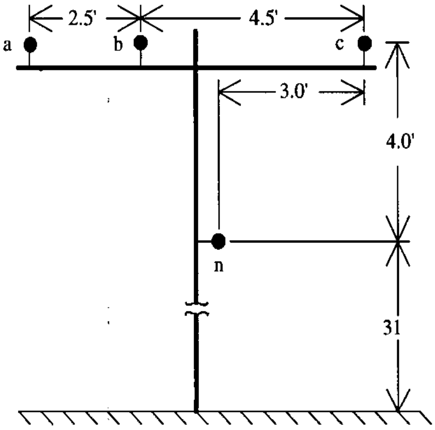

Fig. 2 Pole Spacing

The conductors used in Figure 2 are:
Phase Conductors: 336,400 26/7 ACSR
Neutral Conductor: 4/0 ACSR

The voltage levels for the system shown in Fig 1:
Source: 12,470 volts line to line
Load: 4,160 volts line to line

The loads used for *11k* system I Figure 1 are:
Unbalanced 1500 kVA,0.85 PF (a-b), 2000 kVA,0.9 PF (b-c),2500 kVA, 0.95 PF (c-a).

Using the pole spacing's the four-wire wye line segment is in Figure 2 and the phase and neutral conductors as given. The phase impedance matrix using the modified Carson's equations in [2] in ohms/mile is:

$$Z_4 = \begin{bmatrix} 0.4576+j1.0780 & 0.1559+j0.5017 & 0.1535+j0.3849 \\ 0.1559+j0.5017 & 0.4666+j1.0482 & 0.1580+j0.4236 \\ 0.1535+j0.3849 & 0.1580+j0.4236 & 0.4615+j1.0651 \end{bmatrix}\Omega/mile \quad (4)$$

Transforming the phase impedance matrix to the symmetrical component matrix provides the following sequence impedances:

$$Z_{4+} = 0.3061 + j0.6270 \quad \Omega/mile$$
$$Z_{40} = 0.7735 + j1.9373$$

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The secondary line of three wire delta uses the similar pole spacing and phase conductors. There is no neutral for this case. The phase impedance matrix per mile is:

$$Z_3 = \begin{bmatrix} 0.4013 + j1.4133 & 0.0953 + j0.8515 & 0.0953 + j0.7266 \\ 0.0953 + j0.8515 & 0.4013 + j1.4133 & 0.0953 + j0.7802 \\ 0.0953 + j0.7266 & 0.0953 + j0.7802 & 0.4013 + j1.4133 \end{bmatrix} \Omega / mile \quad (5)$$

Converting to the sequence impedances for this case gives:

$$\begin{matrix} Z_{3+} = 0.3060 + j0.6272 \\ Z_{30} = 0.5919 + j2.9855 \end{matrix} \; \Omega / mile$$

The four-wire wye impedances are used for the impedances of windings while the three wire delta impedances are used for a line segment associated to wye connected transformer the impedances of a line connected to delta connected transformer windings.

3. ITERATIVE ANALYSIS

The method of analysis is the ladder (forward and backward) iterative technique using the transformer and line models of reference [2].In this procedure the two line segments are modeled by their phase impedance matrices as defined previously . The constant reactive power loads are modeled and it is expected that the voltages at node 1 are balanced three phase line to ground voltages of 7200 volts/phase. For the line segments and transformer bank the general equation for the forward sweep is :

$$\begin{aligned} [VLN_{abc}]_n &= [a]*[VLN_{abc}]_m + [b]*[I_{abc}]_m \\ [I_{abc}]_n &= [c]*[VLN_{abc}]_m + [d]*[I_{abc}]_m \end{aligned} \quad (6)$$

The general equation for the backward sweep is:

$$[VLN_{abc}]_m = [A]*[VLN_{abc}]_n - [B]*[I_{abc}]_m \quad (7)$$

Note in equation 7 that the current used is the identical to that of the forward sweep i.e, the forward sweep current computed are held constants for the backward sweep. At particular voltages at the substation as the voltages at node n the backward sweep starts, when the shunt admittance of the line segments is ignored the general parameters are:

[a]= [d] =Unity matrix (8)
[b]=Phase impedance matrix (9)
[c]=zero matrix (10)

For the specified ungrounded wye-delta transformer bank, the transformer ratio is:

$$n_t = \frac{7200}{4160} = 1.73077 \quad (11)$$

The general parameters for transformer bank [1] are:

$$[a_t] = n_t \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \quad (12)$$

$$[b_t] = \frac{n_t}{3} \begin{bmatrix} z_{tab} & -z_{tab} & 0 \\ z_{tbc} & 2z_{tbc} & 0 \\ 2z_{tca} & -z_{tca} & 0 \end{bmatrix} \quad (13)$$

$$[c_t] = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad (14)$$

$$[d_t] = \frac{1}{3*n_t} \begin{bmatrix} 1 & -1 & 0 \\ 1 & 2 & 0 \\ -2 & -1 & 0 \end{bmatrix} \quad (15)$$

$$[A_t] = \frac{1}{3*n_t} \begin{bmatrix} 2 & 1 & 0 \\ 0 & 2 & 1 \\ 1 & 0 & 2 \end{bmatrix} \quad (16)$$

$$[B_t] = \frac{1}{9} \begin{bmatrix} 2z_{tab} + z_{tbc} & 2z_{tbc} - z_{tab} & 0 \\ z_{tbc} - 2z_{tca} & 4z_{tbc} - z_{tca} & 0 \\ z_{tab} - 4z_{tca} & -z_{tab} - 2z_{tca} & 0 \end{bmatrix} \quad (17)$$

The forward sweep starts by assuming nominal line to line voltages at the loads. The computed delta current are line the currents utilizing KCL at the three nodes. Equivalent lines to neutral voltages are computed using equation [7].

$$[VLN_{abc}]_4 = [W].[VLL_{abc}]_4 \quad (18)$$

Where

$$[W] = \frac{1}{3} \begin{bmatrix} 2 & 1 & 0 \\ 0 & 2 & 1 \\ 1 & 0 & 2 \end{bmatrix} \quad (19)$$

Next at node 3 the equivalent line to neutral voltages and the line currents are computed using 1. Now using the generalized parameters for the transformer at node

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2 where the equivalent line to neutral voltages are determined and entering transformer bank line currents are computed. At this point it must be understood that there is a difference between the line to neutral and line to ground voltages at node 2 in the forward sweep. Since the source voltages are equivalent line to ground voltages, the line to ground voltages at node 2 must be used in the continuation with the forward sweep.

Initially, it is assumed as the source line to ground voltages instead of the line to ground voltages at node. The forward sweep is completed by computing the voltages and currents at node 1 using these lines to ground voltages and the just computed current. In the iterative process the computed node 1voltages will be compared to the specified source voltages. When the specified voltages are within a small tolerance value convergence is obtained. The tolerance was specified 0.00001 per unit. The backward sweep starts when convergence has not been with setting the node 1voltages to the particular line to ground voltages and then computing the line to ground voltages at node 2 again calculates the difference between line to ground and equivalent line to neutral voltages must be done. In the backward sweep the calculated line to ground voltages are converted to line to line voltages and with equation 13 the equivalent line of neutral transformer voltages is computed.

These voltages are used to continue the backward sweep. It should be indicated that on the next forward sweep, the computed line to ground voltages. It is calculated from the previous backward sweep which will be used at the node 2 for the continuation of the forward sweep. Till convergence is achieved forward and backward sweep is carried out.

4. RESULTS AND DISCUSSION

The success of the FBS structure will lies on the coding scheme. In Forward and Backward Sweep Algorithm can be done by MATLAB Software. In the study the practical coding scheme is selected for voltage control and applied in the radial distribution networks. In this work, the radial distribution systems have one potential node. And all others nodes are the load nodes. So, DS can be incorporate in any load node available in the network except potential node.

4.1 Generalized Matrices

The table 4.1 shows the generalized matrices for IEEE 4 Node test system using delta to grounded wye transformer.

4.2 Forward Sweep

Voltage drop determination with possible current or power flow values is done in forward sweep. Nodal voltages are upgraded in a forward sweep initiating from branches in the first layer until those in the last. The motive for the forward Propagation is to calculate the voltages at each node beginning from the feeder source node. The table 4.2 shows the forward sweep by computing the voltages and currents at all 4 nodes.

TABLE 4.1 GENERALIZED MATRICES OF IEEE 4 NODE TEST SYSTEM

PARAMETER	RESULTS
$[a_t]$	$\begin{bmatrix} 0 & -3.4639 & -1.7319 \\ -1.7319 & 0 & -3.4639 \\ -3.4639 & -1.7319 & 0 \end{bmatrix}$
$[b_t]$	$\begin{bmatrix} 0 & -0.0998-j0.5986 & -0.0499-j0.2993 \\ -0.0499-j0.2993 & 0 & -0.0998-j0.5986 \\ -0.0998-j0.5986 & -0.0499-j0.2993 & 0 \end{bmatrix}$
$[c_t]$	$\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$
$[d_t]$	$\begin{bmatrix} 0.1925 & -0.1925 & 0 \\ 0 & 0.1925 & -0.1925 \\ -0.1925 & 0 & 0.1925 \end{bmatrix}$
$[A_t]$	$\begin{bmatrix} 0.1925 & -0.1925 & 0 \\ 0 & 0.1925 & -0.1925 \\ -0.1925 & 0 & 0.1925 \end{bmatrix}$
$[B_t]$	$\begin{bmatrix} 0.0288+j0.1728 & 0 & 0 \\ 0 & 0.0288+j0.1728 & 0 \\ 0 & 0 & 0.0288+j0.1728 \end{bmatrix}$

TABLE 4.2 FORWARD SWEEP BY COMPUTING THE VOLTAGES AND CURRENTS AT ALL 4 NODES

PARAMETER	RESULTS
$[V4]$	$\begin{bmatrix} 1.4767-j2.7541 \\ -4.1558-j0.3052 \\ 1.6266+j4.9475 \end{bmatrix} A$
$[I4]$	$\begin{bmatrix} 2078.46-j1200 \\ -2078.46-j1200 \\ 0+j2400 \end{bmatrix} V$
$[V3]$	$\begin{bmatrix} 2150.56-j1216.73 \\ -2158.62-j1327.99 \\ -179.42-j2503.08 \end{bmatrix} V$
$[I3]$	$\begin{bmatrix} 147.67+j275.41 \\ -415.58-j30.52 \\ 162.66+j494.75 \end{bmatrix} A$

$[V2]$	$\begin{bmatrix} 7943.21+j458.0 \\ -2961.85-j6740.45 \\ -3879.12+j6585.43 \end{bmatrix} V$
$[I2]$	$\begin{bmatrix} 108.4-j47.13 \\ -111.34-j100.96 \\ 2.846+j148.27 \end{bmatrix} A$
$[V1]$	$\begin{bmatrix} 7971.84+j473.61 \\ -2903.59-j6774.58 \\ -3917.70+j6598.16 \end{bmatrix} V$
$[I1]$	$\begin{bmatrix} 108.4-j47.13 \\ -111.34-j100.96 \\ 2.846+j148.27 \end{bmatrix} A$
$[VLL1]$	$\begin{bmatrix} 10871.56+j7250.43 \\ 1005.57-j13373.65 \\ -11886.06+j6134.85 \end{bmatrix} V$
$[Error]_{pu}$	$\begin{bmatrix} 0.0809 \\ 0.1086 \\ 0.0876 \end{bmatrix} perunit$

4.3 Backward Sweep

Since these errors are greater than the usual tolerance of 0.001 per unit, the backward sweep begins. The backward sweep utilizes the equivalent line to neutral voltage from the source as the Node 1 voltage, and proceeds to Node 4 using the line currents from the forward sweep. The table 4.3 shows the backward sweep by computing the voltages at all 4 nodes.

TABLE 4.3 BACKWARD SWEEP BY COMPUTING THE VOLTAGES AT ALL 4 NODES

PARAMETER	RESULTS
$[V2]$	$\begin{bmatrix} 7171.09-j12.52 \\ -3610.02-j6202.64 \\ -3562.96+j6221.27 \end{bmatrix} V$
$[V3]$	$\begin{bmatrix} 2013.53-j1219.44 \\ -2068.05-j1118.19 \\ 90.21+j2348.17 \end{bmatrix} V$
$[V4]$	$\begin{bmatrix} 1943-j1200.02 \\ -1989.73-j987.71 \\ 267.71+j2245.1 \end{bmatrix} V$

This completes the first iteration. Current is computed in the second cycle at Node 4 load using the updated values of the Node 4 voltages. The forward sweep uses these new current values. The forward and backward sweeps continue until the error at the source is less than the specified tolerance of 0.001 per unit. The solution has converted to a tolerance of 0.0003 per unit after 4 iterations. The resulting load voltages at Node 4 are

$$\left[V4_{final}\right] = \begin{bmatrix} \text{1936.65-j1200.77} \\ \text{-1968.68-j981.55} \\ \text{265.65+j2195.19} \end{bmatrix} V \quad (20)$$

5. CONCLUSION

In this paper, three different steps have been presented for the analysis of the feeder. First the ladder iterative technique for the unbalanced distribution feeder for generalized matrix. Second IEEE 4 Node test system in three phase delta ground wye transformer connection is tested and evaluated. Thus, the distribution system for voltage control method using IEEE 4 Node test system within specified limits and the results obtained by MATLAB Software.

6. FUTURE SCOPE

This paper can be further extended to various ways to improve the performance of distribution system,

- To implement the Voltage control in higher order system.
- To include the various objective functions such as security, transient stability, and operational cost minimization to be achieved.
- To allocated the other FACTS devices and observe the improvement of the system response.

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