Load Flow Independent Method for Estimating Neutral Voltage in Three-Phase Power Systems

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Abstract: A precise modeling of three-phase power systems is of great importance due to its ability to represent load unbalance and asymmetry in system components. A further enhancement in power system modeling is the computation of neutral voltages, which has been frequently neglected in earlier works. In this Letter, a novel approximate method is proposed for estimating neutral voltages. The method has as its main advantage not requiring the use of load flow algorithms with explicit neutral conductor modeling, thus being applicable to available load flow results in which the neutral voltage was originally omitted.

Keywords: neutral voltage; load flow; grounding; approximate methods

1. Introduction

Load flow algorithms with representation of three-phase network elements by primitive admittance matrices and of voltages and currents by phase-frame components have seen intense use in recent works concerning the analysis of distribution systems [1–5]. Such modeling is of interest due to its ability of representing load unbalance and asymmetry in system components, which are significant at the distribution level. However, neutral voltage is neglected in these works.

In general, the assumption of perfect grounding is adopted in order to allow the application of Kron reduction for incorporating effects of neutral impedance in the phase conductors [6]. The trade-off for such implicit representation of the neutral conductor is the inability of computing neutral voltage via load flow. In the much fewer works where neutral voltage is considered [7–11], the generally adopted approach consists in using explicit representation of the neutral when constructing the system admittance matrix and, subsequently, running a load flow algorithm. We now briefly review the explicit-neutral load flow-based methods proposed in such works.

In Reference [7], a generalization of the three-phase current summation load flow method is proposed for incorporating ground current computation. The adopted approach consists of explicitly representing the fictitious ground conductor of Carsons’s line equations in the system admittance matrix, which enables computing voltages in the fictitious conductor and ground current. In [8], this approach was further extended via explicit representation of neutral conductor impedances, allowing the evaluation of neutral voltages. The main limitation of [7,8] is that such methods are not applicable to meshed networks, due to their dependence on current-sum load flow. Additionally, the assumption of perfect grounding is still used and for this reason, grounding impedances are not able to be modeled.

In Reference [9], the current injection method for three-phase load flow is extended to four-wire systems by including neutral conductors in the admittance matrix. This procedure advantageously enables the computation of neutral voltages for arbitrary network topologies, since current injection is not limited to radial networks. The authors in [10] show that the method in [9] can be used for solving...
imperfect grounding scenarios; to achieve this, the selected grounding admittances are added to the node auto-admittance matrices, which in turn are used to construct the system admittance matrix.

In Reference [11], a fringe current-based method is proposed for computing load flow in four-wire systems with arbitrary grounding impedances. The main reported advantage consists in reduced computational complexity with respect to standard load flow methods, which is achieved due to the method iterations only requiring the inversion of a submatrix of the system admittance matrix. Additionally, the method also avoids computational problems caused by the ill-conditioning of the four-wire admittance matrix.

All the above-mentioned methods entail two main disadvantages, namely:

- Higher-order and possibly ill-conditioned admittance matrix, due to neutral current being a linear combination of phase and ground currents on wye-connected transformers and loads;
- Necessity of running a new load flow simulation for obtaining neutral voltages, even if a previous Kron reduction-based result is available. Furthermore, load flow must be iterated for each set of system grounding impedances for which neutral voltage is assessed.

Taking into account the above disadvantages, a novel method for computing neutral voltage based on implicit-neutral load flow results is proposed in this Letter. The method is based on the fact that, for limited neutral voltages, the perfect grounding approximation provides an adequate estimate of the neutral conductor current. As will be shown, the advantages of the proposed method are:

- Significantly reducing the number of load flow iterations required for the analysis of neutral voltage for multiple sets of grounding impedances;
- Using implicit-neutral load flow and, consequently, reducing admittance matrix order and avoiding ill-conditioning due to neutral and phase current linear dependences;
- Providing a means of directly estimating neutral voltage for any set of grounding impedances by using available implicit-neutral load flow results as input;
- Compatibility with any three-phase, three-wire load flow algorithm, which enables application of the method to arbitrary network topologies.

2. Proposed Method

Consider a three-phase transmission line in a wye section of a distribution network that connects buses indexed as $i$ and $j$. The voltage drop equations for this line, including neutral conductor, are:

$$
\begin{bmatrix}
\Delta \hat{V}_i^a \\
\Delta \hat{V}_i^b \\
\Delta \hat{V}_i^c \\
\Delta \hat{V}_j^a \\
\Delta \hat{V}_j^b \\
\Delta \hat{V}_j^c \\
\end{bmatrix} =
\begin{bmatrix}
\hat{V}_i^a - \hat{V}_j^a \\
\hat{V}_i^b - \hat{V}_j^b \\
\hat{V}_i^c - \hat{V}_j^c \\
\hat{V}_i^a - \hat{V}_j^a \\
\hat{V}_i^b - \hat{V}_j^b \\
\hat{V}_i^c - \hat{V}_j^c \\
\end{bmatrix} \equiv
\begin{bmatrix}
z_{aa} & z_{ab} & z_{ac} & z_{an} \\
z_{ba} & z_{bb} & z_{bc} & z_{bn} \\
z_{ca} & z_{cb} & z_{cc} & z_{cn} \\
z_{na} & z_{nb} & z_{nc} & z_{nn} \\
\end{bmatrix}
\begin{bmatrix}
\hat{I}_i^a \\
\hat{I}_i^b \\
\hat{I}_i^c \\
\hat{I}_j^a \\
\hat{I}_j^b \\
\hat{I}_j^c \\
\end{bmatrix}
$$

where $z_{rs}$ is the self-impedance of phase $r$, $z_{rs}$ is the mutual impedance between phases $r$ and $s$, $\hat{V}_r$ is the voltage phasor of phase $r$ in bus $i$ and $\hat{I}_r$ is the current phasor flowing in phase $r$ from $i$ to $j$, with $r,s \in \{a,b,c,n\}$ and $i,j = 1,2,\ldots,N$, where $N$ is the total number of power system buses.

The last row in Equation (1) can be expressed as:

$$
\hat{I}_j^n = \frac{\Delta \hat{V}_j^n}{z_{nn}} - z_{na} \hat{I}_j^a - z_{nb} \hat{I}_j^b - z_{nc} \hat{I}_j^c
$$

It is clear that setting $\Delta \hat{V}_j^n = 0$ in Equation (2) corresponds to the perfect grounding approximation, which in turn allows Kron reduction. However, even for non-zero neutral voltages, in usual distribution system operation the term $\Delta \hat{V}_j^n$ is dominated by the others terms in the numerator of Equation (2). In fact, grounded buses have their neutral potentials driven sufficiently low by the grounding impedances that, even if they are not zero, the contribution of the voltage drop term in Equation (2) is negligible.
Ungrounded wye systems are an exception to this, since the lack of grounding causes \( \Delta \hat{V}_n \) to equal the full voltage drop through the neutral conductor impedances. However, solving for neutral voltages in this type of system is trivial due to the following constraint for isolated systems:

\[
\hat{V}_i^n = \frac{1}{3}(\hat{V}_a^i + \hat{V}_b^i + \hat{V}_c^i)
\]  

(3)

where the \( \hat{V}_r^i, r \in \{a, b, c\} \), are phase voltage phasors obtained after solving implicit-neutral load flow.

For this reason, we henceforth assume the system is grounded and Equation (3) may not be applied.

From previous considerations, \( \hat{I}_n^i \) is significantly insensitive to \( \Delta \hat{V}_n \) in grounded systems and the error incurred in estimating it via Kron reduction is small, even if system grounding is imperfect. On the other hand, neutral voltages are strongly dependent on phase and neutral currents.

Hence, using the \( \Delta \hat{V}_n \equiv 0 \) approximation in Equation (2) and solving load flow, the obtained phase currents can be used to estimate neutral current:

\[
\hat{I}_n^i \approx -z_{na} \hat{I}_a^i + z_{nb} \hat{I}_b^i + z_{nc} \hat{I}_c^i - z_{nn} \hat{I}_n^i
\]  

(4)

A method is now proposed by means of which an equivalent circuit may be formed that allows estimation of neutral voltages. From the viewpoint of the neutral conductor, the \( \hat{I}_n^i \) computed in Equation (4) can be modeled as a current source, owing to its insensitivity to neutral voltage. Considering that Equation (4) already incorporates mutual impedances in neutral current, the transmission line can be modeled as a series impedance \( z_{nn} \), which may be more clearly seen by recalling that Equation (2) originates from a voltage drop equation in Equation (1). Finally, all existing grounding impedances \( z_i^g \) are connected from their respective neutral nodes to earth.

After assembling the equivalent circuit via the above procedures, it may be solved for obtaining the estimates of neutral voltages. The proposed method is given as pseudocode in Algorithm 1, in which an initial check is used to verify if the system is grounded; if the answer is negative, the algorithm switches to the direct application of Equation (3).

It should be noted that the proposed method is compatible with any algorithm designed for solving three-phase, three-wire load flow. In fact, Equation (4) shows that its input currents \( \hat{I}_n^i \) are functions of corresponding phase currents, which can be obtained by any load flow algorithm. Hence, the most convenient algorithm may be selected depending on the considered network topology.

### Algorithm 1: Method for estimation of neutral voltage

**Input:** \( \hat{I}_n^i, z_{ij}^{ij}, z_i^g; i, j = 1, 2, ..., N \).

1. if the system is grounded then
   2. for \( 1 \leq i \leq N \) do
      3. for \( 1 \leq j \leq N \) do
         4. Connect \( \hat{I}_n^i \) and \( \hat{I}_n^j \) from nodes \( i \) and \( j \), respectively, to ground, adjusting source directions for upstream and downstream currents.
         5. Connect \( z_{nn}^{ij} \) between nodes \( i \) and \( j \).
      6. end for
      7. Connect \( z_i^g \) from node \( i \) to ground.
   8. end for
   9. Solve the equivalent circuit.
8. else
11. Apply Equation (3) for all \( i = 1, 2, ..., N \).
12. end if
13. return \( \hat{V}_n^i; i = 1, 2, ..., N \).
As an example, the application of the proposed method is illustrated for the system shown in Figure 1, which is comprised of a grounded wye-connected load connected to an impedance-grounded source by means of transmission lines and a wye-wye transformer grounded on both sides. The resulting equivalent circuit is shown in Figure 2.

![Figure 1. Example system for constructing equivalent circuit.](image1)

In Figure 2, the current sources simulate the injection of current in the neutral circuit at each node, with the source directions arranged in order to account for upstream or downstream currents from Figure 1. The obtained circuit may be solved for the voltages via standard Y-bus matrix inversion.

### 3. Complexity Reduction

Suppose it is desired to compute all \( \hat{V}_{ni} \), \( i = 1, 2, \ldots, N \), as functions of the \( z_{ig} \) defined in an impedance domain \( z_{ig} \in \mathbb{Z} = \{z_{ig}^{(1)}, z_{ig}^{(2)}, \ldots, z_{ig}^{(M)}\} \), \( M \in \mathbb{N}^* \). In order to evaluate neutral voltages for all possible combinations of \( z_{ig} \) values via load flow, a total of \( MN \) load flow problems have to be solved, which shows that the problem complexity grows exponentially with \( N \).

If the proposed method is applied, all \( \hat{I}_{ni} \) are estimated by applying any three-wire load flow algorithm and Equation (4). Subsequently, neutral voltages are computed for each combination of grounding impedances by solving the equivalent circuit via Y-bus inversion. Hence, for the impedance domain \( Z \), a total of one three-wire load flow and \( MN \) iterations of Y-bus inversion is required. This is a favorable scenario in comparison with the execution of \( MN \) four-wire load flows, since:

- Y-bus inversion is linear and consists in one matrix inversion, whereas load flow is nonlinear and may require multiple Jacobian inversions;
- Four-wire load flow may lead to a poorly conditioned Jacobian, owing to the linear dependence between phase and neutral currents in each bus.

Suppose each load flow execution requires, on average, \( B \) matrix inversions. From previous considerations, the proposed method has, advantageously, a computational cost of \( B + MN \) inversions, whereas using four-wire load flow implies in \( BMN \) inversions. In Table 1, the comparison between computational requirements is summarized.

### Table 1. Comparison of computational requirements.

| Method          | # Load Flow Executions | # Y-Bus Inversions | # Matrix Inversions |
|-----------------|------------------------|--------------------|--------------------|
| Four-wire load flow | \( MN \)                | 0                  | \( BMN \)          |
| Proposed        | 1                      | \( MN \)           | \( B + MN \)       |

From the present discussion and general results shown in Table 1, it can be concluded that the proposed method provides significant complexity reduction if any of the following conditions is true:
• The system is ill-conditioned for load flow (large $B$);
• Neutral voltage must be computed over a large impedance domain (large $M$);
• There is a high number of buses in the system (large $N$).

4. Case Study 1—Comparison with Load Flow-Based Computations in the IEEE 4-Bus Feeder

For validating the proposed method, it was applied to a standard test system for which a result of neutral voltage computation with imperfect grounding already exists in the literature [10]. Furthermore, the system was simulated in the SimPowerSystems package in MATLAB for additional comparison.

The system is the IEEE 4-bus test feeder in delta-wye step-down transformer and unbalanced configuration. It consists in a grounded wye-connected unbalanced load (bus 4) being fed by the grounded wye secondary of a step-down transformer (bus 3). The transformer primary is delta-connected (bus 2) and is fed by an infinite bus (bus 1). Documentation of the test feeder and reference load flow results are discussed in [12]. This test system was selected since it is considered an ideal reference for testing load flow results when three-phase unbalanced models are used [13].

In Reference [10], explicit-neutral load flow based on the current injection method was used for computing neutral voltage magnitudes on the IEEE 4-bus test feeder for a grounding resistance of $R_g = 0.3 \ \Omega$ on buses 3 and 4. The reported results in [10] were $|\hat{V}_n^3| = |\hat{V}_n^4| = 74 \ \text{V}$. For further comparisons, we reproduced and solved the test feeder with imperfect grounding in the SimPowerSystems software. The corresponding implementation is given in Figure 3, where the current sources are controlled in order to emulate constant-power loads; all circuit elements were specified according to [12]. After running the simulation, the obtained results were $|\hat{V}_n^3| = |\hat{V}_n^4| = 73.2631 \ \text{V}$.

![Figure 3. Implementation of test system with imperfect grounding in SimPowerSystems.](image)

We now proceed with applying the proposed method to the test feeder. For illustration, computation of the neutral voltage estimates is carried out analytically. Considering the topology of the test feeder, it is clear that its wye side exactly corresponds to the right-hand side circuit on Figure 1. Furthermore, the delta side does not need to be represented in the circuit owing to absence of neutral current. Hence, the neutral equivalent circuit of the test feeder is given by the right-hand side circuit on Figure 2. Converting this circuit to voltage source representation, the equivalent circuit in Figure 4 is obtained.

![Figure 4. Equivalent neutral circuit for test system.](image)

Applying the superposition theorem to the circuit given in Figure 4 and using the fact that the currents $i_{43}^n = -i_{34}^n$, the following equations are obtained:
In Equations (5) and (6), \( z_3^g = z_4^g = R_g = 0.3 \Omega \). Using documented conductor impedance and phase current data [12] in Equation (4), an estimate \( \hat{I}_{n34}^n = 245.3267 \angle -72.09^\circ \) A is obtained. Also according to [12], the neutral conductor self-impedance is \( z_{nn}^{34} = 0.3254 + j0.7322 \Omega \). Applying this on Equations (5) and (6) yields \( |\hat{V}_{3n}^n| = |\hat{V}_{4n}^n| = 73.5980 \) V. It is of interest to note that the equivalent circuit structure correctly captures the equality in neutral voltage magnitude values; by substituting \( R_g \) for the grounding impedances in Equations (5) and (6), it is clear that \( |\hat{V}_{n3}^n| = |\hat{V}_{n4}^n| = R_g |\hat{I}_{n34}^n| \).

In Table 2, the results obtained for neutral voltage magnitude with the proposed method are compared to those computed with SimPowerSystems and reported in [10].

| Method                | \( |\hat{V}_{3n}^n| = |\hat{V}_{4n}^n| \) (V) | Percentual Difference from [10] (%) |
|----------------------|------------------------------------------|-----------------------------------|
| Alam et al. [10]     | 74.0000                                  | -                                 |
| SimPowerSystems      | 73.2631                                  | 1.00                              |
| Proposed             | 73.5980                                  | 0.54                              |

5. Case Study 2—Neutral Voltages as Functions of Grounding Impedance

As an example application of the proposed method, an analysis of neutral voltage as a function of grounding impedances is carried out for the previously considered IEEE 4-bus test system. By using Equations (5) and (6), the neutral voltages are estimated as functions of \( z_3^g \) and \( z_4^g \), without the need of repeatedly solving load flow for each ground impedance.

A domain of possible grounding impedance values is defined, namely \( |z_i^g| \in [0 \ \Omega, 0.4 \ \Omega] \) and \( \text{arg}\{z_i^g\} = 0 \) (resistive impedances), \( i \in \{3, 4\} \). The maximum resistance value of 0.4 \( \Omega \) was selected for being approximately half of \( |z_{nn}| \), which already implies significantly imperfect grounding. The impedance domain was discretized for simulation, according to \( z_i^g \in Z_0 = \{0.01k, k = 1, 2, \ldots, 40\} \).

In Figure 5, magnitude of the neutral voltages on buses 3 and 4 are plotted. Similarly, the corresponding voltage phase angles are plotted in Figure 6.
Interesting features of the results are now highlighted:

- As would be expected from the test feeder topology, symmetry around the hyperplane $|z^3_3| = |z^4_4|$ is observed in Figures 4 and 5;
- The subset of highest values of $|\hat{V}_n^3|$ for each $|z^4_4|$ are located in the hyperplane $|z^3_3| = 0.4 \, \Omega$; the same applies to $|\hat{V}_n^4|$ and each value of $|z^3_3|$ in the $|z^3_3| = 0.4 \, \Omega$ hyperplane. Furthermore, each $|\hat{V}_n^i|$ has stronger dependence on its respective $|z^i_3|$, which is coherent with the fact that neutral voltage is, to a significant degree, determined by local grounding.
- Each phase angle $\arg\{\hat{V}_n^i\}$ presents rapid convergence to zero in the neighborhood of its associated $|z^i_3| = 0$ hyperplane, which corresponds to the impedance seen from neutral being dominated by the resistive grounding impedances for close to ideal grounding.

As a means of further validating this case study, $|\Delta\hat{V}_n^{34}|$ is plotted in Figure 7 as a function of the grounding impedance magnitudes. The maximum obtained magnitude is $|\Delta\hat{V}_n^{34}| = 76.2858 \, V$, which happened for the cases $|z^3_3| = 0 \, \Omega$, $|z^4_4| = 0.4 \, \Omega$ and vice-versa. Averaging over the impedance domain, the value $|\Delta\hat{V}_n^{34}|_{\text{avg}} = 26.1410 \, V$ is obtained. Hence, the estimated voltage magnitudes are such that $|\Delta\hat{V}_n^{34}|$ is always one order of magnitude smaller than $|I_n^{34}|$ and thus the approximation of Equation (4) is validated for the selected impedance domain.

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**Figure 6.** Neutral voltage phase angles on buses 3 and 4.

**Figure 7.** Magnitude of $\Delta\hat{V}_n^{34}$ for all grounding impedances.
To test the previously discussed computational complexity of the proposed method, this case study was also solved via SimPowerSystems software and the method proposed in [10]. The corresponding execution times were recorded and are given in Table 3, from which it is clear that the proposed method provides significant reduction in processing time.

An adequate degree of accuracy in neutral voltage magnitude was verified. For all possible pairs of $z_i^g \in \mathbb{Z}_o, i = 3, 4$, the maximum percentual differences between $|\hat{V}_{34}^n|$ computed with the proposed method and those obtained with SimPowerSystems and [10] were, respectively, 6.8% and 5.5%. In both cases, such maximum errors were obtained for the cases $|z_3^g| = 0 \, \Omega, |z_4^g| = 0.4 \, \Omega$ and vice-versa, which is coherent with the previous discussion regarding error due to non-zero values of $|\Delta\hat{V}_{34}^n|$.

Table 3. Comparison of case study execution times.

| Method               | Time (ms) |
|----------------------|-----------|
| Alam et al. [10]     | 303.92    |
| SimPowerSystems      | 1541.10   |
| Proposed             | 40.30     |

6. Conclusions

In this Letter, a novel method for estimating neutral voltages independently from explicit-neutral load flow has been proposed. The method is of practical interest because it allows estimation of neutral voltage without the need of solving load flow for every set of grounding impedance values and uses implicit-neutral load flow data as input. Validation was done via comparison with a load flow-based results, which suggests the proposed method has adequate accuracy. A case study based on the proposed method was carried out to demonstrate its usefulness in estimating neutral voltages as functions of grounding impedances, which was achieved with significantly smaller execution times with respect to standard load flow methods.

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