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ORIGINAL ARTICLE

Engineering-Based Steady-State Analysis of Voltage Profile and Power Flow in Three-Phase Unbalanced Distribution Systems

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ABSTRACT

This study presents a detailed engineering-based assessment of the steady-state electrical behavior of three-phase unbalanced distribution systems. The modeling and simulation were conducted on a professional-grade engineering platform, enabling high-resolution analysis of phase asymmetries inherent in the system. Power flow distribution, voltage profiles, regulator responses, and system losses were examined on a per-phase basis to capture the impact of asymmetrical loading conditions. According to the simulation results, voltage unbalance factors reached up to 1.2% with voltage deviations exceeding 2.5% at certain nodes, and significant drops were observed especially in phase C at terminal busbars. Most of the total active and reactive power losses were concentrated in heavily loaded phases and long feeder branches, and these losses were calculated as 111.06 kW and 324.65 kVAr, respectively. The findings provide a technically based reference for understanding the voltage behavior in unbalanced systems. In addition, this study contributes to the development of phase balancing strategies, regulator control algorithms, and advanced load integration scenarios within distribution networks. The findings provide a technically based reference for understanding the voltage behavior in unbalanced systems and serve as a foundation for future investigations into harmonics, probabilistic load dynamics, and renewable energy integration.

Index Terms—Distributed system, power flow, unbalanced system, voltage profile

I. INTRODUCTION

A. Motivation

The dynamic nature of modern distribution systems has become a more complex engineering challenge under conditions such as increasing load diversity and permanent phase unbalance. In low and medium voltage networks, the increasing concentration of single-phase loads leads to voltage deviations, higher line losses, and asymmetric power flow between phases [1,2]. Such structural imbalances weaken the system stability and seriously degrade the voltage quality, especially at the end-of-line busbars.

Unbalanced load distribution between phases not only causes differences in voltage magnitudes but also leads to excessive neutral current flow. This contributes to problems such as unbalanced transformer loading, phase-specific reactive power unbalances, and reduced effectiveness of traditional compensation strategies [3]. Accordingly, the voltage unbalance factor (VUF) has become an important quantitative indicator for monitoring power quality and system performance. Exceeding the recommended limits (usually between 1% and 2% in many standards) can lead to torque fluctuations in motors, resonance in capacitor banks, harmonic distortion in power electronics, and false triggering of protection devices [4-6].

Since the load density varies both temporally and spatially, certain areas of the system experience significant undervoltages while others experience overvoltage conditions. Such fluctuations pose serious challenges to grid stability, especially in grids where voltage regulators operate with fixed tap positions. Today, utilities and operators are moving towards more advanced solutions such as increased monitoring points, active phase balancing mechanisms, and smart regulation strategies [7-9].

To correctly analyze such events, traditional load flow models based on balanced system assumptions are no longer sufficient. Instead, detailed phase-by-phase unbalanced power flow analysis has become essential. To address this need, engineering-grade software tools (such as CYME [10], GridLAB-D [11], and ePHASORSIM [12]) have been developed to enable high-resolution simulations that

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replicate both theoretical scenarios and real-world configurations. These platforms provide detailed information on phase-specific current paths, regulator tap behavior, VUF response, and system losses, providing a foundation for advanced decision support mechanisms in distribution system planning and operation.

This study analyzes the inherent asymmetry of a three-phase unbalanced distribution grid without introducing specific load types such as electric vehicles or heat pumps. System-level responses, including voltage profiles, unbalance factors, directional power flows, and phase-based regulation dynamics, are examined from an engineering perspective. The results aim to provide a technically grounded framework for evaluating both existing structural imbalances and potential future integration scenarios involving unbalanced loads.

It is important to note that the scope of this study is intentionally limited to steady-state analysis. While dynamic phenomena such as sudden load changes and fault conditions are highly relevant in real-world operation, they are beyond the scope of this paper and are planned to be addressed in future work.

B. Literature Review

Three-phase unbalanced distribution systems have become increasingly sensitive to power losses, voltage deviations, and power quality disturbances. This is mainly due to the increase in single-phase loads and the increasing asymmetry in load distribution among phases. Recent studies have placed significant emphasis on phase-specific voltage distortion, asymmetric regulator responses, VUF, and reactive power compensation methods. In this direction, simulation-based studies using standard test feeders have further enriched the literature by providing a more detailed analysis of how unbalanced conditions affect overall system performance.

A large number of studies have investigated the technical implications of asymmetric operation scenarios using various system topologies and modeling frameworks. For example, Morales-España and Ramos [13] examined the limitations of traditional power flow methods in representing unbalanced system behavior and emphasized the need for phase-specific approaches. Again, Zhang et al. [14] found that the presence of single-phase loads on distribution feeders can increase VUF levels by up to 2% and pose significant risks to power quality.

Chen and Xu [15], in their study, investigated the effect of phase level on voltage profiles and showed that unequal regulator responses between phases can destabilize voltage control. In line with the study, Khademi and Mohseni [16] proposed a phase-oriented reactive power compensation strategy that significantly reduces voltage deviations. Completing the related studies, Balogun and Venayagamoorthy [17] developed a dynamic modeling framework that captures phase behaviors under time-varying load conditions and shows a strong correlation between real-time voltage fluctuations and system loading patterns.

In a comparative study, Blevins and Ghosh [18] evaluated multiple simulation platforms and reported significant differences in convergence stability, phase-specific accuracy, and load flow responses.

In terms of voltage regulation and tap optimization, Medina-Gaitán et al. [19] applied fixed-step capacitor banks and phase-matching algorithms to improve voltage profiles. Likewise, Lim et al. [20] analyzed field data to demonstrate that tap positions optimized per phase enhanced voltage compliance. Li et al. [21] proposed a coordinated control scheme combining smart inverters and on-load tap changers (OLTCs), resulting in improved system balance and lower VUF levels.

The very definition of voltage unbalance has also been challenged. Girigoudar and Roald [22] showed that the choice of the VUF metric can significantly alter optimization outcomes. Abujubbeh et al. [23] introduced phase-wise voltage sensitivity analysis as a preemptive diagnostic tool, extending the safe operating envelope of unbalanced systems.

Salih and Chen [24] analytically demonstrated the engineering impacts of elevated VUF, linking it to torque fluctuations in motors, harmonic distortion, and increased transformer losses. Kansal and Kumar [25] developed three-phase power flow algorithms that more accurately compute voltage variations under unbalanced loading. Abdel-Akher et al. [26] proposed sequence-component-based solutions as an alternative to conventional modeling, addressing stability issues in asymmetrical conditions.

Moreover, the suitability of different software platforms for analyzing unbalanced networks has been discussed extensively. Silva and Lopes [27] compared OpenDSS and ETAP, concluding that ETAP offered more realistic modeling of tap behavior across phases. Saeed and Al-Hadithi [28] compared ETAP and PSCAD using benchmark test systems, identifying notable differences in their phase-wise simulation performance.

These developments have been extended to more flexible simulation environments such as GridLAB-D and ePHASORSIM. Supported by the U.S. Department of Energy [29], GridLAB-D enables detailed

Main Points

- A three-phase unbalanced distribution system was modeled using a standard IEEE 13-bus configuration to evaluate voltage profiles, phase loading, and system losses under natural asymmetry.
- Simulation results indicate that structural load imbalance leads to notable deviations in voltage quality and power distribution across phases.
- The phase-wise operation of the voltage regulator demonstrates adaptive response behavior, yet highlights the limitations of conventional control methods under unbalanced conditions.
- The study offers an engineering-level reference for understanding the operational challenges of unbalanced distribution networks, especially in scenarios without artificially imposed load asymmetry.

unbalanced scenario generation, while ePHASORSIM by OPAL-RT [30] is widely used for real-time simulations of unbalanced systems. Together, these platforms support detailed engineering modeling and more reliable analysis of real-world grid behavior.

Finally, Bansal and Bhatti [31] offered a comprehensive evaluation of how load imbalance affects system reliability, emphasizing that load optimization and phase balancing are crucial strategies for improving operational stability in distribution networks.

In contrast to earlier studies that often analyze isolated phenomena—such as VUF, voltage drops, or regulator behavior—this study provides a synchronized, multi-metric evaluation of three-phase unbalanced distribution networks. Specifically, it concurrently assesses voltage profiles, tap changer dynamics, directional power flows, and system losses under naturally occurring phase asymmetries without introducing artificial disturbances. This holistic and integrative approach allows for a more realistic and engineering-relevant understanding of operational challenges in unbalanced networks, which, to the best of our knowledge, has not been comprehensively addressed in the existing literature.

C. Research Gap

The studies discussed above have successfully addressed several dimensions of three-phase unbalanced distribution systems and have clearly demonstrated the necessity of phase-specific analysis from an engineering standpoint. However, a significant portion of the existing literature tends to treat parameters such as phase-wise voltage behavior, power flow, and regulation response in isolation. Comprehensive investigations that evaluate these parameters holistically and in synchronization—under the natural imbalance of the system—remain noticeably limited.

In many instances, artificial load imbalance scenarios are introduced by distributing predefined percentages of load across phases, which may help create controlled test conditions but fail to reflect the organic behavior of real-world systems. This approach, while analytically useful, does not offer a direct lens into how the system performs under its native topology and inherent phase asymmetries.

Furthermore, engineering-grade commercial simulation platforms such as ETAP are often utilized for validation or comparative purposes, yet their capacity to extract detailed engineering insights—such as phase-specific voltage responses, tap adjustment behavior, or directional power flows—is rarely explored in depth. Even in studies using standardized test feeders, attention is frequently limited to one or two isolated metrics like voltage drop or the VUF, with little-to-no assessment of critical aspects such as phase-wise loss distribution or regulator coordination across phases.

Therefore, there remains a considerable gap in the literature regarding both the application of high-resolution unbalanced load flow simulations using professional engineering platforms and the comprehensive evaluation of phase asymmetries across multiple interdependent dimensions—namely, voltage profiles, regulator operations, and power losses—within the context of a system's actual topology. This work builds upon those foundations by offering a unified, phase-wise analysis of interacting technical parameters, aiming to fill a major methodological gap in the literature.

D. Contribution and Paper Organization

This study is designed to examine, in detail, the operational behavior of a three-phase unbalanced distribution system under its naturally occurring phase asymmetries. Without introducing any external disturbance scenarios or artificially constructed loading patterns, key electrical parameters—such as voltage profile, VUF, power flow, regulator tap positions, and system losses—have been analyzed through a rigorous engineering perspective based on the system's inherent configuration.

The modeling process was performed using a widely adopted professional-grade simulation platform that provides high-fidelity insights into phase-specific voltage responses, individual regulator tap behaviors, and directional power flows between busbars. Furthermore, the simulation results were cross-validated with standardized IEEE test data to ensure model reliability and practical relevance. The strong agreement observed in the benchmarks confirms both the validity of the analytical framework and its applicability to real-world grid scenarios.

Unlike traditional studies that usually rely on theoretical unbalanced scenarios or controlled phase injections, this study presents an application-oriented analysis based on the actual structural conditions of the system. In doing so, it provides a technically sound foundation for future developments in unbalanced load integration, phase balancing strategies, and advanced voltage regulation control algorithms.

The paper is organized as follows: Section 2 describes the configuration of the test system, including load profiles, voltage regulation components, and simulation environment specifications under Materials and Methods. Section 3 presents the simulation results, focusing on voltage trends, VUF values, tap location behaviors, and loss distributions supported by detailed tables and visualizations. Finally, Chapter 4 interprets these findings through an engineering lens, providing insights into system behavior and suggesting potential strategies for future applications.

II. METHODS

In this paper, a three-phase unbalanced distribution system is modeled in an engineering-grade simulation environment to allow for detailed phase-specific analysis. The selected system represents a medium-voltage reference network containing a mixture of single-phase and multi-phase load connections, voltage regulation units, and shunt compensation components. The configuration is compatible with standardized IEEE benchmark structures widely used in power systems research [32, 33].

A. Structure and Characteristics of the Test System

The test system for which simulation studies were conducted operates at 4.16 kV and consists of 13 busbars, 12 line segments, two shunt capacitor banks, and a three-phase voltage regulator. Loads are connected throughout the system in a variety of formats: some single-phase (e.g., busbar 652), some two-phase (e.g., busbar 646), and others three-phase (e.g., busbar 634). This variety provides a realistic basis for evaluating phase asymmetry and voltage unbalance under actual distribution conditions [34].

Although the IEEE 13-bus test feeder is not based on real-world measurements, it is widely regarded in the literature as a representative benchmark for validating voltage regulation strategies and load asymmetry effects in medium-voltage distribution networks due to its structural complexity and phase diversity.

Key system components include:

- Buses (13 total): Featuring single-phase (e.g., 652), two-phase (e.g., 646), and three-phase (e.g., 634) configurations.
- Overhead and underground Lines (12 segments): Configured based on IEEE types 601–607.
- Voltage oltage regulator: A three-phase Resistance-to-Reactance ratio (RX) type regulator with independent tap settings, located between buses 650 and 632.
- Transformers: A main 5000 kVA transformer (115 kV / 4.16 kV) and an auxiliary transformer (XFM-1).
- Shunt capacitor banks: Installed at Bus 675 (three × 200 kVAR per phase) and Bus 611 (100 kVAR on phase C).
- Load Models: Mixed configuration using Y–PQ, D–PQ, Y–Z, and D–I types distributed across the network.

B. Line Configurations: Overhead and Underground

The transmission infrastructure was modeled using IEEE configurations 601 (overhead) and 606 (underground). Phase-specific line impedances were represented using π-model equivalents, which are essential for accurately capturing asymmetrical behaviors in unbalanced systems [35].

Sample impedance values:

- Overhead (601): $Z_{AB} = 0.3465 + j1.0179\ \Omega/mil$
- Underground (606): $Z_{AA} = 0.7982 + j0.4463\ \Omega/mil$

C. Load Profile and Phase Distribution

Loads were modeled using fixed PQ (active/reactive), constant impedance (Z), and constant current (I) characteristics. The concentration of single-phase loads at specific buses led to distinct voltage variations among phases. Such diversified load modeling is widely supported in the literature as a realistic approach to simulate unbalanced systems [36, 37].

Total load distribution:

- Active power: A: 1158 kW, B: 973 kW, C: 1135 kW
- Reactive power: A: 606 kVAr, B: 627 kVAR, C: 753 kVAr

This structure creates a structural voltage imbalance in the system and directly affects the regulator's performance.

D. Voltage Regulator Modeling

A three-phase RX-type regulator with independent tap settings per phase was modeled to evaluate system response under unbalanced voltage conditions. Phase-specific regulation allows for more detailed voltage control, enabling engineers to assess both magnitude and inter-phase symmetry [38, 39].

The regulator was modeled as a Wye-connected RX-type unit with fully decoupled tap adjustment per phase.

E. Shunt Capacitor Placement and Capacity

Shunt compensation was implemented using fixed capacitor banks installed at phase-specific locations to support local voltage levels and balance reactive power. This configuration allowed for detailed observation of their impact on voltage quality across the system [40].

Capacitor placement and ratings:

- Bus 675: 200 kVAR per phase → 600 kVAR total
- Bus 611: 100 kVAR on Phase C
- Total capacity: 700 kVAR (all fixed)

F. Simulation Parameters and Solution Method

The load flow was solved using a full three-phase Newton–Raphson algorithm, known for its numerical stability in unbalanced systems and widespread use in industrial applications. The convergence tolerance was set to 1.0 × 10−41.0 \times 10^{−4}1.0 × 10−4 per unit, with a maximum of 25 iterations allowed [41].

All simulations were performed using a high-precision solution engine integrated within a professional-grade simulation platform. The following settings were used:

- Load flow algorithm: Three-phase Newton–Raphson (full matrix)
- Voltage deviation threshold: ±5%
- Convergence criterion: 1.0e–4 per unit
- Load model: Constant PQ (active + reactive)
- Max iterations: 25
- Line lengths: Defined per IEEE dataset (e.g., 632–645 = 500 ft)

The PQ load model was uniformly applied across all buses to ensure consistency in phase-specific load representation.

II. RESULTS

This section presents a detailed phase-by-phase analysis of voltage behavior, power flow characteristics, voltage unbalance, and regulation responses within a three-phase unbalanced distribution system. All simulations were conducted using the IEEE 13-bus standard test system implemented within a professional engineering software environment.

The focus was to evaluate the system's inherent response under its naturally unbalanced load configuration, providing a comprehensive understanding of voltage deviations, directional power flows, and system losses across individual phases. Analyses were performed under a constant PQ load model using a full three-phase Newton–Raphson solution algorithm.

III. DISCUSSION

A. Simulation Parameters and Solution Method

Prior to the simulation phase, the entire distribution system—including buses, loads, transformer, voltage regulator, and shunt compensation elements—was meticulously defined on a per-phase basis using ETAP simulation software. Both the network topology and the distribution of load types were carefully modeled, with particular attention given to the placement of single- and two-phase loads, which are key contributors to system asymmetry and critical for analyzing unbalanced behavior.Loads were modeled using Y–PQ (wye-connected constant power), D–PQ (delta-connected constant power), D–Z (delta-connected constant impedance), and Z (constant impedance) types. The constant PQ (active + reactive) load representation was applied consistently across buses, as summarized in Table I. All simulations in this study were carried out using ETAP version 22.0.0. The load flow analysis employed a full three-phase Newton–Raphson solver with a convergence tolerance of 1.0×10^{-4} per unit and a maximum iteration limit of 25. The voltage deviation threshold was set at ±5%. Constant PQ load models were used uniformly across all buses, and line lengths were defined based on IEEE standard dataset values. The regulator settings, including CT/PT ratio (Current Transformer/Potential Transformer ratio) and R/X (resistance-to-reactance) configuration, are presented in Table II.

Fig. 1 illustrates the overall topology of the configured test system prior to running the simulation. It provides a clear visualization of line impedances, load configurations at each bus, capacitor placements, and the exact location of the voltage regulator within the network.

Visualization generated using ETAP v22.0.0. Export resolution: 300 dpi. Color-coded elements represent per-phase voltage levels and directional power flows.

TABLE I.
PHASE-WISE POWER LOADS AT SELECTED BUSES

Bus	Model	Phase A (kW/kVAr)	Phase B (kW/kVAr)	Phase C (kW/kVAr)
634	Y–PQ	160/110	120/90	120/90
645	Y–PQ	0/0	170/125	0/0
646	D–Z	0/0	230/132	0/0
671	D–PQ	385/220		
675	Y–PQ	485/190	68/60	290/212

TABLE II.
PHASE-SPECIFIC REGULATOR SETTINGS

Parameter	Phase A	Phase B	Phase C
Nominal Voltage (V)	122	122	122
Bandwidth (V)	2.0	2.0	2.0
CT/PT Ratio	700/20	700/20	700/20
Tap Position	10	8	11
R / X Setting	3/9	3/9	3/9

B. Unbalanced Load Flow Simulation and Voltage Behavior

Once the simulation was executed, the system's phase-specific voltage profiles, power flow directions, and voltage deviations—arising from its inherently unbalanced load structure—were carefully recorded. The voltage regulator operated independently for each phase, and distinct tap positions were observed at buses with high loading levels. This confirms that each phase demands a separate regulation response and demonstrates the necessity of phase-resolved simulation analysis.

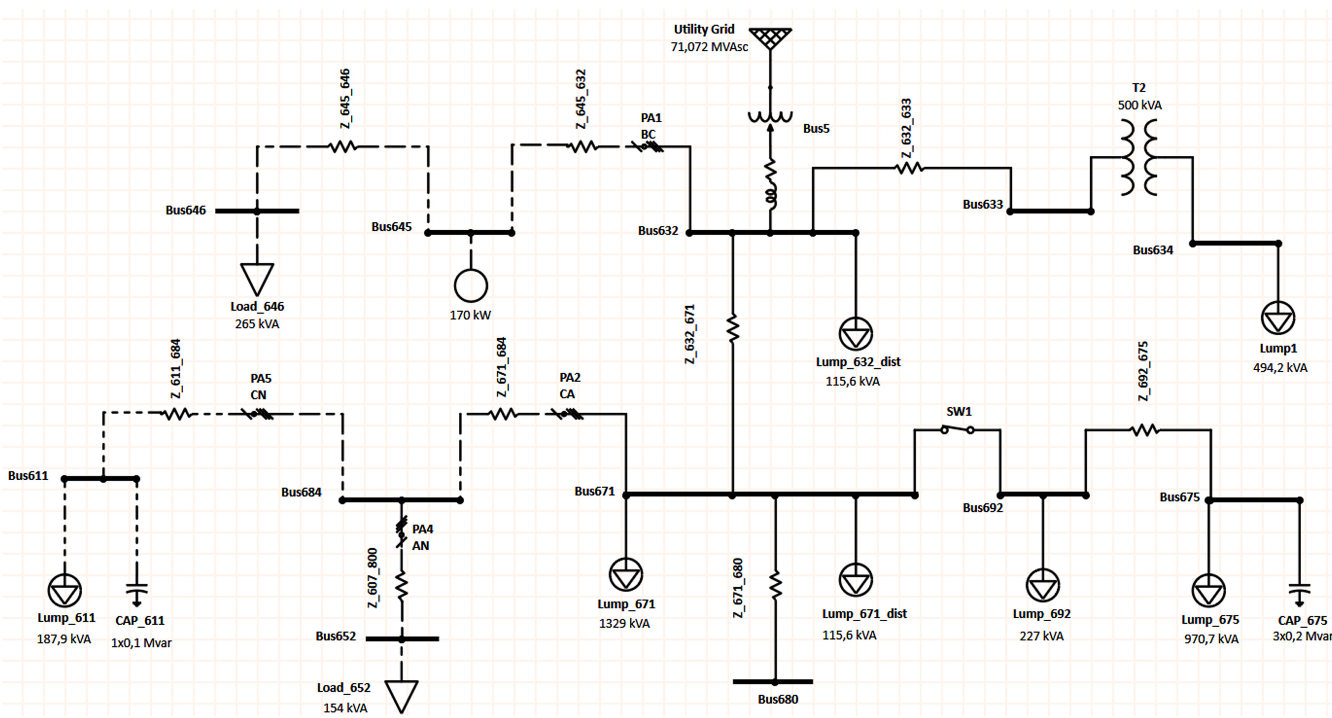

Fig. 1. Schematic diagram of the three-phase unbalanced distribution system before simulation.

At several buses approaching the lower voltage threshold (e.g., Bus 680 and Bus 675), significant voltage drops were observed. Conversely, minor overvoltages were detected at others (e.g., Bus 634). These localized fluctuations illustrate how the system responds to inter-phase load imbalances.

Fig. 2 displays the post-simulation outputs, including voltage profiles, directional power flows, regulation behavior, and system losses under unbalanced loading. Phase voltages, current directions between buses, and inter-phase differences are visualized through color-coded circular elements. Buses with critical voltage drops (e.g., Bus 652) are marked in red tones, while more balanced regions are shown in green to blue hues for intuitive visual interpretation.

Figures illustrating system topology and voltage behavior were captured directly from the ETAP simulation interface using native export functions at 300 dpi resolution to maintain visual accuracy.

C. Voltage Imbalance and Regulation Responses

Analysis of the simulation results revealed that, at specific locations such as Bus 675 and Bus 680, the voltage on phase C dropped by more than 5% (e.g., from 116.0 V to 110.3 V). This was largely due to excessive phase-specific loading and resulted in significant voltage asymmetry.

Additionally, an overvoltage of approximately 2.3% was recorded on phase A at Bus 634—caused by the regulator's inability to uniformly balance voltage under unbalanced loading conditions. Notably, the tap settings differed across all three phases: +10 for phase A, +8 for phase B, and +11 for phase C. While this demonstrates the system's adaptive regulation capacity, it also points to the limitations of traditional tap control strategies when dealing with unbalanced loads.

D. Voltage Unbalance Factor Analysis

The VUF was calculated based on differences in both voltage magnitude and angle across phases. Results indicated that VUF levels reached up to 1.2% at high-load buses such as Bus 671 and Bus 675. Given that most standards recommend maintaining VUF below 1.0%, the system exhibits marginal voltage quality under these loading conditions.

This confirms that VUF not only serves as a useful measure of voltage symmetry but also acts as an early indicator of potential power quality risks stemming from phase imbalance. A table summarizing these VUF values may be included in future versions of the paper.

E. Power Flow and System Losses

The total active and reactive power losses calculated across the system were 111.06 kW and 324.65 kVAR, respectively. These losses were mainly concentrated in buses experiencing substantial phase-specific imbalance, particularly Bus 675, Bus 680, and Bus 652—located toward the end of heavily loaded feeder lines.

Detailed phase-wise current flow analysis showed that:

- Phase A: Carried a significant portion of the load, with current predominantly flowing from Bus 671 to Bus 675 and Bus 680, marking this path as the system's most heavily utilized corridor.
- Phase B: Exhibited reverse current flow in certain segments due to underloading.
- Phase C: Showed intensified current flow in both the Bus 632 branch and the segment connected to Bus 652.

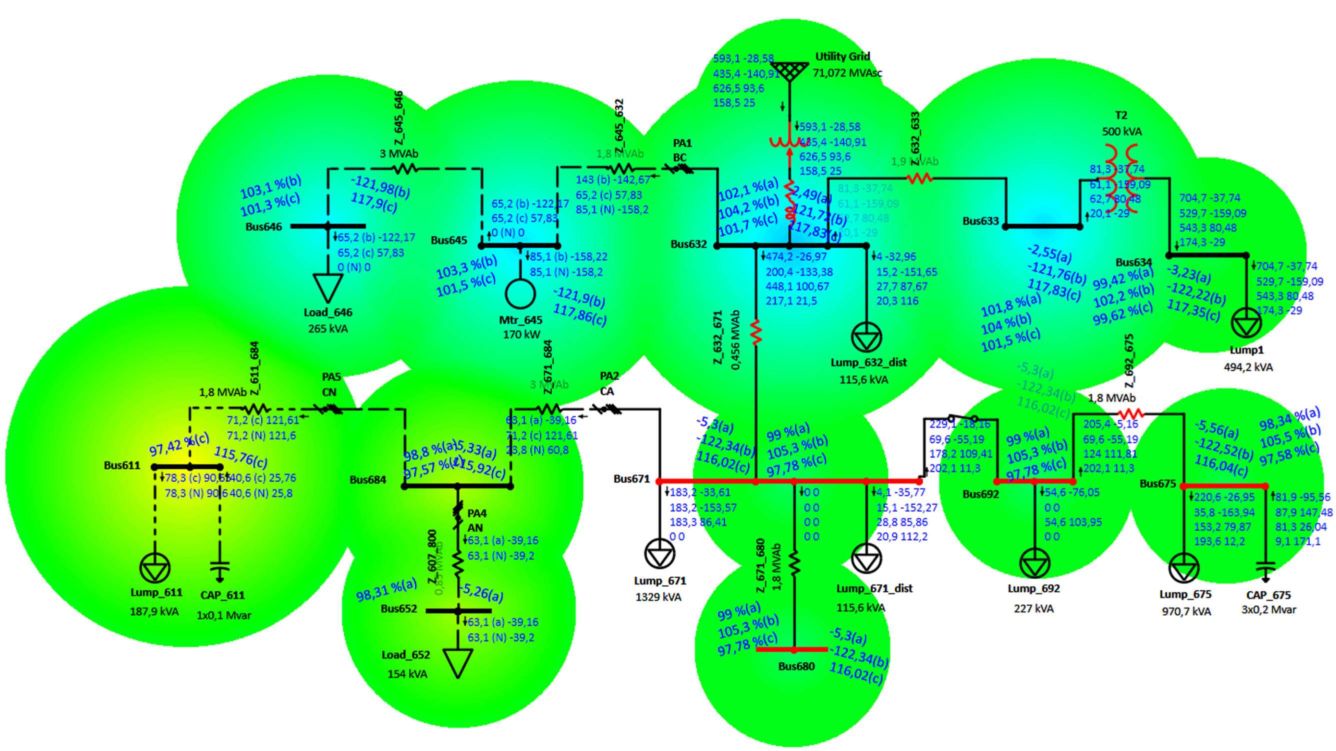

Fig. 2. Voltage profiles and power flow directions under unbalanced loading.

These directional asymmetries highlight the uneven load distribution among phases and its direct impact on system losses and voltage deviations.

F. Engineering Interpretation

Based on all simulation results, the engineering response of the system under naturally unbalanced loading conditions can be summarized as follows:

- The voltage regulator exhibited adaptive behavior on a per-phase basis, yet was insufficient in reducing voltage deviations below 2.5% across all phases.
- Voltage unbalance factor values exceeded acceptable thresholds at certain buses, indicating the need for advanced regulation algorithms, reactive power control strategies, and phase balancing mechanisms.
- Buses 675, 680, and 634 were identified as the most voltage-sensitive points in the network, due to both their load intensity and voltage drop patterns.

These findings are not only valuable for understanding the intrinsic electrical behavior of unbalanced systems but also serve as a technical reference for future integration scenarios involving inherently unbalanced and distributed loads, such as electric vehicle (EV) charging stations or photovoltaic (PV) arrays.

G. Limitations and Future Work

While the present study offers a high-resolution steady-state analysis of three-phase unbalanced distribution systems, several important aspects are beyond its current scope and are acknowledged as limitations.

First, the simulations are based on static load models and do not incorporate temporal or stochastic variations in demand. Real-world distribution networks exhibit dynamic behaviors influenced by seasonal, daily, or probabilistic fluctuations. Therefore, future research will aim to include historical load profiles and probabilistic simulations to better reflect actual operating conditions.

Second, harmonic distortions and their cumulative effects on voltage quality, equipment aging, and protection coordination have not been evaluated. Considering the growing integration of nonlinear and power-electronic-based devices, future studies will incorporate detailed harmonic analysis to assess waveform integrity and system resilience.

Third, the current framework does not model transient scenarios such as abrupt faults, switching operations, or renewable intermittency. These dynamic events play a critical role in the stability and control performance of distribution systems. Thus, transient stability studies and time-domain simulations will be carried out in subsequent phases of this research.

Moreover, the integration of distributed energy resources (DERs)—including photovoltaic arrays and wind turbines—will be examined in different case studies. Their impact on phase unbalance, regulator response, and local voltage support will be analyzed under both steady-state and dynamic conditions.

Finally, to ensure that the proposed methodology remains not only technically robust but also economically feasible, future work will include comprehensive assessments of operational costs, control complexity, and practical deployment challenges in real utility environments.

IV. CONCLUSION

This study presents a comprehensive modeling and simulation effort aimed at analyzing three-phase unbalanced distribution systems from an engineering perspective. Phase-specific voltage deviations, system losses, and regulation behaviors resulting from asymmetric load distribution were examined in detail, providing technical insights into the operational impact of structural imbalance in distribution networks.

Simulation results revealed significant voltage discrepancies between phases—particularly at heavily loaded nodes such as Bus 675, 680, and 652. At these buses, phase C voltages exhibited drops exceeding 5%, while the regulator's responses to the asymmetrical load patterns were found to be insufficiently balanced or timely. Although independent tap positions per phase indicated that the regulator was responding adaptively, the system failed to keep all voltage deviations within acceptable thresholds. This outcome suggests that conventional RX-type regulation schemes may lack the flexibility required to accommodate the evolving diversity of load types in modern distribution systems.

In terms of the VUF, values reaching up to 1.2% at critical buses such as 671 and 675 indicated that the system was operating near its power quality limits. This level of imbalance narrows the safety margin for inverter-based technologies and sensitive industrial equipment. The simulations confirmed that without phase-wise reactive power compensation and strategic load balancing, such asymmetries can have a measurable negative impact on both performance and reliability.

When considering total system losses, the findings also point to a clear link between unbalanced loading conditions and reductions in energy efficiency and system stability. Phase A was observed to carry a disproportionate share of the load, while reverse current flows in underutilized segments of phase B underscored the presence of structural asymmetry not only in voltage levels but also in directional power distribution.

As a natural extension of this study, future research will focus on dynamic simulations involving abrupt load variations, transient faults, and time-dependent control strategies, thereby capturing the full spectrum of operational challenges in unbalanced distribution networks.

Although this study is restricted to steady-state behavior, the framework sets the foundation for future extensions involving dynamic and economic analyses under renewable integration scenarios.

In terms of practical recommendations and future directions, given the limited response time of traditional tap-changing mechanisms under established voltage sensitivities and unbalanced conditions, several advanced control strategies are proposed for future applications. These include:

- Phase-based OLTC optimization algorithms that dynamically adjust tap positions independently for each phase based on local voltage deviations.
- Reactive power compensation using smart inverters with voltage unbalance detection and fast response capabilities.
- Artificial intelligence–powered regulation schemes trained on historical and real-time data are designed to predict unbalanced trends and preemptively implement corrective control actions. These techniques can significantly improve the adaptability, responsiveness, and phase balance of modern distribution grids operating under increasing load asymmetry and DER penetration.

Ultimately, the detailed phase-specific modeling and load flow analysis carried out in this study not only allowed for an in-depth assessment of the current system's performance but also shed light on the engineering preparations necessary for integrating future asymmetrical loads such as EV chargers and PV arrays. The results emphasize the growing need for more sensitive, phase-aware, and adaptive control mechanisms in modern distribution systems. In future studies, we plan to validate the simulation results using real-world distribution system data to further enhance the practical relevance of the findings.

Data Availability Statement: The data that support the findings of this study are available on request from the corresponding author.

Peer-review: Externally peer-reviewed.

Author Contributions: Concept – F.A.F.; Design – F.A.F.; Supervision – F.A.F.; Resources – F.A.F.; Materials – F.A.F.; Data Collection and/or Processing – F.A.F.; Analysis and/or Interpretation – F.A.F.; Literature Search – F.A.F.; Writing – F.A.F.; Critical Review – F.A.F.

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