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Impact of Nonlinear and Unbalanced Loads on Neutral Conductors in Three-Phase Systems: Modelling and Simulation Analysis

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Abstract: The rise of nonlinear and unbalanced loads in modern electrical systems poses challenges to power quality management. These loads, prevalent in electronic devices and industrial equipment, induce harmonic distortions and unbalance, adversely affecting the neutral conductor in three-phase systems. This study investigates these effects through modeling and simulation using MATLAB/Simulink and symmetrical components theory for detailed power quality analysis. The research focuses on three scenarios: nonlinear loads, unbalanced loads, and combined nonlinear-unbalanced loads. Simulation results show that nonlinear loads significantly increase harmonic content, while unbalanced loads lead to notable power quality deviations. When combined, these conditions exacerbate harmonic distortions and unbalance, resulting in higher neutral current magnitudes. Key findings highlight the severe impact of combined load conditions on the neutral conductor, emphasizing the need for accurate modeling and analysis. This research provides valuable insights and practical recommendations for addressing the challenges of nonlinear and unbalanced loads, contributing to improved power system design and management.

Keywords: Power Quality; Unbalanced Load; Nonlinear Load; neutral Current

1 Introduction

POWER quality has emerged as a critical aspect of modern electrical power systems, driven by the increasing integration of sensitive electronic devices, advanced industrial equipment, and distributed generation sources. Power quality issues can manifest in various forms, including voltage sags, swells, transients, and harmonic distortions [1]. Among these, harmonic distortions and unbalanced loads are particularly significant, as they can severely affect the performance and reliability of power systems. The presence of these issues is closely related to the behaviour of the neutral current in three-phase systems [2] [3].

Harmonic distortions are primarily introduced by nonlinear loads, such as switch mode power supplies (SMPS), variable frequency drives, computers, and other electronic devices. These loads draw current in a non-linear fashion, causing the current waveform to deviate from the ideal sinusoidal shape. This deviation results in the generation of harmonics—integer multiples of the fundamental frequency—that propagate through the power network [4]. Harmonics can lead to several detrimental effects, including increased system losses, overheating of equipment, interference with communication systems, and potential resonance conditions that can amplify distortion and cause equipment failure [5].

Unbalanced loads, on the other hand, occur when the power consumption in the phases of a three-phase system is not equal [6]. This imbalance can arise from the uneven distribution of single-phase loads, varying load demands across phases, or faults within the system.

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Unbalanced loads lead to unequal currents in each phase, resulting in voltage imbalances and increased neutral currents. The neutral conductor, which ideally carries minimal current in a balanced system, becomes a significant pathway for the imbalance current in unbalanced systems. This can cause overheating, increased losses, and potential damage to the neutral conductor [7].

The neutral current in three-phase systems is a critical parameter influenced by both harmonic distortions and load imbalance. Under ideal balanced conditions, the neutral current should theoretically be zero. However, in practical systems, the presence of nonlinear and unbalanced loads leads to substantial neutral currents [8]. This current is composed of both the fundamental frequency component and harmonic components, which together can exacerbate the thermal stress on the neutral conductor and other system components [9].

This paper aims to address these challenges by providing a comprehensive analysis of the impact of nonlinear and unbalanced loads on the neutral conductor in three-phase systems. Utilizing MATLAB/Simulink for detailed modelling and simulation, this study offers insights into the behavior of neutral currents under various loading conditions. The research focuses on three primary case studies: purely nonlinear loads, purely unbalanced loads, and the combined effects of nonlinear and unbalanced loads. By understanding the complex interactions between these factors, we can develop more effective strategies to enhance power quality and ensure the reliable operation of modern electrical power systems.

1.1 Nonlinear Loads and Harmonics

Nonlinear loads are characterized by their non-linear voltage-current relationships, resulting in current waveforms that are highly distorted compared to the sinusoidal voltage waveform. This distortion introduces harmonics into the power system, which can propagate through the network, causing various power quality issues.

The harmonics generated by nonlinear loads can have several detrimental effects on power systems. They increase the overall losses in the system, cause overheating of equipment, and can interfere with the operation of sensitive electronic devices. Harmonics can also result in resonance conditions, which can amplify the distortion and lead to equipment failure. According to Mahela et. al., the presence of nonlinear loads significantly contributes to the total harmonic distortion (THD) in the power system, which is a critical parameter for assessing power quality [10] [11].

The formula for calculating the Total Harmonic Distortion (THD) of a current waveform is:

$$\mathrm{THD} = \sqrt{\sum_{n=2}^{\infty}\left(\frac{I_n}{I_1}\right)^2} \times 100 \qquad (1)$$

where I_n is the RMS value of the nth harmonic current and I_1 is the RMS value of the fundamental current. This formula quantifies the distortion in terms of the relative magnitudes of the harmonic components compared to the fundamental component.

The neutral current (I_n) in a system with nonlinear loads can be significantly higher due to the presence of harmonics [10]. For a three-phase system, the effective neutral current considering harmonics can be calculated using the following formula:

$$I_n = \sqrt{I_{n_1}^2 + \sum_{h=2}^{\infty} I_{n_h}^2} \qquad (2)$$

where I_{n_1} is the fundamental component of the neutral current and I_{n_h} is the harmonic component of the neutral current for the h-th harmonic.

Previous studies have extensively examined the impact of nonlinear loads on power systems. For instance, [11] investigated the harmonic modelling and harmonic activity analysis of equipment with SMPS using MATLAB and Simulink. They highlighted that the harmonic currents generated by nonlinear loads could cause overheating, overloading of neutral conductors, and excessive heating of wiring and connections. Their study also demonstrated the effectiveness of using Simulink models for harmonic analysis, showing that the symmetrical components theory could be successfully applied under balanced nonsinusoidal conditions [11]. Further research by [12], focused on the voltage unbalance and harmonic analysis in distribution systems with nonlinear loads. They emphasized the importance of considering both harmonic distortions and load imbalance when analysing power quality issues. Their findings indicated that nonlinear loads could significantly increase the harmonic content in the system, leading to higher levels of THD and more severe power quality problems [12].

Recent research has focused on the integration of renewable energy sources and distributed generation into power systems, which can introduce new challenges related to harmonics. Distributed generation systems, such as solar panels and wind turbines, often include power electronic interfaces that can generate significant harmonic content. A study by [13] examined the impact of integrating renewable energy sources on harmonic distortion in distribution systems. Their research found that the variability of renewable energy sources could exacerbate existing harmonic issues, necessitating advanced harmonic mitigation techniques. They emphasized the role of modern power electronics in managing harmonics and ensuring reliable operation of power systems with high penetration of renewable energy [13].

Harmonics, primarily introduced by nonlinear loads, have been extensively studied for their adverse effects on power systems. Nonlinear loads, such as variable frequency drives, rectifiers, and other electronic devices, generate harmonics that propagate through the power network, causing increased losses, overheating of equipment, and interference with communication systems. A study by Mahela *et. al*., emphasized the significant contribution of nonlinear loads to harmonic distortion in power systems and the consequent challenges in maintaining power quality. Their research highlighted the need for advanced harmonic mitigation techniques to minimize the adverse effects of harmonics on the power system components [14].

1.2 Unbalanced Load

Unbalanced loads occur when the power consumption in the phases of a three-phase system is not equal. This imbalance can result from the uneven distribution of single-phase loads or varying load demands across the phases. Unbalanced loads lead to unequal currents in each phase, causing voltage imbalances and increased neutral currents [15]. The neutral conductor, which ideally carries minimal current in a balanced system, can become a significant pathway for the imbalance current, leading to overheating and potential damage. Voltage unbalance can also adversely affect three-phase motors and other equipment, reducing their efficiency and lifespan [16]. The unbalanced percentage will be calculated using Equation (3) below as explain by A. Vinayagam *et. al*. [17]

$$\%\, Unbalanced = \frac{\max deviation}{average\ current} \times 100 \tag{3}$$

Research has extensively explored the effects of unbalanced loads on power systems. For example, [18] studied the impact of load imbalance on neutral current and voltage in a three-phase four-wire distribution system. They found that unbalanced loads could cause significant neutral currents even when the phase currents were balanced. Their study highlighted the need for accurate modelling and analysis to understand the behaviour of neutral currents in unbalanced systems [18]. Another significant study by [19] examined the modelling of nonlinear loads and estimation of harmonics in distributed photovoltaic system. They emphasized the importance of considering load unbalance when analysing power quality issues, as unbalanced loads could exacerbate the harmonic content in the system. Their research provided valuable insights into the combined effects of nonlinear and unbalanced loads on power quality, highlighting the need for comprehensive analysis and accurate modelling techniques [19].

The formula for calculating the neutral current (I_N) in an unbalanced three-phase system can be expressed as:

$$I_N = \sqrt{I_A^2 + I_B^2 + I_C^2 - I_A I_B - I_B I_C - I_C I_A} \tag{4}$$

where I_A, I_B and I_C are the RMS currents of phases A, B, and C, respectively. This formula highlights the direct relationship between the phase currents and the resulting neutral current in an unbalanced system [17].

Another critical aspect of power systems is the presence of unbalanced loads, which cause unequal power consumption in the phases of a three-phase system. This imbalance leads to unequal phase currents, resulting in voltage imbalances and increased neutral currents. Unbalanced loads are a significant cause of voltage unbalance in power systems, which can adversely affect the performance and lifespan of three-phase motors and other equipment. Modelling and analysis of unbalanced loads are essential for developing effective mitigation strategies [20].

1.3 Combined Effects of Nonlinear and Unbalanced Loads

The combination of nonlinear and unbalanced loads presents a particularly challenging scenario for power quality management. The interplay between harmonics and load imbalance can exacerbate power quality issues, making it crucial to understand their combined effects on the power system [15]. Accurate modelling and analysis of these effects are essential for developing effective mitigation strategies and ensuring the reliable operation of the power system [21].

Furthermore, advanced modelling and simulation tools such as MATLAB/Simulink have been instrumental in studying the impact of harmonics and unbalance in power systems. A study by [22] demonstrated the effectiveness of using Simulink models for harmonic analysis in systems with significant nonlinear loads. Their research showed that detailed simulations could provide valuable insights into the behaviour of harmonics and their propagation through the network, aiding in the development of effective mitigation strategies [22].

Despite extensive research on the individual impacts of nonlinear and unbalanced loads on power systems, there remains a significant gap in understanding their combined effects, which are more severe than those caused by either type alone. This research aims to address this gap by investigating the interplay between harmonic distortions from nonlinear loads and voltage imbalances from unbalanced loads. Understanding these combined effects is crucial for improving power quality management, enhancing system reliability and efficiency, and developing advanced mitigation strategies. Additionally, this research is particularly significant in the context of integrating renewable energy sources, which further complicate power quality issues. By providing comprehensive insights and accurate modelling, this study contributes to both academic knowledge and practical solutions for optimizing modern electrical networks.

The primary objective of this research is to comprehensively analyze the combined effects of nonlinear and unbalanced loads on the neutral conductor in three-phase power systems. By utilizing advanced modelling and simulation tools, specifically MATLAB/Simulink, this study aims to provide detailed insights into the behavior of neutral currents under various loading conditions. The research focuses on three specific scenarios: purely nonlinear loads, purely unbalanced loads, and the combined effects of nonlinear and unbalanced loads. Through this analysis, the research seeks to fill the existing gap in understanding how these combined loads interact to exacerbate power quality issues.

2 Methodology

This research employs a comprehensive simulation-based approach using MATLAB/Simulink to analyze the effects of nonlinear and unbalanced loads on the neutral current in three-phase power systems. The methodology is designed to systematically investigate the impact of different loading conditions and provide insights into the behavior of neutral currents. A study by [23], provides a foundational basis, offering insights into the behavior of nonlinear loads in three-phase systems. It discusses the modeling of nonlinear electrical loads and the harmonic analysis necessary to understand their impact on distribution systems. This research reinforces the validity of the current simulation approach [23].

2.1 System Modeling

As shown in Figure 1 below, the system is modeled as a three-phase four-wire distribution network in MATLAB/Simulink as suggest by [24]. The primary components of the system include a three-phase voltage source, loads connected to each phase, and measurement blocks for capturing current and voltage data. The loads are designed to represent both nonlinear and unbalanced conditions. Electrical source for the circuit was pure sinusoidal 400 V, 3-phase, 50 Hz with no phase shift. The waveform of the current should be analysed at 512 samples per cycle at 10 cycle for each waveform should be analyzed as required by standard [25] [26]. A signal of 0.6 second long would be generated, although the analysis window would only start from 0.4th second. This was to eliminate any non-steady state condition and error in RMS calculation. Cable size choice for the simulation is 4mm^2. Internal resistance for conductor was modelled as RC. Subsequently, RCa, RCb and RCc corresponding to each phase conductor A, B and C. The conductor resistance was set for 0.23Ω as per cable datasheet. [27]. Each phase was equipped with identical SMPS set. As part of SMPS architecture, capacitor C had been provided. This SMPS was then supplied a pure resistive load R, quoted in W. Every diode, capacitor and load for each phase was identical. The circuit was powered using a three-phase AC power supply.

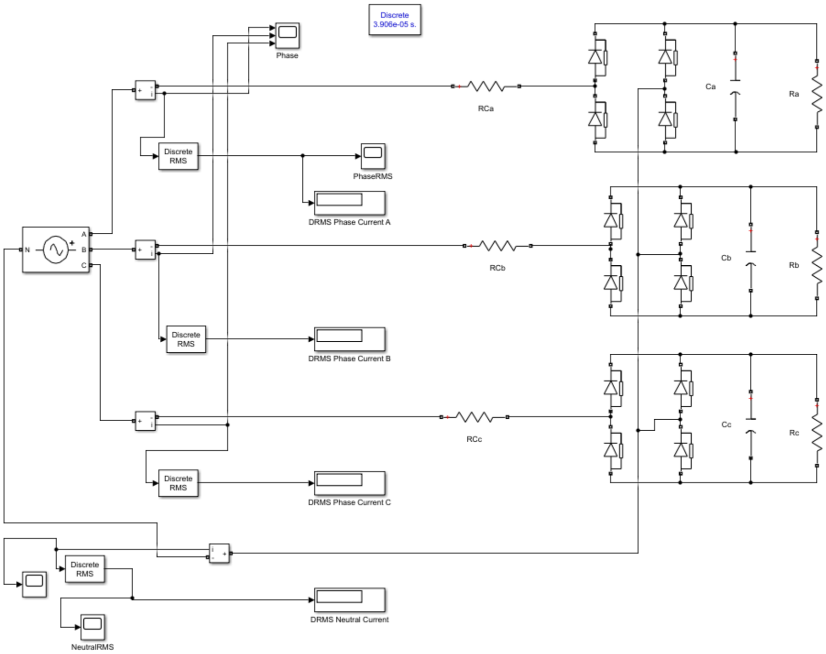

Fig 1. Simulink Model of a Three-Phase Four-Wire Distribution System with Nonlinear and Unbalanced Loads

2.2 Nonlinear Load Modeling

Nonlinear loads are modeled using combinations of resistive and capacitive elements in parallel with diode bridges, as depicted in Figure 1. These elements simulate the behavior of common nonlinear loads such as variable frequency drives, rectifiers, and other electronic devices. The nonlinear characteristics of these loads introduce harmonic distortions into the current waveform. The Total Harmonic Distortion (THDi) of the current is calculated using the Fast Fourier Transform (FFT) analysis tool within the Powergui block in Simulink. For nonlinear and balanced load condition, the load power at each phase were set at 5652W as the it will supply 24A current to phase cable. This is the maximum current carrying capacity for $4mm^2$ cable while the value of capacitor varies from 20μF until 3000μF. **Table 1** shows the value of capacitor C and the THDi injected to the system.

Table 1. Capacitor value and THDi injected to system for nonlinear balanced load condition

C (μF)	THDi (%)
20	1.60
40	3.35
60	5.54
80	7.92
100	10.41
120	13.04
140	15.62
160	18.16
180	20.72
200	23.23
240	27.89
280	32.30
300	34.39
350	39.11
400	43.54
450	47.45
500	51.04
550	54.32
600	57.32
650	60.08
700	62.65
750	64.97
800	67.15
850	69.16
900	70.07
950	72.79
1000	74.43
2000	92.82
3000	99.11

2.3 Unbalanced Load Modeling

Unbalanced loads are simulated by varying the resistive elements connected to each phase, creating unequal current draws in the phases. This imbalance results in unequal phase currents and increased neutral current. To simulate under various unbalanced condition, only power at Phase A are varies from 1W until 4900W while Phase B and C will be fixed at 5652W as shown in **Table 2** below. R_a, R_b and R_c are load at each phase in Watt while I_a, I_b and I_c are current draw by each load. The unbalanced percentage will be calculated using Equation (3) and created degree of unbalanced from 5% until 50%.

2.4 Combined Load Modeling

To analyze the combined effects of nonlinear and unbalanced loads, the system is configured with both types of loads simultaneously combing configuration for pure nonlinear and pure unbalanced. For this model, THDi and degree of unbalanced are varies from 20μF till 3000μF and 5% till 50% respectively.

3 Results

3.1 Simulated Data Analysis

Simulation has initially been done using load of 24 A as a basis. As harmonic contents kept on added into the system, changes in neutral current magnitude were recorded. In the meantime, fundamental current must be kept constant according to cable's initial maximum ampacity. Subsequently, neutral current was recorded. The process was then repeated for all case scenario.

3.2 Nonlinear and Balanced Load Scenario

The graph in Figure 2 illustrating the relationship between Total Harmonic Distortion of current (THDi) and Neutral Current (I_N) for a nonlinear and balanced load reveals significant insights into power quality management. A clear positive correlation is observed, where an increase in THDi results in a corresponding rise in neutral current. This trend appears almost linear, especially at higher THDi values, indicating a proportional relationship between harmonic distortion and neutral current. In the low THDi region (below 10%), the neutral current increases gradually, suggesting that minor distortions have a limited impact. However, at higher THDi levels, the neutral current rises sharply, emphasizing the substantial contribution of significant harmonic distortions. This linear trend underscores the critical importance of controlling harmonic distortion in systems with nonlinear loads, as elevated THDi can lead to high neutral current levels, potentially causing overheating and other issues in the neutral conductor. Given that the load is balanced, the observed neutral current is primarily due to harmonics, highlighting their significant impact on neutral conductors in such systems.

Table 2. Various unbalanced load condition for unbalanced load modelling

Ra (W)	Rb (W)	Rc (W)	Ia	Ib	Ic	Average	Max Current	Max Deviation	% Unbalanced
1	5652	5652	0.00	24.00	24.00	16.00	24.00	8.00	50
400	5652	5652	1.70	24.00	24.00	16.57	24.00	7.43	45
800	5652	5652	3.40	24.00	24.00	17.13	24.00	6.87	40
1300	5652	5652	5.52	24.00	24.00	17.84	24.00	6.16	35
1700	5652	5652	7.22	24.00	24.00	18.41	24.00	5.59	30
2300	5652	5652	9.77	24.00	24.00	19.26	24.00	4.74	25
2800	5652	5652	11.89	24.00	24.00	19.96	24.00	4.04	20
3500	5652	5652	14.86	24.00	24.00	20.95	24.00	3.05	15
4100	5652	5652	17.41	24.00	24.00	21.80	24.00	2.20	10
4900	5652	5652	20.81	24.00	24.00	22.94	24.00	1.06	5

This analysis points to the necessity of implementing effective harmonic mitigation strategies to manage neutral current levels and ensure optimal power quality in electrical systems with nonlinear loads.

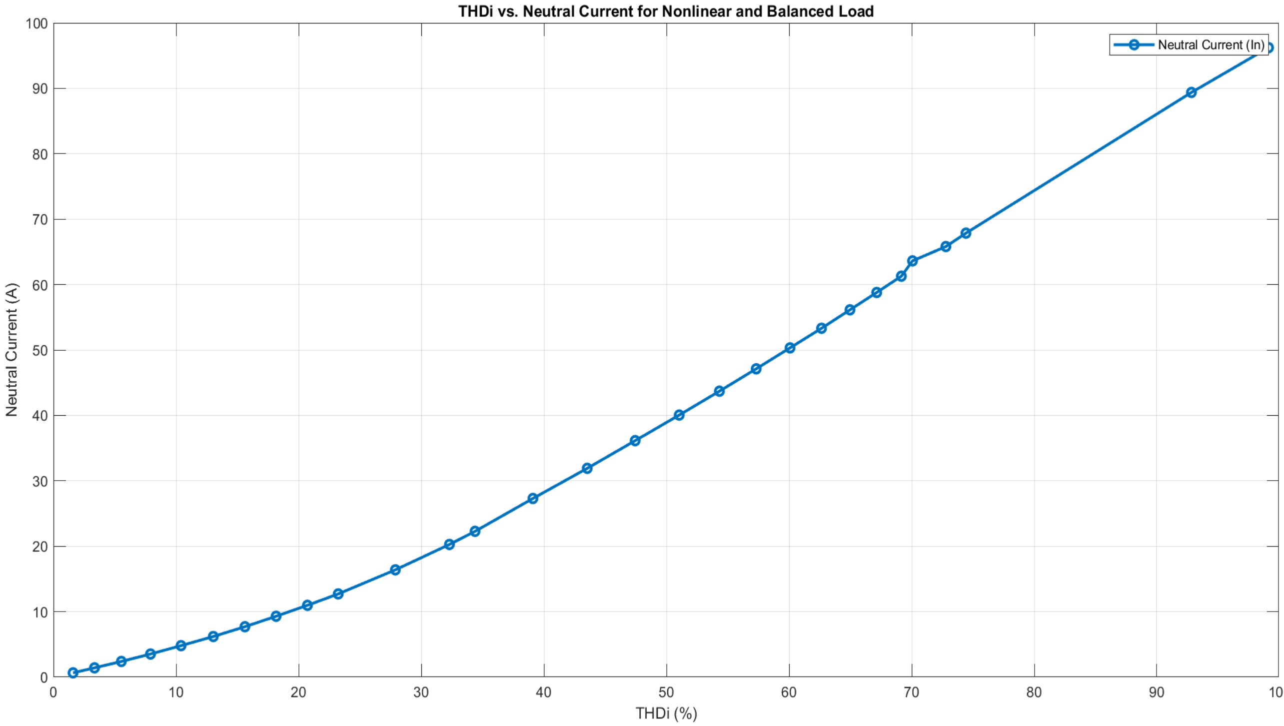

Fig 2. Relationship between Total Harmonic Distortion of current (THDi) and Neutral Current (I_N) in a Nonlinear and Balanced Load System.

3.3 Linear and Unbalanced Load Scenario

The graph in Figure 3 shows a clear linear relationship between the percentage of unbalanced load and the resulting neutral current. As the percentage of unbalance increases from 0% to 50%, the neutral current correspondingly rises in a linear manner, reaching approximately 25 A at 50% unbalance. This indicates that higher levels of load imbalance directly contribute to increased neutral currents in a linear load scenario, emphasizing the critical need for balancing loads to maintain lower neutral currents and improve power quality.

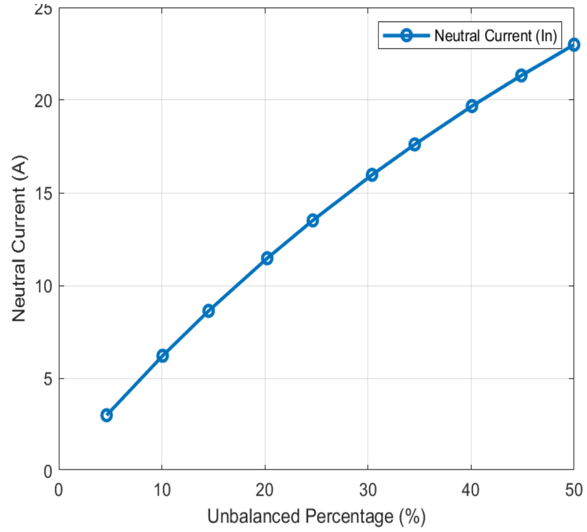

Fig 3. Relationship between Unbalanced Percentage and Neutral Current (I_N) for Linear and Unbalanced Load

3.4 Nonlinear and Unbalanced Load Scenario

The relationship between unbalanced percentage and Total Harmonic Distortion (THD%) is depicted in the Figure 4 below, highlighting how variations in unbalance affect the Neutral Current as THD% increases. The unbalanced percentage represents the degree of asymmetry in the load distribution among the phases in an electrical system. As the unbalanced percentage increases, it indicates a greater deviation from an ideal balanced load condition.

From the graph, it is apparent that as the unbalanced percentage increases, the Neutral Current also increases for any given level of THD%. This indicates a direct correlation between the degree of load unbalance and the magnitude of Neutral Current. For lower unbalanced percentages, such as 4.64% and 10.08%, the increase in Neutral Current with rising THD% is relatively gradual. In contrast, higher unbalanced percentages, such as 40.09% and 49.99%, result in a more significant and steeper increase in Neutral Current as THD% rises.

The behaviour of Neutral Current under different unbalanced conditions can be understood in the context of harmonic distortion. In a balanced system, harmonic currents generated by nonlinear loads tend to cancel out in the neutral conductor. However, as the system becomes more unbalanced, this cancellation effect diminishes, leading to higher Neutral Currents. Thus, higher unbalanced percentages exacerbate the impact of harmonic distortion, causing a more pronounced increase in Neutral Current with increasing THD%.

Overall, the graph clearly demonstrates that higher unbalanced conditions intensify the adverse effects of harmonic distortion on Neutral Current, necessitating careful consideration in the design and maintenance of electrical systems to mitigate potential issues arising from unbalance and harmonic distortion.

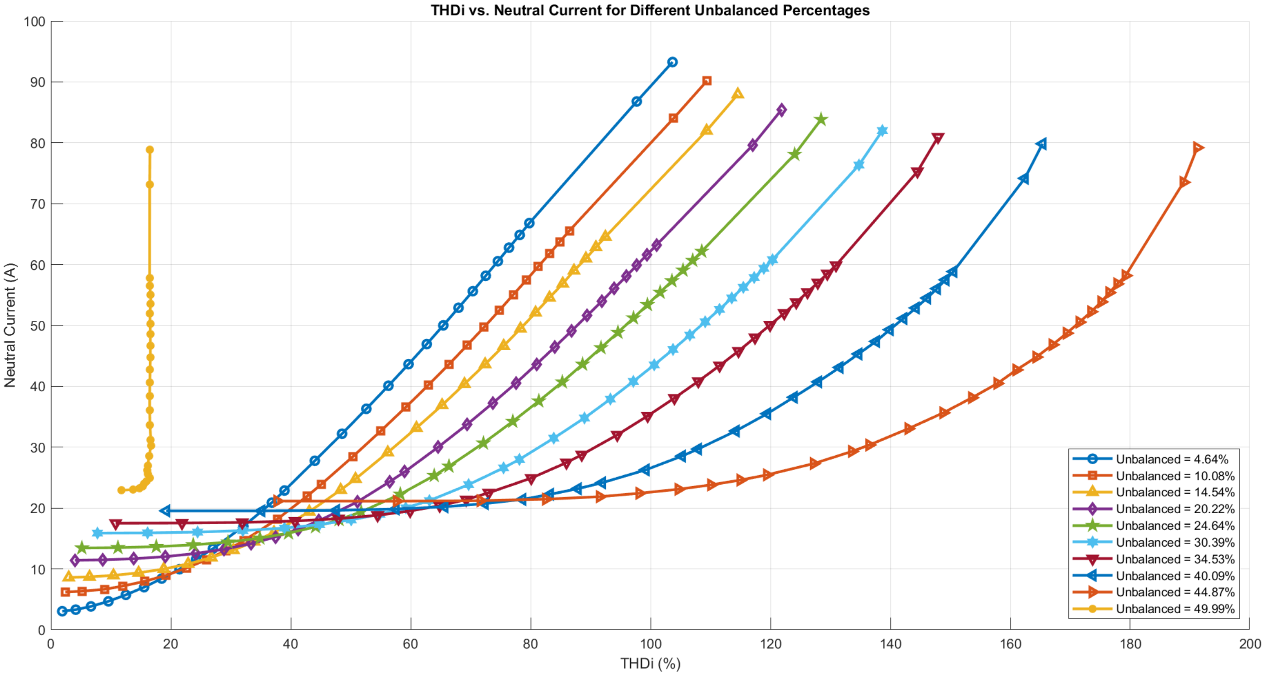

Fig 4. THDi vs. Neutral Current for Different Unbalanced Percentages in a Three-Phase System

3.5 Summary

The analysis of the three graphs provides crucial insights into the behaviour of neutral currents in power systems under different conditions.

For nonlinear and balanced loads condition, reveals a clear linear relationship, where an increase in THDi leads to a proportional rise in neutral current. This emphasizes the direct impact of harmonic distortions on the neutral current, suggesting potential overheating and system inefficiencies with higher harmonic levels.

The second scenario, showing linear and unbalanced loads, demonstrates that as the load imbalance increases, the neutral current also rises almost linearly. This indicates that maintaining balanced loads is essential to prevent excessive neutral current, which can cause overheating and damage to the neutral conductor.

The last scenario which the most crucial condition, depicting THDi and neutral current for different unbalanced percentages, provides a comprehensive view of how both harmonic distortion and load imbalance affect the neutral current. The curves corresponding to higher unbalance percentages are steeper, highlighting the compounded effect of both factors on neutral current. This underscores the need for effective management and mitigation strategies to maintain system reliability and prevent potential damage due to high neutral currents.

Overall, the analyses show that both harmonic distortion and load imbalance significantly impact neutral current levels, and effective strategies are crucial for maintaining power system reliability and preventing damage**.**

4 Conclusions

The findings of this research provide a comprehensive analysis of the behaviour of neutral currents in three-phase power systems under different loading conditions, specifically focusing on nonlinear and unbalanced loads. The study utilized detailed simulations conducted in MATLAB/Simulink to model and analyse the effects of these loads on the neutral conductor, addressing key aspects of power quality management.

The investigation into the impact of nonlinear loads on neutral current revealed a direct and proportional relationship between THDi and the neutral current. The results demonstrated that as the THDi increases, the neutral current correspondingly rises. This linear relationship underscores the significant influence of harmonic distortions introduced by nonlinear loads on the neutral current. Higher levels of harmonic distortion led to increased losses in the system, potential overheating of equipment, and interference with sensitive electronic devices. The effective management of harmonic distortions is crucial to maintaining system efficiency and reliability.

In the case of unbalanced loads, the study highlighted the critical impact of load imbalance on the neutral current. The analysis showed that as the percentage of load unbalance increases, the neutral current also increases in a nearly linear fashion. This finding emphasizes the importance of maintaining balanced loads in three-phase systems to minimize the neutral current. Excessive neutral currents resulting from load imbalances can lead to overheating of the neutral conductor and potential damage, reducing the overall efficiency and lifespan of electrical equipment.

The combined analysis of THDi and neutral current for different unbalanced percentages provided further insights into the compounded effects of harmonic distortion and load imbalance on the neutral current. The results indicated that higher unbalance percentages exacerbate the impact of THDi on the neutral current. The curves representing higher unbalance percentages were steeper, indicating a more significant increase in neutral current with rising THDi. This compounded effect highlights the complexity of managing power quality in systems with both nonlinear and unbalanced loads.

The findings from this research address the primary objectives of understanding the behaviour of neutral currents under nonlinear and unbalanced load conditions and developing effective strategies for power quality management. The study confirms that both harmonic distortion and load imbalance significantly contribute to the magnitude of neutral currents in three-phase systems. These insights are essential for developing targeted mitigation strategies to manage and reduce the adverse effects of these loads.

The practical implications of this research are significant for the design and operation of modern power systems. The findings emphasize the need for integrated power quality management strategies that address both harmonic distortion and load imbalance. Effective mitigation strategies may include the use of active power filters, phase balancing techniques, and advanced control algorithms. Active power filters can dynamically compensate for harmonic currents and unbalanced phase currents, providing a comprehensive solution for improving power quality. Phase balancing techniques can redistribute loads among phases to minimize imbalance, while advanced control algorithms can adjust the operation of power electronic devices in real time to manage both harmonics and unbalance.

In conclusion, this research provides a detailed and comprehensive analysis of the impact of nonlinear and unbalanced loads on the neutral conductor in three-phase power systems. The findings highlight the significant influence of harmonic distortion and load imbalance on neutral current levels, underscoring the need for effective power quality management strategies. The use of advanced modelling and simulation tools such as MATLAB/Simulink has been instrumental in providing accurate and detailed insights into these complex interactions. The practical implications of these findings are crucial for the design and operation of reliable and efficient modern power systems. Future research may focus on developing and testing integrated mitigation strategies in real-world scenarios to further validate the findings and enhance the practical applications of this research.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

MZ. Mohd Radzi : Conceptual, Simulation, Data Analyse, Original draft preparation. **B. Ismail**: Supervision, Reviewing. **M. M. Azizan**: Supervision, Reviewing

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