Journal of Electrical Engineering Vol: 1, No 4, 2025, Page: 1-11

Quadratic Polynomial-Based APSD PWM Technique for Dual Three-Phase Inverters

I Ketut Wiryajati*, Wahyu Satiawan, I Made Budi Suksmadana, Ida Bagus Fery Citarsa, Supriono

Department of Electrical Engineering, Universitas Mataram, Jl. Majapahit No. 62, Mataram, 83115

DOI: https://doi.org/10.47134/jte.v1i4.3957
Correspondence: I Ketut Wiryajati
Email: kjatiwirya@unaram.ac.id

Received: 10-12-2024
Accepted: 22-12-2024
Published: 30-01-2025

Abstract: Three-phase inverters are widely used in industrial applications, including motor drives, renewable energy systems, and electric vehicles. One significant issue in these systems is harmonic distortion, which lowers power efficiency and degrades output voltage quality. To address this, the study proposes a quadratic polynomial fitting technique to optimize Pulse Width Modulation (PWM) signals, aiming to reduce harmonics and improve power quality. This research focuses on a dual three-phase inverter configuration, which provides better current distribution, reduced power losses, and increased resilience to electrical disturbances. The use of quadratic polynomial fitting allows for more precise PWM waveform generation, resulting in lower Total Harmonic Distortion (THDi). The methodology involves mathematical modeling, simulation using MATLAB/Simulink, and experimental validation with a prototype inverter. Results indicate that the technique significantly reduces THDi, especially at optimal modulation indices. Additionally, implementing an LC filter further improves harmonic suppression, producing a cleaner and more stable output. This approach enhances power conversion performance and is highly suitable for industrial and renewable energy applications where efficiency and power quality are critical

Keywords: Dual Three-Phase Inverter, Quadratic Polynomial Fitting, Alternate Phase Shifted Disposition PWM, Power Conversion Efficiency, APSD

Introduction

The system has been rapidly developing in line with the increasing demand for energy efficiency and high-quality electrical power (Li et al., 2023). Three-phase inverters are widely used in various industrial applications, including electric motor drives(Zhang et al., 2022), renewable energy systems, and electric transportation applications(LIU, 2023). To enhance inverter performance, Pulse Width Modulation (PWM) techniques play a crucial role in controlling output voltage and reducing harmonics(Cosmas, 2023)(Testa et al., 2023). Various PWM modulation methods have been developed to improve power conversion efficiency and optimize inverter performance, including sinusoidal PWM (SPWM) (Popa, 2022). space vector PWM (SVPWM)(Shneen et al., 2024), and polynomial function-based modulation techniques(Palanisamy et al., 2024).

One of the main challenges in inverter systems is the emergence of harmonics, which can reduce power efficiency and cause distortion in the output voltage(R., 2024). To address this issue, a quadratic polynomial fitting method can be used to design more optimal PWM modulation signals. This approach allows for more precise estimation and correction of the output voltage waveform, thus reducing harmonics and improving power quality(Stonier et al., 2020)(Liu et al., 2024). In addition, applying quadratic polynomial fitting to PWM modulation techniques also has the potential to improve inverter switching efficiency by optimizing the generated pulse profile.

Dual three-phase inverters are architectures used in high-power motor drive systems and power applications that require more flexible power control(Cagliari et al., 2024). Compared to conventional three-phase inverters, dual three-phase inverters offer advantages in more evenly distributing current, reducing power losses, and increasing resilience to electrical disturbances (Odeh et al., 2022)(Wiryajati et al., 2021). Therefore, developing more optimal modulation strategies for this type of inverter is essential to enhance the efficiency and stability of power conversion systems.

The quadratic polynomial fitting approach in PWM modulation techniques offers advantages in designing smoother modulation signals that align better with inverter system characteristics. This method utilizes quadratic polynomial equations(Ben-Ari, 2022) to form a more precise reference waveform function compared to conventional methods such as SPWM. As a result, output voltage values can be more accurately controlled, harmonic distortion can be reduced, and switching efficiency can be optimized. Although some studies have addressed this(Wang & Baba, 2024), its application in dual three-phase inverters has not been extensively explored.

In this study, we propose the design of a PWM modulation technique based on quadratic polynomial fitting applied to a dual three-phase inverter. The study aims to evaluate the effectiveness of this approach in reducing harmonics, increasing power conversion efficiency, and improving output voltage quality. Additionally, this research analyzes inverter switching performance based on various operational parameters, such as switching frequency, Total Harmonic Distortion (THD), and power efficiency(Wiryajati et al., 2018).

The approach used in this research involves several main stages, including designing a mathematical model of quadratic polynomial fitting for PWM modulation signals, and simulating inverter performance using MATLAB/Simulink-based software. By conducting systematic simulations, this study is expected to contribute to the development of more efficient and adaptive PWM modulation techniques for various operational conditions.

The main contributions of this study cover three aspects. First, the development of a quadratic polynomial fitting model that can be used to improve inverter performance by reducing harmonic distortion. Second, a comparative analysis between the quadratic polynomial fitting method and conventional PWM modulation techniques such as SPWM, in terms of power efficiency and output voltage quality.

The results of this study are expected to provide deeper insights into optimal strategies in designing PWM modulation techniques for dual three-phase inverters. With the growing need for more efficient and high-performance power conversion systems, the quadratic polynomial fitting-based approach can be a potential solution to improve power quality, switching efficiency, and the durability of inverter systems.

Methodology

This study employs a quadratic polynomial fitting approach to determine the relationship between the modulation index (M) and the Total Harmonic Distortion of current (THDi) under a resistive load. The analysis process is carried out through several systematic stages as follows:

1. Data Collection

   The first step in this study is to collect experimental data in the form of pairs of modulation index (M) and THDi values that have been measured. These data are obtained through direct simulation on a dual three-phase inverter system with a resistive load.

2. Selection of Approximation Model

   Based on preliminary observations of the acquired data, the relationship between the modulation index (M) and THDi exhibits nonlinear characteristics. Therefore, a quadratic polynomial approach is selected as the approximation model to describe this relationship. The mathematical model used is expressed in the following equation:.

   $$THD_i(M) = aM^2 + bM + c \quad (1)$$

   where a, b, and c are coefficients to be determined through the fitting process.

3. Quadratic Polynomial Fitting Process

   Polynomial fitting is carried out using the quadratic regression method, which aims to determine the values of a, b, and c such that the error between the measured values and the values predicted by the model is minimized. This process is performed using the Least Squares Approximation technique, which ensures that the approximation model has an optimal fit to the experimental data.

4. Software Implementation

   After the approximation model is determined, the quadratic polynomial fitting is implemented in software based on numerical programming, using MATLAB. At this stage, the quadratic regression algorithm is applied to numerically compute the values of the coefficients a, b, and c.

5. Derivation of the Approximation Equation

   Once the fitting process is complete, the values of a, b, and c are obtained in the standard form of a quadratic equation. This equation is then used to estimate the value of THDi based on the modulation index M within a specified range of values.

6. Analysis and Interpretation of Results

   The resulting equation is used to analyze the trend of THDi variation with respect to the modulation index. By inputting M values into the approximation model, the estimated THDi values can be calculated across various modulation index ranges. Subsequently, the characteristics of the relationship between the modulation index and THDi are evaluated, including identifying the optimal point at which THDi reaches its minimum value.

   By applying this approach, the study can identify a more accurate mathematical relationship between the modulation index and THDi, which can ultimately be used to improve inverter system efficiency and optimize output power quality

Result and Discussion

The circuit used in this study is an inverter with a dual inverter topology, as shown in Figure 1, which illustrates an open-end winding-based inverter topology used to drive an induction motor. This system consists of two three-phase inverters connected to each end of the motor's stator windings. Each inverter is supplied with a voltage of Vdc/2, allowing independent control of the phase voltage with respect to the supply midpoint;

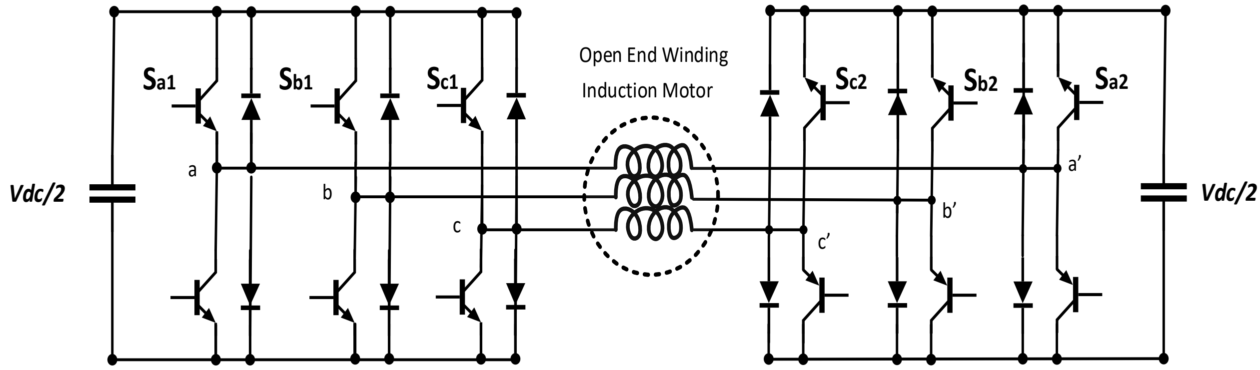

Figure 1. Dual-supply inverter topology.

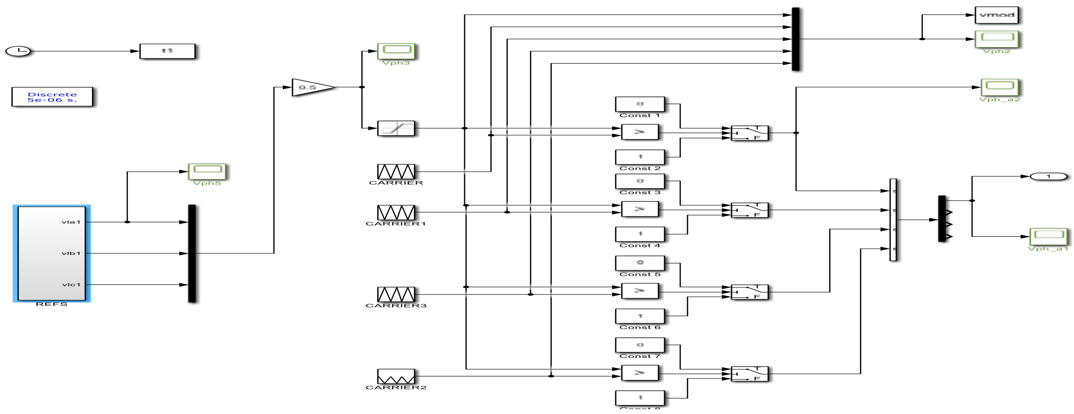

Figure 2. Schematic of the dual-supply inverter topology with APSD PWM

Figure 2 shows a Simulink diagram implementing a comparison-based PWM (Pulse Width Modulation) technique to control the switching signals of an inverter using APSD. From the block structure, it can be seen that the reference (modulation) signal is compared with four carrier waveforms, configured using comparators to generate modulation signals. The modulation technique uses Sinusoidal Pulse Width Modulation (SPWM), where:

- The reference signal is a sinusoidal waveform that determines the output voltage pattern.
- Each carrier signal is a triangular waveform that is compared with the reference signal.
- The comparator logic block determines when the switches in the inverter should be activated to produce the desired output waveform.

This technique is used to control multilevel or conventional inverters in order to generate smoother output voltages, reduce harmonics, and increase power efficiency in motor drive and power conversion applications.

The simulation results are shown in the following figure:

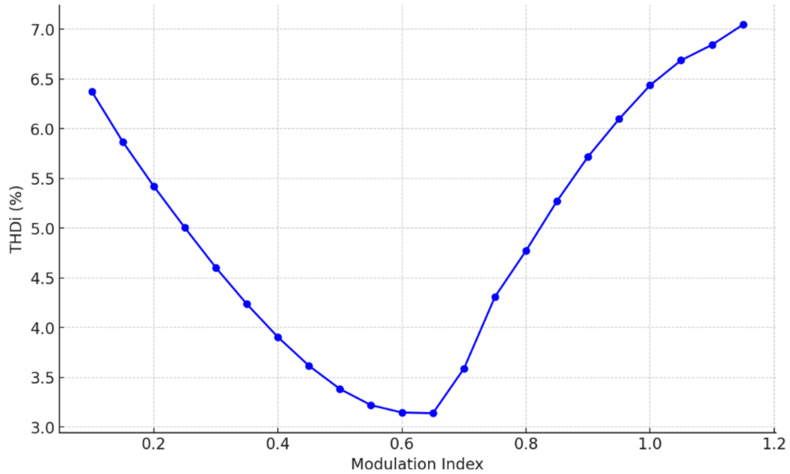

Figure 3. Graph of the relationship between the modulation index and THDi in a Dual Inverter with APSD PWM technology under resistive load.

From Figure 3, it can be observed that THDi decreases as the modulation index increases up to approximately 0.6, after which THDi starts to rise again. This phenomenon indicates the presence of an optimal point around a modulation index value of 0.6, where THDi reaches its minimum.

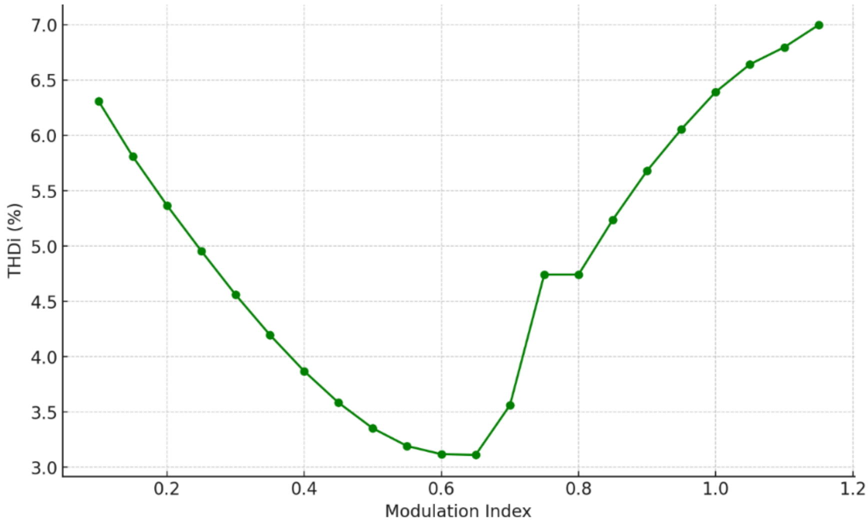

Figure 4. Relationship between modulation index and THDi in a Dual Inverter with APSD PWM under RL load.

To understand the mathematical relationship between the modulation index (M) and THDi, we can search for an approximation function or perform a fitting using a quadratic equation or other higher-order polynomial functions. For example, we may attempt a quadratic equation.

Figure 4 shows the graph of the relationship between the modulation index and THDi under an RL load. The graph reveals an interesting pattern: THDi decreases as the modulation index increases from 0.1 to approximately 0.6. This decline in THDi in that range indicates that current harmonics decrease as the modulation index increases, which may be attributed to improved power conversion efficiency of the inverter under certain conditions. At a modulation index of around 0.6, the THDi reaches its lowest value, representing an optimal point where current harmonic distortion is at a minimum.

Beyond this optimal point, THDi begins to increase significantly as the modulation index continues to rise, indicating a stronger influence of harmonics on the RL load when the modulation index exceeds 0.6. This pattern is consistent with the characteristics of inductive (RL) loads, where current harmonics may increase at higher excitation levels, resulting in greater distortion in the output signal.

In the modulation index range between 0.7 and 0.85, the graph shows an anomaly in the form of a significant increase in THDi after previously reaching its minimum around 0.6. This phenomenon may be caused by several factors related to the characteristics of the inductive (RL) load and the inverter itself.

Partial Resonance Effect: In certain ranges, particularly at higher modulation indices, the inverter system with an RL load may experience partial resonance, where the inductive and capacitive components in the circuit interact in such a way that they amplify certain harmonic frequencies. This leads to higher harmonic distortion than expected, especially when the switching or excitation frequency approaches the resonance frequency of the RL components.

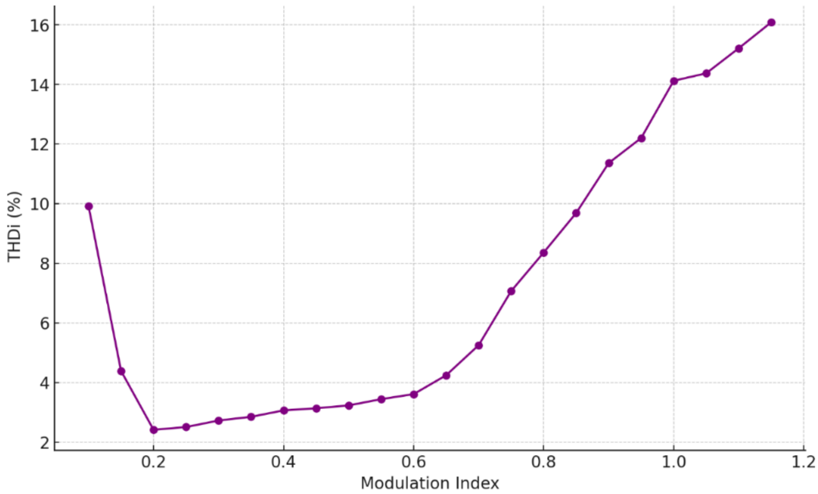

Figure 5. Relationship between modulation index and THDi under induction motor load.

At modulation indices approaching the upper operational limit of the inverter, the PWM (Pulse Width Modulation) modulator can become unstable, producing pulses with irregular and uncontrolled widths. This instability may increase the harmonic content in the output current, contributing to higher THDi values.

Increased Influence of Nonlinearities: At high excitation levels (higher modulation indices), the nonlinear characteristics of inverter switching components become more prominent, which can worsen signal distortion and lead to a rise in THDi.

Figure 5 shows the graph of the relationship between modulation index and THDi under an induction motor load, illustrating the characteristic harmonic distortion behavior of induction motors as the modulation frequency changes. Initially, THDi decreases sharply with an increase in the modulation index from 0.1 to approximately 0.2, indicating a reduction in harmonics at low modulation levels. This decline may be attributed to improved switching efficiency, which results in lower harmonic distortion in the current at optimal excitation levels.

After reaching a minimum value at a modulation index around 0.2, THDi remains stable in the range of 0.2 to 0.6, indicating that within this range, the induction motor operates with relatively controlled current harmonics. However, as the modulation index continues to rise beyond 0.6, THDi begins to increase sharply. This is likely caused by increased harmonics in the current, induced by the nonlinear behavior of the induction motor under higher excitation.

The rise in harmonics above a modulation index of 0.6 indicates that inverters with induction motor loads are more susceptible to harmonic distortion at high modulation levels. Therefore, operating the inverter within the optimal modulation index range is crucial to minimizing THDi and maintaining system efficiency, especially in applications that require high power quality.

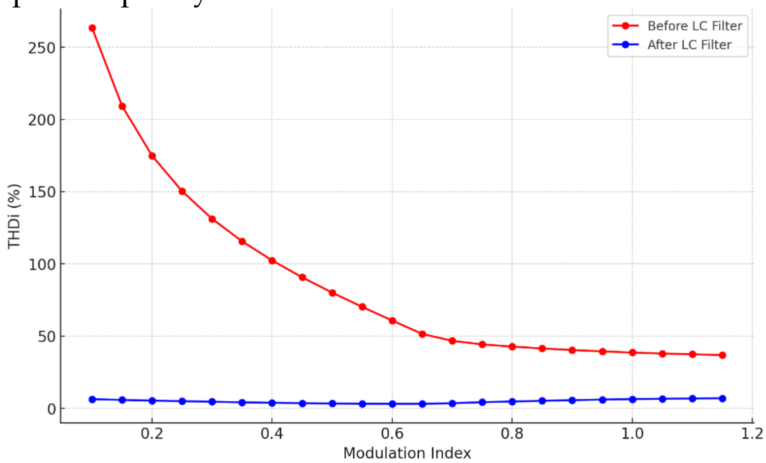

Figure 6. Comparison graph of Dual Inverter with resistive load (R) before and after LC filtering

Figure 6 shows the relationship between the modulation index and THDi for a resistive load before and after applying an LC filter on a dual-supply inverter with APSD PWM technology. Before the LC Filter (red line): THDi shows very high values at low modulation indices and continues to decrease as the modulation index increases. The high THDi values are caused by significant harmonic content that has not yet been filtered.

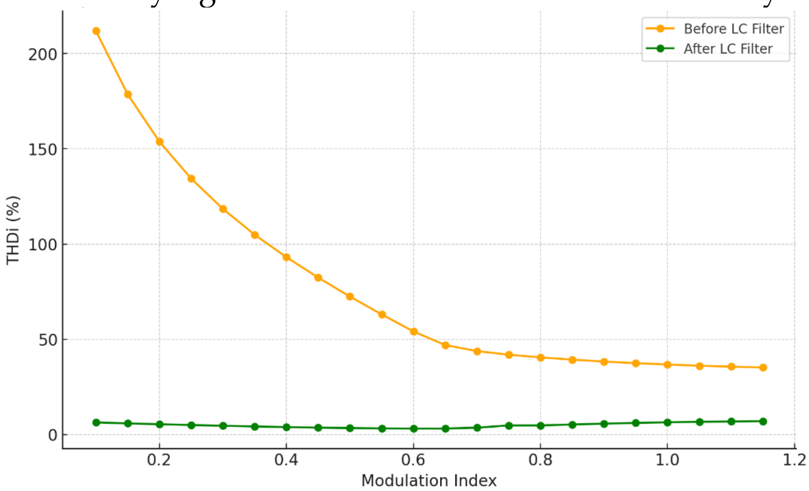

Figure 7. Comparison graph of Dual Inverter with RL load before and after LC filtering.

After applying the LC filter (blue line), THDi decreases drastically and remains stable at a very low level across the entire range of modulation indices. This indicates that the LC filter is effective in attenuating harmonics, resulting in cleaner and more stable current. This THDi reduction is important for applications requiring high power quality, as lower harmonics mean more efficient current and less interference with connected devices. Overall, the LC filter significantly improves the inverter system's performance.

Figure 7 illustrates the significant impact of LC filter application on THDi reduction for an RL load on a dual-supply inverter using APSD PWM. Before the LC filter is applied (orange line), THDi remains high at low modulation indices and decreases as the modulation index increases, reflecting high current harmonics. After the LC filter is applied (green line), THDi drops sharply and remains stable at low levels throughout the modulation index range. The LC filter proves effective in reducing harmonic distortion, producing cleaner current and improving power performance for inductive load applications.

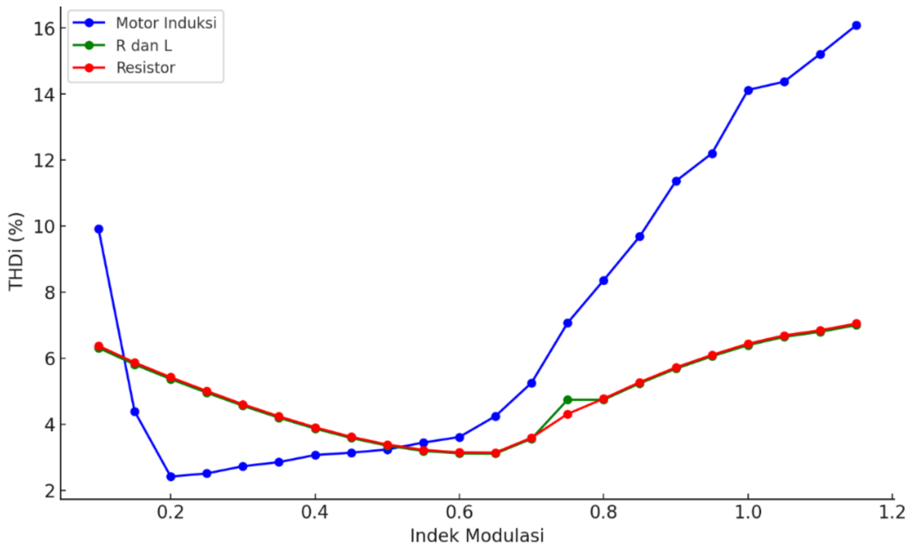

Figure 8. Graph of the relationship between the modulation index and THDi for R, RL, and Induction Motor loads

Figure 8 illustrates the relationship between the modulation index and THDi (Total Harmonic Distortion of current) for three types of loads: induction motor, RL load, and resistor, within an inverter system equipped with an LC filter. In general, this graph provides insights into how THDi behaves as the modulation index increases across the three loads.F or the induction motor load (blue line), THDi shows a significant decrease at lower modulation indices. From approximately 0.1 to 0.3, THDi sharply drops from around 9.91% to about 2.5%. However, after reaching its lowest point around a modulation index of 0.4, THDi gradually begins to rise again, showing an exponential growth pattern as the modulation index exceeds 0.6. It continues to increase, reaching around 16% at a modulation index of 1.15. This pattern indicates that harmonic distortion has a considerable impact on induction motors at higher modulation indices.

For the RL load (green line), the THDi pattern is relatively stable compared to that of the induction motor. Initially, THDi gradually decreases, reaching its lowest value of approximately 3.11% at a modulation index around 0.65. After this point, THDi slightly increases but does not exhibit a significant rise as seen in the induction motor case. This suggests that harmonics in RL loads are more manageable and tend to remain stable at higher modulation indices.

For the resistor load (red line), the THDi pattern is nearly similar to that of the RL load, with a steady initial decrease and a mild increase beyond a modulation index of 0.7. THDi reaches about 7% at the highest modulation index. The resistor load demonstrates relatively consistent characteristics, indicating that it is not highly sensitive to modulation index variations in terms of harmonic distortion.

Overall, the induction motor is more sensitive to increasing modulation indices, with THDi rising sharply at higher values. RL and resistor loads exhibit better THDi stability, making them more suitable for applications where harmonic control is essential.

Conclusion

This study analyzes the relationship between the modulation index and the Total Harmonic Distortion of current (THDi) in a dual three-phase inverter system using APSD PWM technology for various types of loads, namely resistor, RL, and induction motor. The analysis results show that THDi decreases as the modulation index increases, reaching an optimal point before rising again at higher modulation index values. For resistor and RL loads, the optimal THDi point occurs around a modulation index of 0.6, whereas for induction motor loads, the minimum THDi is achieved earlier, at a modulation index between approximately 0.2 and 0.4.

The increase in THDi beyond the optimal point indicates the influence of partial resonance, PWM modulator instability, and increased nonlinear effects in the inverter system. To address these issues, a quadratic polynomial fitting approach is employed to optimize the modulation waveform, effectively reducing harmonics and improving power quality. In addition, the implementation of LC filters has proven to be highly effective in significantly reducing THDi, especially at lower modulation indices.

Overall, this study provides new insights into optimal strategies for designing PWM-based inverter systems that are more efficient, stable, and capable of significantly mitigating harmonic distortion.

References

Ben-Ari, M. (2022). *Solving Quadratic Equations BT - Mathematical Surprises* (M. Ben-Ari (ed.); pp. 73–87). Springer International Publishing. https://doi.org/10.1007/978-3-031-13566-8_7

Cagliari, G. A., Femia, A., Vancini, L., Sala, G., Rizzoli, G., Mancini, M., & Nuzzo, S. (2024). On Control of the Auxiliary Current Space Vector of Dual Three-Phase Permanent Magnet Motors. *2024 IEEE International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles & International Transportation Electrification Conference (ESARS-ITEC)*, 1–6. https://doi.org/10.1109/ESARS-ITEC60450.2024.10819844

Cosmas, O. C. (2023). Optimizing Energy Efficiency in Electrical Power Systems. *International Journal of Latest Technology in Engineering, Management & Applied Science,* *XII*(XI), 01–07. https://doi.org/10.51583/ijltemas.2023.121101

Li, C., Gao, H., Gong, L., Dong, X., & Dai, J. (2023). Research on Open Circuit Fault Location and Fault Tolerant Control of Inverter Power Transistor. *Journal of Physics: Conference Series*, *2527*(1). https://doi.org/10.1088/1742-6596/2527/1/012045

Liu, A., Wang, Y., Zhu, Y., & Park, S.-J. (2024). Research on power quality improvement system based on dynamic voltage restorer. *IET Power Electronics*, *17*(11), 1399–1410. https://doi.org/https://doi.org/10.1049/pel2.12696

LIU, C. (2023). Electrical Power Quality, Availability, and Energy Efficiency. *Engineering and Technology Journal*, *08*(06), 2311–2315. https://doi.org/10.47191/etj/v8i6.02

Odeh, C. I., Lewicki, A., Morawiec, M., & Jąderko, A. (2022). Integrated Three-Level Dual-Phase Inverter. *Energies*, *15*(8), 2897. https://doi.org/10.3390/en15082897

Palanisamy, R., Santhakumari, V. T., Venkatarajan, S., Hemalatha, S., Hepzibah, A. A., Ramkumar, R., & Sugavanam, V. (2024). Space vector pulse width modulation realization for three-phase voltage source inverter. *Indonesian Journal of Electrical Engineering and Computer Science*, *36*(3), 1976–1984. https://doi.org/10.11591/ijeecs.v36.i3.pp1976-1984

Popa, G. N. (2022). Electric Power Quality through Analysis and Experiment. In *Energies* (Vol. 15, Issue 21). https://doi.org/10.3390/en15217947

R., S. A. D. S.-S. Y. A. U.-N. F. H. V.-T. M. (2024). *View of Analysis of Harmonic Contamination at the Output of a 3kVA Hybrid Inverter.pdf*.

Shneen, S. W., Abdullah, Z. B., & Dakheel, H. S. (2024). Design and Implementation of Voltage Source Inverter Using Sinusoidal Pulse Width Modulation Technique to Drive A Single-Phase Induction Motor. In *International Journal of Robotics and Control Systems* (Vol. 4, Issue 4, pp. 1527–1546). https://doi.org/10.31763/ijrcs.v4i3.1541

Stonier, A. A., Murugesan, S., Samikannu, R., Venkatachary, S. K., Kumar, S. S., & Arumugam, P. (2020). Power Quality Improvement in Solar Fed Cascaded Multilevel Inverter With Output Voltage Regulation Techniques. *IEEE Access*, *8*, 178360–178371. https://doi.org/10.1109/ACCESS.2020.3027784

Testa, A., Chang, G., & Verde, P. (2023). Editorial Special Section on "Power Quality in the Energy Transition: Selected Papers From ICHQP 2022." *IEEE Open Access Journal of Power and Energy*, *10*, 349–350. https://doi.org/10.1109/OAJPE.2023.3276548

Wang, Y., & Baba, J. (2024). An Inflection Point Polynomial Fitting Based Estimation Method for Center of Inertia Frequency and Its Rates of Change Using Single Machine Measurements. *2024 IEEE Power & Energy Society General Meeting (PESGM)*, 1–5. https://doi.org/10.1109/PESGM51994.2024.10688858

Wiryajati, I. K., Giriantari, I. A. D., Kumara, I. N. S., & Jasa, L. (2018). Simple carrier based Space Vector PWM schemes of dual-inverter fed three-phase open-end winding motor drives with equal DC-link voltage. *2018 International Conference on Smart Green Technology in Electrical and Information Systems (ICSGTEIS)*, 65–70. https://doi.org/10.1109/ICSGTEIS.2018.8709104

Wiryajati, I. K., Giriantari, I. A. D., Kumara, I. N. S., & Jasa, L. (2021). The performance analysis of dual-inverter three phase fed induction motor with open-end winding using various PWM schemes. *Wireless Networks*, *27*(2), 871–880. https://doi.org/10.1007/s11276-019-02182-5

Zhang, C., Takongmo, M., & Salmon, J. (2022). High-Quality PWM Scheme for High-Speed Electric Drives. *IEEE Transactions on Power Electronics*, *37*(2), 1228–1233. https://doi.org/10.1109/TPEL.2021.3108667