Harmonic Analysis and Performance of a VFD-Controlled Single-Phase Motor

Jakariya Jakariya[1], and Doane Puri Mustika[1*]

[1]Power Plant Technology Study Program, Department of Energy Conversion Engineering, Politeknik Negeri Bandung, Bandung, Indonesia

[*]Email: jakariya@polban.ac.id

Received on 27-10-2025 | Revised on 18-12-2025 | Accepted on 18-12-2025

***Abstract*— The application of Variable Frequency Drives (VFDs) in single-phase induction motors is increasingly common, although it may introduce harmonic distortion that affects power quality. This study analyzes harmonic characteristics and motor performance under variable frequency operation. Measurements of voltage and current harmonics were carried out using a Fluke 434 Power Quality Analyzer at VFD frequencies ranging from 10 to 50 Hz. The results indicate that voltage harmonic distortion (THD-V) decreased from 5,0% to 3,2% on L1 and from 5,8% to 4,1% on the neutral conductor, remaining within IEEE 519-2014 limits. In contrast, current distortion (TDD) reached 71,8% at 50 Hz but decreased to 23% at 20 Hz due to network impedance effects. Dominant harmonics were observed at H3–H13, with triplen harmonics prevailing in the neutral line. Overall, VFD-based frequency control improves motor efficiency and voltage quality but requires additional filtering to limit current distortion within standards.**

Keywords: Harmonic Distortion, IEEE 519-2014, Single-Phase Motor, Variable Frequency Drive, VFD

I. INTRODUCTION

The development of power electronics control systems worldwide has advanced significantly, with diverse applications in both industrial and household sectors. Several decades ago, induction motors were known as types of electric motors whose speed could not be easily controlled, since even when the voltage was varied, the motor continued to operate near its nominal speed. Electric motors are widely used in domestic applications to drive cutting tools, water pumps, air conditioners, and other equipment that requires an AC power supply. This convenience and compatibility with AC systems have made induction motors one of the most extensively applied types of electric motors [1].

During operation, induction motors exhibit a high starting current, typically ranging from three to five times the rated current. For large-capacity motors, this condition can significantly affect the protection system, requiring appropriate protective devices to be installed [2]. However, in small-scale applications, the impact is generally limited to increased electricity consumption, which leads to higher utility bills due to more frequent motor operation [3]. To overcome this issue, a VFD or Variable Frequency Drive (VFD) is employed. This device operates by precisely adjusting the supply frequency and voltage, utilizing power electronic components such as MOSFETs, IGBTs, rectifiers, thyristors, and DC links. However, the use of these components results in the generation of harmonics. Harmonics refer to the distortion of sinusoidal waveforms caused by the presence of nonlinear loads [4]. In the operation of a VFD, the sinusoidal AC input voltage is first converted into DC, and then reconverted into AC. During this process, the switching actions performed by the power electronic components cause distortions in the output waveform of the VFD. The lower the operating frequency, the greater the harmonic distortion generated by the switching process [5][6].

A study on frequency control based on a variable speed drive on the water pump 1 phase system has previously been conducted, focusing on controlling the speed of an induction motor by adjusting the fundamental frequency [7]. The system utilized a Variable Frequency Drive (VFD), in which the VFD served as the main component. The VFD employed MOSFET IRFZ44N devices as power switches in a full-bridge configuration to convert DC power into AC power [8].

Another study on single-phase motors was conducted to design a Sinusoidal Pulse Width Modulation (SPWM) VFD based on an ATmega8 microcontroller for efficient AC motor speed control. The VFD design produced sinusoidal PWM signals with 126 pulses per half cycle and a frequency range of 20–100 Hz. The experimental results demonstrated that the system performed effectively, was capable of accurately adjusting the output frequency, and provided an efficient solution for AC motor speed regulation [9].

Previous studies have predominantly focused on harmonics in three-phase motors, as they are considered to have a greater impact compared to single-phase motors [10]. In addition, most studies have been conducted at the nominal frequency of 50 Hz, while the effects of operating at lower frequencies have not been extensively discussed [11].

This study focuses on analyzing the harmonic characteristics that arise from frequency control and evaluating motor performance under various frequency settings [12]. Differences in frequency adjustment are expected to influence the types and orders of harmonics generated, as well as the extent to which these harmonic levels exceed the limits specified in the IEEE 519-2014 standard [13].

II. METHOD

A. Standard IEEE 519-2014

The IEEE Standard 519-2014, known as the “IEEE Standard for Harmonic Control in Electric Power Systems,” serves as a widely accepted and influential reference for managing harmonic distortion in electrical systems. Its main objective is to maintain power quality by setting permissible limits for voltage and current harmonics at the Point of Common Coupling (PCC).

Although IEEE 519 functions as a recommended guideline rather than a mandatory regulation, many utility companies adopt and enforce it within their interconnection agreements to safeguard the electrical grid from the negative impacts of harmonics produced by non-linear loads.

Based on this standard, it is explained that the permissible limit of voltage harmonic distortion (THD) for operating voltage levels of V ≤ 1,0 kV is 8%, while the limit for current harmonic distortion (TDD) with a ratio of Isc/IL < 20 is 5%. These limits are shown in Table 1&2 below.

TABLE I
VOLTAGE DISTORTION LIMITS

Bus Voltage at PCC	Individual Harmonic (%) h≤50	Total Harmonic Distortion THD (%)
V≤ 1.0 kV	5,0	8,0
1 kV <V≤ 69 kV	3,0	5,0
69 kV < V ≤ 161 kV	1,5	2,5
161 kV <	1,0	1,5

TABLE 2
CURRENT DISTORTION LIMITS

Maximum harmonic current distortion in percent of I_L						
	Individual Harmonic Order					
I_{sc}/I_L	2≤h<11	11≤h<17	17 ≤ h < 23	23 ≤ h < 35	35 ≤ h ≤ 50	TDD
<20	4,0	2,0	1,5	0,6	0,3	5,0
20<50	7,0	3,5	2,5	1,0	0,5	8,0
50<100	10,0	4,5	4,0	1,5	0,7	12,0
100<1000	12,0	5,5	5,0	2,0	1,0	15,0
>1000	15,0	7,0	6,0	2,5	1,4	20,0

B. Materials

The experimental setup utilized a 125-watt single-phase motor, the specifications of which are detailed in Table 3.

TABLE 3
SPECIFICATION OF MOTOR

Parameter	Unit
Output (W)	125
Input (W)	310
Maximum Suction Head (m)	9
Maximum Total Head (m)	33
Maximum Capacity (L/min)	36
Head (m)	5/20
Capacity (L/min)	28/10

To analyze the harmonic effects caused by the use of a single-phase VFD on a laboratory water pump motor, a Fluke 434 Power Quality Analyzer was employed, as shown in Figure 1. This instrument is capable of measuring Total Harmonic Distortion (THD) in both voltage and current, as well as other electrical parameters related to power quality testing.

Figure 1. Fluke Power Quality 434, VFD 1 Phase & Motor

The VFD specification used in this study has a maximum capacity designed for driving a 1,5 kW single-phase pump motor. The detailed specifications are as follows:

TABLE 4
SPECIFICATION OF VPD

Parameter	Unit
Model	9600D-1T-00150M
Input (V)	220 V
Power	1,5 kW
Current	7A
Made in	Shenzen Nflixin
Production	2023

This study was conducted to analyze the impact of using a Variable Frequency Drive (VFD) on power quality in a water pumping system based on a single-phase induction motor. Two experimental configurations were designed, as illustrated in the block diagrams shown in Figures 2 and 3.

In the first configuration (Figure 2), the system was operated without a VFD. A 220 V AC power source was directly connected to the water pump motor. A power quality analyzer was installed at a single measurement point, simultaneously measuring electrical parameters from both the source side (AC mains) and the motor input side. This configuration served as the baseline condition, where the motor operated at a constant speed with a purely sinusoidal power supply; therefore, any measured power quality disturbances originated directly from the interaction between the motor and the grid.

In the second configuration (Figure 3), a single-phase VFD was inserted between the power source and the motor. This configuration required two separate measurement points to enable a comprehensive analysis. The first power quality analyzer was installed at the VFD input to record the characteristics of the power drawn from the grid, including potential harmonic disturbances caused by the rectification process at the VFD input stage. The second power quality analyzer was installed at the VFD output, directly upstream of the motor, to measure the Pulse Width Modulation (PWM) waveform generated by the VFD. This dual-measurement approach is essential to distinguish the impact of the VFD on the electrical grid from its effects on motor performance, given that PWM waveforms contain high-frequency harmonics that may increase motor losses and thermal stress.

A comparison of the measurement results from both configurations reveals the effects of VFD implementation not only in terms of efficiency and speed control, but also with respect to power quality degradation, such as harmonic distortion, voltage fluctuations, and reactive power disturbances. Consequently, this study provides a holistic perspective on the trade-off between motor control flexibility and power system integrity in household or light industrial water pumping applications.

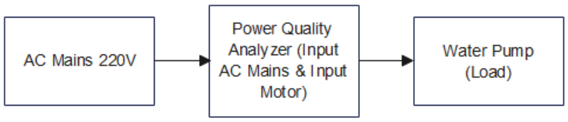

Figure 2. Block Diagram Without VFD

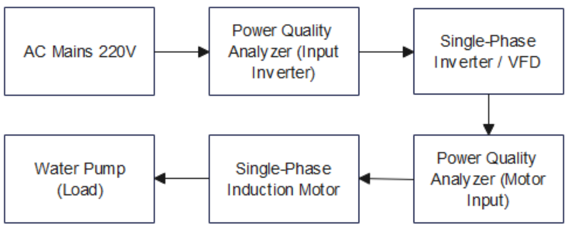

Figure 3. Block Diagram Measurement with VFD

C. *Research Process Block Diagram*

The study adopts an experimental methodology to achieve its objectives [14], The experimental method was employed to fulfill the research objectives, which involve adjusting the VFD frequency within the range of 10–50 Hz and analyzing both the harmonic order characteristics and the performance of the single-phase motor pump. Moreover, this method highlights the use of field test data, the validity of which is ensured through calibrated measurement instruments.

The research Process Block Diagram is presented as follows;

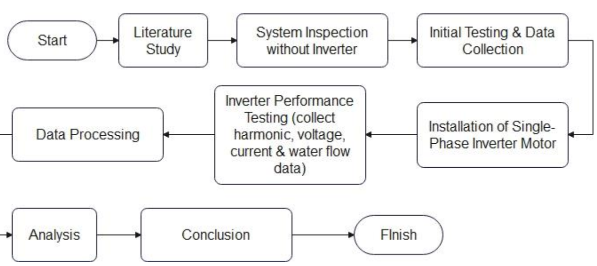

Figure 4. Research Process Block Diagram

Based on Figure 4, the research stages can be described as follows:

1. *Literature Study Stage*

At this stage, the researcher explores relevant scientific concepts related to the study by reviewing articles, applicable standards, and reference books.

2. *System Inspection Without VFD*

In this phase, the water pump is installed and operated under normal conditions without any control system, using a standard voltage supply of 220V.

3. *Initial Testing and Data Collection*

This stage involves recording power, voltage, current, and harmonic data before installing the VFD using a PQ analyzer. The VFD frequency settings to be tested are 10 Hz, 20 Hz, 30 Hz, 40 Hz, and 50 Hz.

4. *Installation of Single-Phase Motor VFD on the Water Pump*

At this stage, the single-phase motor VFD and its circuit are installed on the water pump, with several frequency adjustments to be conducted.

5. *VFD Testing and Data Collection (Harmonics, Voltage, Current, and Water Flow Rate)*

During this testing stage, the PQ analyzer is used to measure harmonics, voltage, and current values resulting from the use of a single-phase motor VFD with variable frequency control applied to the water pump.

6. *Data Processing*

Data processing involves comparing the initial and final test results, including voltage harmonics, current harmonics, and water flow rate. Total Harmonic Distortion (THD) is calculated and compared with the IEEE 519-2014 standard, along with data segmentation by frequency and time interval.

7. *Analysis*

This phase examines the extent to which the use of a single-phase motor VFD influences harmonic generation and evaluates the magnitude of the effect under different frequency settings.

8. *Conclusion*

The final stage draws conclusions based on the background, objectives, and research questions, determining the degree of harmonic impact resulting from the use of a variable speed drive on the water pump 1 phase.

III. RESULT AND DISCUSSION

A. *Initial Measurement Results*

The harmonic data and performance characteristics were obtained using a Fluke Power Quality Analyzer, with a measuring cylinder used as a validation tool for pump performance. Measurements were conducted in two stages. In the first stage, the single-phase motor was operated directly from a 220 V power source without an VFD to obtain baseline harmonic reference data [15]. In the second stage, after the reference data were collected, the motor was connected to the VFD output, and the harmonic spectrum was measured at operating frequencies of 10 Hz, 20 Hz, 30 Hz, 40 Hz, and 50 Hz. For further clarity, the initial measurement data are presented in Table 5 and 6 below.

TABLE 5
BASELINE MEASUREMENT RESULT I

Test	Parameters				
	Motor Current (A)	Source voltage (V)	Motor Voltage (V)	*Cos Phi*	Power (W)
Without VFD	1,12	221,00	220,80	0,96	237,40
Frekuency 50Hz	0,95	221,00	204,60	1,00	194,37
Frekuency 40Hz	0,88	221,30	169,20	1,00	148,90
Frekuency 30Hz	0,88	222,30	125,70	1,00	110,62
Frekuency 20Hz	0,80	222,10	82,90	1,00	66,32
Frekuency 10Hz	0,59	222,50	42,00	1,00	24,78

TABLE 6
BASELINE MEASUREMENT RESULT II

Test	Parameters					
	THD I L1 (%)	THD V L1 (%)	THD I N (%)	THD V N (%)	Debit (L/S)	rpm Motor
Without VFD	19,90	5,00	17,9	5,8	0,125	2872
Frequency 50Hz	122,30	3,60	121,8	4,5	0,125	2874
Frequency 40Hz	133,80	3,5	131,8	4,7	0,111	2307
Frequency 30Hz	143,30	3,30	141,4	4,3	0,091	1725
Frequency 20Hz	155,60	3,30	153,5	4,4	0,059	1144
Frequency 10Hz	171,50	3,20	170,9	4,1	0,029	529

Testing of the water pumping system without a Variable Frequency Drive (VFD) demonstrates the operating characteristics of a single-phase induction motor under conventional conditions. The motor is directly connected to a 220 V AC power supply without any speed control device. Measurement results indicate that the motor draws a current of 1,12 A with an active power consumption of 237,40 W. The supply voltage of 221,00 V is almost entirely delivered to the motor terminals (220,80 V), indicating a very minimal voltage drop along the connecting cables.

The system power factor is recorded at 0,96, reflecting very good performance for a single-phase induction motor without external capacitor-based power factor correction. This value represents an optimal conversion of electrical power into mechanical power with limited reactive power losses. Under the configuration without a VFD, the measured voltage harmonic distortion values are 5,0% for phase L and 5,8% for the neutral, which remain within the standard limit of 8%. Meanwhile, the current harmonic distortion reaches 19,9% for phase L and 17,9% for neutral. These current harmonic levels are largely influenced by the supply voltage, which is affected by harmonic distortion originating from other electrical equipment connected in parallel to the same power distribution line, a condition that is difficult to eliminate in shared electrical network

Based on the measurement results of the single-phase motor VFD module, a reduction in frequency from 50 Hz to 10 Hz caused the motor current to decrease from 0,95 A to 0,59 A, while the VFD output voltage dropped from 204,6 V at 50 Hz to 4,.0 V at 10 Hz. The power absorbed by the motor also decreased significantly, from 194.4 W (at 50 Hz) to only 24,8 W (at 10 Hz). This reduction is reflected in the decline of motor speed from 2,874 rpm to 529 rpm and flow rate from 0,125 L/s to 0,029 L/s. Although the power factor (cos φ) remained close to unity (1,00) across all VFD frequencies, the total harmonic distortion of current (THD I L1) and voltage (THD V L1) increased sharply. THD I L1 rose from 122,3% (at 50 Hz) to 171,5% (at 10 Hz), while THD V L1 increased from 121,8% to 170,9%. These findings indicate that speed control by reducing VFD frequency effectively decreases load and rotational speed but has a negative impact on power quality due to the significant increase in harmonic distortion.

B. *Voltage Harmonic Result*

Based on the IEEE 519-2014 Standard, the total harmonic distortion of voltage (THD-V) must not exceed 8% at the Point of Common Coupling (PCC) to ensure acceptable power quality. The 8% threshold is established since excessive harmonic content leads to increased thermal losses in the motor, ultimately degrading its efficiency [16].

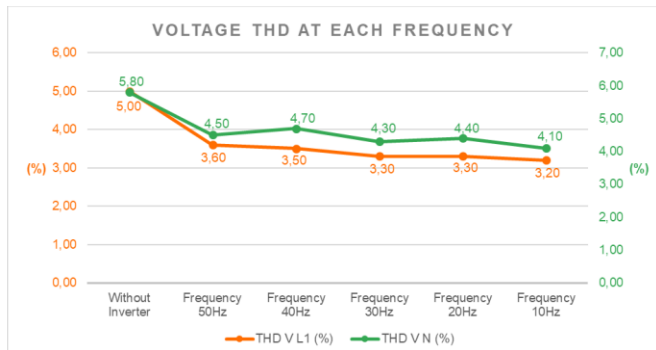

Figure 5. Voltage Harmonic

As shown in Figure 5, the use of a single-phase VFD reduces the phase voltage harmonic distortion (THD V L1) from 5,00 % (without VFD) to 3,60 % at 50 Hz, and continues to improve, reaching a minimum value of 3,20 % at 10 Hz. This improvement indicates that the VFD's DC-link filter and PWM modulation module are capable of producing an output waveform that closely approximates a pure sine wave, thereby significantly reducing low-order harmonic components.

Meanwhile, the THD on the neutral conductor (THD V N) decreased from 5,80% to 4,50% at 50 Hz and fluctuated slightly within the range of 4,30–4,70% for frequencies between 40 Hz and 20 Hz, before dropping further to 4,10% at 10 Hz. These fluctuations are influenced by the interaction between the asymmetric load characteristics and the VFD's internal neutral filter, where the proportion of unbalanced current affects the amplitude of neutral harmonics.

Overall, all THD V values for both phase and neutral remain below the IEEE 519 threshold of 5%, indicating that, in addition to providing speed control, the use of an VFD can also serve as a power quality corrector by suppressing voltage distortion to a safe and stable level across various frequency conditions [17].

Referring to Figure 5, which illustrates the relationship between voltage THD and frequency, these values can be further analyzed based on the harmonic spectrum contributing to the voltage THD. This aspect will be explained in detail with reference to Figure 6.

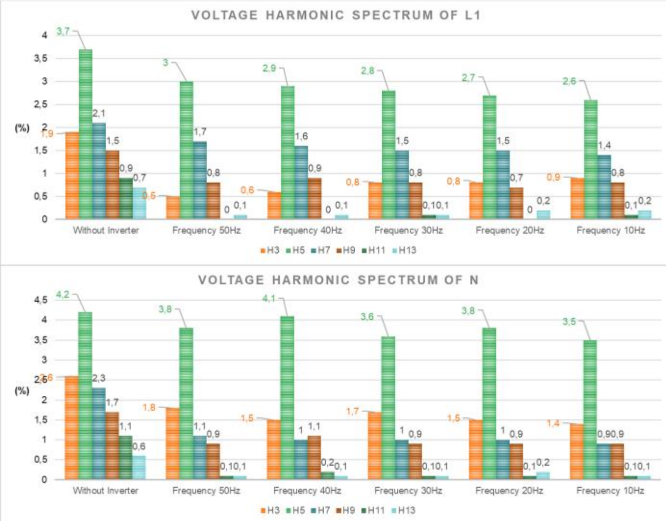

Figure 6. Spectrum Harmonic Voltage L1 & N

In the phase voltage (L1) harmonic spectrum, it can be observed that the low-order odd harmonics, particularly the 5th (H5) and 3rd (H3) harmonics, are the dominant components. The amplitude of H5 decreases from 3,7% without the VFD to 3,0% at 50 Hz and continues to decline to 2,6% at 10 Hz, while H3 decreases from 2,9% to 2,1% (at 50 Hz) and further to 1,4% (at 10 Hz). Higher-order harmonics (H7–H13) remain relatively small (< 1,7 %) and are increasingly attenuated by the VFD's DC-link filter and the motor's inductance as the fundamental frequency decreases.

In the neutral line (N), the 5th harmonic is also dominant, starting at 4,2% without the VFD, fluctuating within the range of 3,6–4,1% for frequencies between 50 Hz and 20 Hz, and then decreasing to 3,5% at 10 Hz. Meanwhile, the 3rd harmonic decreases from 3,6% to 1,4% at 10 Hz. The higher-order harmonics in the neutral line (H7–H13) remain low (< 1,1 %), though slightly higher than those in the phase line, reflecting the accumulation of unbalanced components and the current flowing through the neutral conductor (15).

Technically, the reduction in phase harmonic amplitudes as the fundamental frequency decreases indicates the effectiveness of the VFD's PWM module and DC-link filter in approximating a sinusoidal waveform [18]. In contrast, the fluctuation and magnitude of the neutral harmonics suggest the need for a dedicated neutral filter design or optimized grounding configuration to mitigate triplen harmonics under asymmetric load conditions. Based on the harmonic spectrum analysis, all harmonic components remain below the 5% threshold, ensuring that the total voltage THD of both L1 and N complies with the IEEE 519-2014 Standard.

C. *Current Harmonic Result*

Current harmonics are components of the electrical current that have frequencies which are integer multiples of the system's fundamental frequency (50 Hz). These harmonics are typically generated by non-linear loads such as VFDs, UPS units, VFD-driven motors, computers, and electronic lighting systems (16). In the case of a single-phase VFD used for motor speed control, according to the IEEE 519-2014 Standard, current harmonics are evaluated based on the Total Demand Distortion (TDD). As specified in the standard, when the ratio of short-circuit current to maximum load current (Isc/IL) is less than 20, the permissible TDD limit is 5% [19].

TABLE 7
THD AND TDD CURRENT HARMONIC

Test	Parameters			
	THD IL1 (%)	TDD IL1 (%)	THD IN (%)	TDD IN (%)
Without VFD	19,90	19,90	17,90	18,00
Frequency 50Hz	122,30	71,80	121,80	71,60
Frequency 40Hz	133,80	52,00	131,80	51,70
Frequency 30Hz	143,30	30,40	141,40	30,30
Frequency 20Hz	155,60	23,40	153,50	23,30
Frequency 10Hz	171,50	23,40	170,90	24,00

THD (Total Harmonic Distortion) and TDD (Total Demand Distortion) essentially measure the same harmonic distortion — the square root of the sum of the squares of all harmonic currents — but they use different reference bases. In THD, the sum of harmonic currents is divided by the fundamental current at the time of measurement (I_1). Consequently, when the load is light (i.e., I_1 is small), the THD value may appear excessively high even though the actual harmonic magnitude remains constant. Conversely, TDD divides the harmonic current sum by the maximum or rated load current (IL), which is always equal to or greater than I_1. Since $IL \geq I_1$, the TDD value will always be less than or equal to the THD value under any measurement condition.

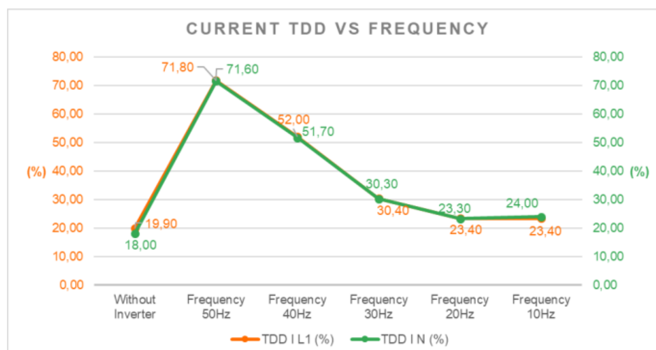

Figure 7. Current TDD vs Frequency

Figure 7 shows that when the motor is operated without an VFD, the current distortion on L1 and N is relatively low, approximately 19% and 18%, respectively. Once the VFD is connected to the motor at 50 Hz, the distortion rises sharply, with the TDD of L1 reaching 71,8% and that of the neutral conductor reaching 71,6%. This occurs because PWM pulses synchronized with the fundamental frequency generate large-amplitude low-order harmonics (3rd, 5th, 7th, etc.). When the switching frequency is reduced to 40 Hz, 30 Hz, and 20 Hz, the low-order harmonic amplitudes move further away from the fundamental band and are more easily attenuated by the network impedance, causing the TDD to gradually decrease to 52%, 30%, and 23%, approaching the level observed without the VFD.

However, at very low frequencies (10 Hz), the pulse-width modulation process reproduces low-order harmonic spectra around 10–30 Hz, leading to a slight increase in TDD to approximately 23–24%. The similarity between TDD values of

L1 and N confirms the dominance of triplen harmonics (3rd, 9th, 15th orders), which do not cancel out in the neutral conductor. From a technical standpoint, this graph indicates that at switching frequencies of 20–30 Hz, the TDD value approaches the non-VFD condition, yet passive filters (LC/LCL) or multilevel VFD configurations are still required to reduce distortion below the ≤ 5% limit recommended by IEEE 519-2014 for operating frequencies between 30 Hz and 50 Hz. Referring to Figure 4, the harmonic spectrum can be further analyzed to identify the dominant orders responsible for preventing TDD compliance with the IEEE 519-2014 standard.

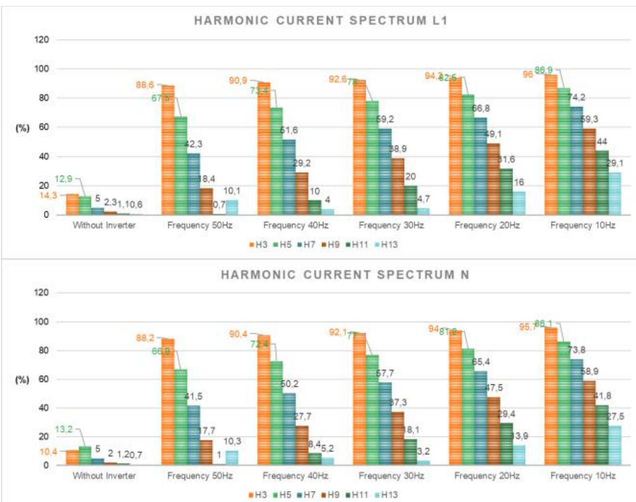

Figure 8. Harmonic Current Spectrum L1 & N

The current harmonic spectrum of phase L1 shows that all odd harmonic components (H3, H5, H7, H9, H11, and H13) exhibit decreasing amplitudes with increasing harmonic order, where H3 ranges from approximately 88–96% and H5 from 67–87%, consistently dominating the spectrum. In contrast, the spectrum on the neutral conductor (N) is dominated only by triplen harmonics (H3, H9, H15, etc.), while non-triplen harmonics (H5, H7, H11, H13) are nearly zero due to phase cancellation. At high PWM frequencies (50 Hz), the magnitudes of H3 and H9 in the neutral line are almost identical to those in L1. As the switching frequency decreases to 40–10 Hz, these components become more pronounced — for instance, the neutral H3 increases from approximately 88% to 96% — confirming that triplen harmonic energy predominantly flows through the neutral conductor.

This characteristic necessitates the design of a neutral conductor with higher current-carrying capacity and the implementation of dedicated filtering circuits to suppress triplen harmonic frequencies (150 Hz, 450 Hz, 750 Hz), ensuring that the neutral current does not exceed the system's rated capacity.

IV. CONCLUSION

Experimental results on the single-phase induction motor show that VFD-generated voltage harmonics decrease with lower operating frequencies. The THD V of phase L1 drops from 5,0% to 3,20% at 10 Hz, while THD V N decreases from 5,8% to 4,10%, remaining within the IEEE 519-2014 limits. Dominant voltage harmonics occur at H3, H5, H7, H9, H11, and H13. Meanwhile, current distortion (TDD) on L1 and N initially reaches 71,8% and 71,6%, respectively, due to low-order harmonics induced by PWM switching. As the switching frequency decreases to 40 Hz, 30 Hz, and 20 Hz, TDD values drop to 52%, 30%, and 23%, indicating improved harmonic suppression through network impedance effects.

REFERENCES

[1] H. G. Beleiu, V. Maier, S. G. Pavel, I. Birou, C. S. Pica, and P. C. Darab, "Harmonics consequences on drive systems with induction motor," *Appl. Sci.*, vol. 10, no. 4, 2020, doi: 10.3390/app10041528.

[2] A. K. Peter, J. Mathew, and K. Gopakumar, "A Simplified DTC-SVPWM Scheme for Induction Motor Drives Using a Single PI Controller," *IEEE Trans. Power Electron.*, vol. 38, no. 1, pp. 750–761, 2023, doi: 10.1109/TPEL.2022.3197362.

[3] M. E. Lima Tostes, O. E. Matos, T. Mota Soares, and U. H. Bezerra, "Voltage Harmonic Impacts on Electric Motors : Motor Classes," *Energies*, vol. 13, no. 3333, pp. 1–18, 2020.

[4] S. Suratno, M. H. Ashabullah, and E. Yadie, "Analisis Kinerja dan Harmonik Motor Induksi 3 Fasa Dengan Variable Frequency Drive pada Boiler Feed Water Pump di PT. Cahaya Fajar Kaltim Menggunakan ETAP," *J. Tek. Elektro Uniba (JTE UNIBA)*, vol. 9, no. 1, pp. 502–510, 2024, doi: 10.36277/jteuniba.v9i1.1099.

[5] W. Zhang and H. Li, "A study of the effect of motor structural components on harmonic noise," *Sci. Rep.*, vol. 15, no. 1, pp. 1–17, 2025, doi: 10.1038/s41598-025-91861-9.

[6] E. L. P. E-issn, P. Variable, and F. Drive, "SATU PHASA DENGAN MENGGUNAKAN METODE SINUSOIDA PULSE WIDTH MODULATION," vol. 17, pp. 32–44, 2022.

[7] J. Neff, E. Cassiano, M. Alo, and C. Watson, "Energy Efficiency for Florida Aquaculture Facilities : Variable Frequency Drives 1," pp. 1–4, 2022.

[8] M. Rusdi, J. Jayadi, P. Mangera, A. Ponadi, and P. Wakole, "Speed Control of Induction Motor Using Variable Frequency Driver (VFD) Method Based On Arduino Nano," *MATEC Web Conf.*, vol. 372, p. 06001, 2022, doi: 10.1051/matecconf/202237206001.

[9] A. Aripriharta, "Desain Kendali Motor Universal Menggunakan Inverter 1 Fasa Metode Spwm," *J. Kaji. Tek. Elektro*, vol. 9, no. 2, pp. 95–101, 2024, doi: 10.52447/jkte.v9i2.6959.

[10] Akshat, M. V. Naik, and R. Kumar, "Performance analysis of an induction motor drive powered by a cascaded H-bridge multilevel inverter," *Discov. Electron.*, vol. 2, no. 1, 2025, doi: 10.1007/s44291-025-00081-y.

[11] A. Arranz-Gimon, A. Zorita-Lamadrid, D. Morinigo-Sotelo, V. Fernandez-Cavero, and O. Duque-Perez, "Harmonic measurement and analysis system for characterization of adjustable speed drives," *Int. J. Electr. Power Energy Syst.*, vol. 162, p. 110217, 2024, doi: https://doi.org/10.1016/j.ijepes.2024.110217.

[12] M. F. S. Ik and M. Sharizal, "Study On Delivery Behaviour Of Simms-Fuel Pump With Variable Frequency Drive (VFD)," vol. 15, no. 2, pp. 9–16, 2024.

[13] Jakariya and B. Eliana, "Analisis pengaruh harmonisa dalam implementasi pengaturan tegangan berbasis dimmer Arduino pada motor AC," *JITEL (Jurnal Ilm. Telekomun. Elektron. dan List. Tenaga)*, vol. 4, no. 3, pp. 221–230, 2024, doi: 10.35313/jitel.v4.i3.2024.221-230.

[14] D. Setiawan, Jakariya, R. Anggrainy, L. Wijayanti, and M. Mulyadi, "Studi Perencanaan Ulang Perpipaan Sistem Filtrasi Air Skala Rumah Tangga ," *J. Permadi Perancangan, Manufaktur, Mater. dan Energi*, vol. 5, no. 03 SE-Articles, Sep. 2023, doi: 10.52005/permadi.v5i03.120.

[15] X. Yan, S. Huang, R. Li, J. Jia, L. Han, and X. Dong, "Harmonic voltage compensation and harmonic current sharing strategy of grid-forming inverter," *Electr. Power Syst. Res.*, vol. 238, p. 111115, 2025, doi: https://doi.org/10.1016/j.epsr.2024.111115.

[16] G. C. Diyoke, C. U. Eya, P. I. Obi, and I. K. Onwuka, “Performance Analysis of Inverter Fed Single Phase Induction Motor Drive,” *ABUAD J. Eng. Res. Dev.*, vol. 7, no. 1, pp. 231–240, 2024, doi: 10.53982/ajerd.2024.0701.24-j.

[17] I. M. W. Kastawan, A. Mudawari, and Y. Hanafi, “Power factor correction of three-phase electrical power supply by using of thyristor controlled reactor VAR compensator,” vol. 01004, 2024.

[18] Y. Chen and C. Liu, “Energy efficient optimization for multi-motor system with novel inverter topology,” *Renew. Sustain. Energy Rev.*, vol. 216, p. 115681, 2025, doi: https://doi.org/10.1016/j.rser.2025.115681.

[19] I. A. Rahardjo, M. Djaohar, M. Subekti, and E. Kamaruddin, “Harmonic mitigation in a single phase inverter,” *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 1098, no. 4, p. 042024, 2021, doi: 10.1088/1757-899x/1098/4/042024.