Harmonic Active Filter Using Multiplication Sine Function Method to Reduce Current Distortion

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ABSTRACT

The use of Variable Frequency Drives (VFDs) is unavoidable, especially in the industrial sector, where motor speed regulation is required to expedite production. VFDs are included in nonlinear loads, which, when in use, can cause the voltage and current of the source to differ. When a source carries a nonlinear load, the current distorts, resulting in a non-sinusoidal shape. The degree of distortion, Total Harmonic Distortion (THD), shows that as THD increases, the signal becomes more distorted. To reduce the distorted source currents, active harmonic filters are used and arranged in parallel between the source and the load. The active harmonic filter works by producing a harmonic current that eliminates the distorted source current, which is achieved by extracting the current distortion signal using the multiplication-with-sine-function method. When the mesh source is loaded with a VFD, the THD of the source current is 45.35%. According to the 2014 IEEE-519 standard, the maximum THD value of the current should be 5%, which is not met, so an active harmonic filter is installed. After installing the active harmonic filter, the THD of the current dropped to 3.57%. This was achieved with a VDC setpoint of 500 V, stabilized by Proportional Integral (PI) control with a *P* value of 17.543 and *I* value of 0.00018.

Keywords-harmonics; non linear load; power quality; Total Harmonic Distortion (THD); multiplication with sine function; PI controller

I. INTRODUCTION

In power systems, loads are classified as either linear or nonlinear. A nonlinear load produces the same output wave as its input wave. Examples of linear loads include resistors, incandescent lamps, and heating elements. Nonlinear loads produce output waves that differ from their inputs. Examples of nonlinear loads include televisions, power converter circuits, welding machines, and motor speed control devices [1]. Authors in [2] examined reducing harmonics caused by VFDs by using an active power filter that employs the p-q theory to extract harmonic currents. The power quality of a system depends on the type of load used. Linear loads tend to improve the power quality, whereas non-linear loads tend to degrade it.

This happens when an alternating current voltage source is given a nonlinear load because the input current and voltage become unequal and the current becomes non-sinusoidal due to the power conversion process. The non-linear loads produce harmonics that can generate waves with frequencies multiple of the fundamental one. In power systems, harmonics are defined as sinusoidal voltages and currents that are combined with other frequencies, which are integer multiples of the main (or fundamental) frequency. The fundamental frequency of electricity in Indonesia is 50 Hz; therefore, the other waves that appear have a frequency of (n×50), where n is the order of the harmonics. THD, measured as the percentage of the root mean square sum of the harmonic values of each order to the root mean square value of the fundamental, is a standard indicator used to determine how much distortion is present in a system [3]. IEEE Std. 519–2014 [4] sets the distortion standards, which are shown in Tables I and II for voltage and current, respectively.

TABLE I. STANDARD VOLTAGE DISTORTION

	Weekly 95th percentile short time		**Daily 99th percentile short time**	
Bus voltage at PCC	Individual harmonic (%)	THD (%)	Individual harmonic (%)	THD (%)
$V \leq 1.0$ kV	5.0	8.0	7.5	12
1 kV < $V \leq 69$ kV	3.0	5.0	4.5	7.5
69 kV < $V \leq 161$ kV	1.5	2.5	2.25	3.75

TABLE II. STANDARD CURRENT DISTORTION

I_{sc}/I_L	**Individual harmonic limits (Odd harmonics). Harmonic values are in % of maximum demand load current**					**THD**
	$3 \leq h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h < 50$	
$I_{sc}/I_L < 20$	4.0	2.0	1.5	0.6	0.3	5.0
$20 < I_{sc}/I_L < 50$	7.0	3.5	2.5	1.0	0.5	8.0
$50 < I_{sc}/I_L < 100$	10.0	4.5	4.0	1.5	0.7	12.0
$100 < I_{sc}/I_L < 1000$	12.0	5.5	5.0	2.0	1.0	15.0
$I_{sc}/I_L > 1000$	15.0	7.0	6.0	2.5	1.4	20.0

The THD current and voltage are:

$$THD_V = \frac{(\sum_{n=2}^{N=50} V_n{}^2)}{V_n{}^2} \quad (1)$$

$$THD_I = \frac{(\sum_{n=2}^{N=50} I_n{}^2)}{I_1{}^2} \quad (2)$$

This research proposes a method for reducing harmonics using a parallel arrayed active harmonic filter that utilizes an inverter to produce a source harmonic correction current [5, 6]. Some advantages of using an active harmonic filter include the fact that it does not interfere with the system's resonance. The principle of an active filter is to generate a current or voltage that matches the shape of the harmonic signal in the system, but with a 180° phase difference, so that the THD is zero. With this concept, the harmonics in the system can be reduced. Figure 1 shows a one-line diagram of the active filter working in parallel. The current drawn by a nonlinear load consists of a fundamental frequency component (I_L) and a distortion component (I_{Ldist}). The load current is measured and filtered to produce a signal proportional to the distortion component. In current-mode control, a switched-mode DC-to-AC converter operates to deliver the I_{Ldist} current to the utility grid. Therefore, under ideal conditions, the harmonics in the utility grid current can be eliminated.

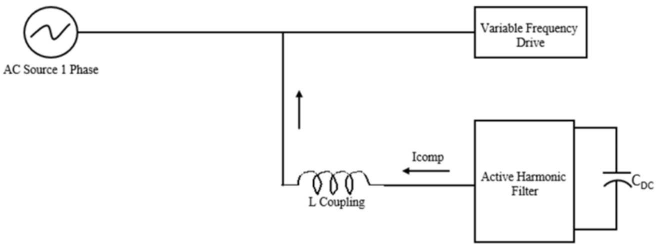

Fig. 1. Topology of active harmonic filter.

Many studies related to active harmonic filters have used the harmonic current extraction method of the p-q theory and the d-q transform. This method requires complicated steps and is generally applied to three-phase systems. When applied to a single-phase system, an additional step is required: converting the single-phase system to three-phase coordinates to calculate the harmonic current extraction. This study uses a simpler method of harmonic current extraction: multiplying the instantaneous voltage and current values of the source to find the instantaneous power. Then, the average power is found, and calculations are made to find the average source current, which is multiplied by the sine function to obtain the average source current in sinusoidal form. To obtain the inverter ignition reference current, the average source current value is subtracted from the load current, which is known to be distorted, to leave only the distorted current without fundamentals.

II. METHODOLOGY

Figure 2 shows the operating principle and workflow of the active harmonic filter when dealing with a distortion current caused by a VFD load.

A. *Variable Frequency Drive Modeling*

The non-linear load used is a VFD, which functions as a converter of a single-phase into a three-phase source for the supply of a three-phase induction motor. Non-linear loads result in current distortion at the source of a system. The VFD circuit comprises a series of interconnected components that work together to regulate the flow of electricity within the system, as depicted in Figure 3. The single-phase source is rectified using a full-wave inverter circuit to reduce ripple. A capacitor is then connected to the output of the rectifier, acting as a filter. This process yields Direct Current (DC) waves, operating as the primary energy source for the 3-phase inverter circuit. The three-phase inverter used in non-linear load modeling employs the Sinusoidal Pulse Width Modulation (SPWM) switching method to manage the load of a three-phase induction motor with a nominal power of 4 kW. The presence of non-linear loads creates a distortion in the current from a single-phase source, resulting in a non-sinusoidal waveform. It is evident that despite the presence of a non-linear load, the voltage waveform maintains a pure sinusoidal form, as demonstrated by the Total Harmonic Distortion Voltage (THD-V) of 0%, displayed in Figure 4. In Figure 5, the current waveform is shown to be distorted due to the presence of a non-linear load, resulting in a shape that deviates from the typical sinusoidal pattern. The Total Harmonic Distortion Current (THD-I) is 45.35%. In this study, the design of an active harmonic filter is used for the reduction of THD-I, restoring the shape of the signal to a sinusoidal curve.

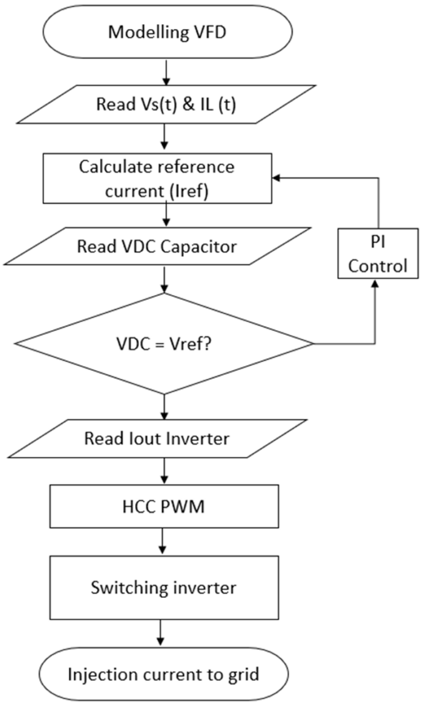

Fig. 2. Flowchart research.

- Reference current signal:

The generation of harmonic adjustment by the inverter is dependent on the presence of a reference signal. There are several methods for obtaining harmonic reference currents, such as the p-q theory [7, 8], d-q transformation [9-11], and multiplication with a sine function [12]. In this study, the reference current is obtained through the multiplication of a sine function. The following steps were taken in order to obtain the reference current:

- The instantaneous voltage and current values of the load are obtained by:

$$V_L(t) = V_m sin\, \omega t \tag{3}$$

$$I_L(t) = I_m sin\, \omega t \tag{4}$$

- The average load power is calculated by:

$$P_L(t) = V_s(t)\, I_s(t) = V_m\, I_m sin^2(\omega t) \tag{5}$$

$$\begin{aligned}
&P_{L\,ave} = \frac{1}{2\pi}\int_0^{2\pi} V_m\, I_m\, sin^2(\omega t) d(\omega t) = \\
&\frac{1}{2\pi}\int_0^{2\pi} V_m\, I_m\, \frac{1-cos\ 2(\mathrm{\omega t})}{2} d(\omega t) = \\
&\frac{V_m\, I_m}{4\pi}\left[\int_0^{2\pi}\ 1\ \mathrm{d\omega t} - \int_0^{2\pi}\ \mathrm{cos2\ (\omega t)\ d\omega t}\right] = \\
&\frac{V_m\, I_m}{4\pi}\left[t\int_0^{2\pi} - \frac{sin\ 2(\mathrm{\omega t})}{2}\int_0^{2\pi}\ \right] = \frac{V_m\, I_m}{4\pi}\Big[2\pi - \\
&\left(\frac{\mathrm{sin\,2(\omega t)}}{2} - 0\ \right)\Big] = \frac{V_m\, I_m}{4\pi}\left[2\pi - \frac{\mathrm{sin\,2(\omega t)}}{2}\right] = \\
&\frac{V_m I_m}{4\pi}\left[2\pi - \frac{\sin 4\pi}{2}\right] = \frac{V_m\, I_m}{4\pi}\ [2\pi] = \frac{V_m\, I_m}{2}
\end{aligned} \tag{6}$$

- Average load current is calculated by:

$$I_{ave} = \frac{2PL_{ave}}{V_m} \tag{7}$$

- The sine function is:

$$\sin \omega t = \frac{V_m \sin \mathrm{\omega t}}{V_m} \tag{8}$$

- The sinusoidal reference current is calculated by:

$$\mathrm{I}_{Refsine}(\mathrm{t}) = \mathrm{I}_{ave}\ \sin \mathrm{\omega t} \tag{9}$$

- The distortion load current is calculated by:

$$\mathrm{I}_{Refdist}(\mathrm{t}) = \mathrm{I}_{Refsine}(\mathrm{t}) - \mathrm{I}_L(\mathrm{t}) \tag{10}$$

The diagram of the steps required to generate a reference current signal is illustrated in Figure 6. This method uses the principle of calculating the average active power required by the load [13]. Subsequently, the mean value is divided by a constant value that represents the maximum value of the voltage in the system. This process enables the calculation of the mean current at the source. The calculation of the average power is determined by the multiplication of the instantaneous value of the system current and voltage.

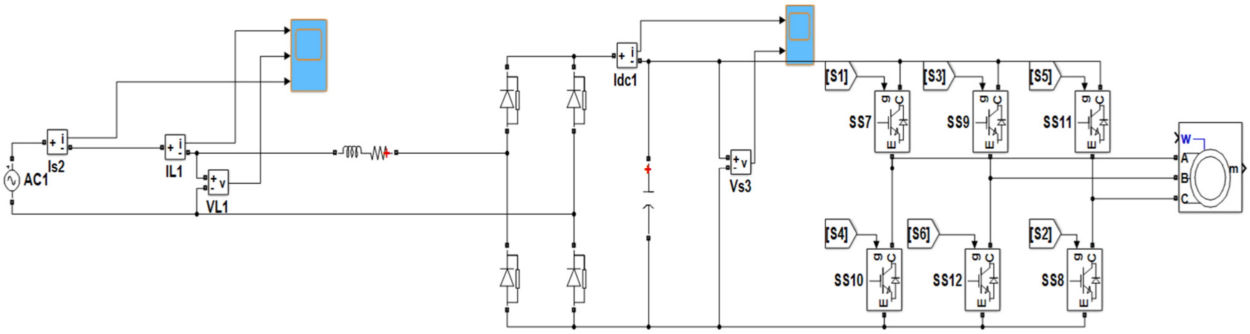

Fig. 3. Circuit of non linear load.

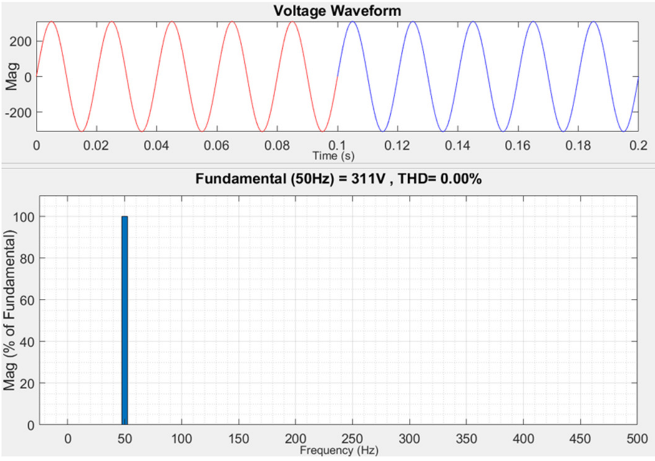

Fig. 4. Voltage waveform and THD.

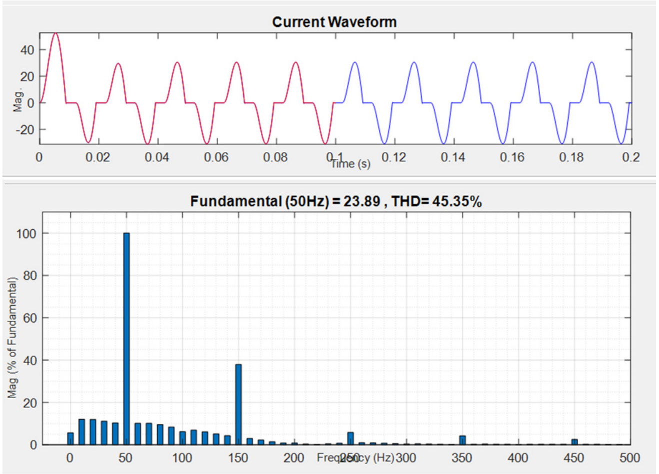

Fig. 5. Current waveform and THD.

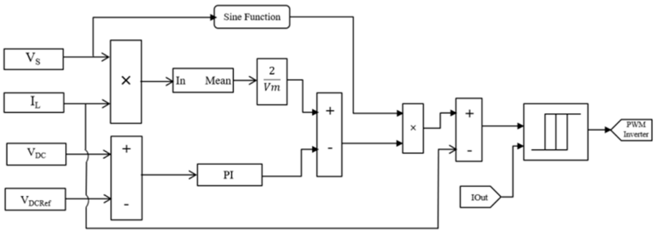

Fig. 6. Block diagram to generate reference current.

B. *Control of the DC Bus Voltage*

The stability of the inverter bus DC voltage amplitude is a critical parameter, as it determines the inverter's capacity to supply correction current according to the demands of the mesh source. Therefore, it is important to regulate the DC bus voltage in order to keep it constant. There are several methods that can be used to regulate the capacitor's DC voltage, such as the step size error cancellation in the self-charging algorithm [14]. In this study, the method used is the Proportional Integral (PI) control, which determines the variation between the reference DC voltage value and the actual DC voltage. The results of this calculation are then transmitted to the PI controller, where they are converted into the DC current necessary to stabilize the capacitor's DC voltage. Subsequently, the value is aggregated with the average reference current [15].

C. *Inductor and Capacitor Design*

Authors in [16] explained that the necessity for capacitors with minimal energy storage is exclusively on the DC side of the converter. This is due to the fact that the inverter output is connected to the grid, thereby functioning as a capacitor charger. The direction of the current flow is determined by the principle of conservation of energy, which states that the current flows from the DC source to the mesh only if the potential difference on the DC side of the inverter is higher than that of the mesh. In this condition, the converter functions as an additional inverter when the potential difference on the AC side exceeds that of the DC side of the inverter. The high frequency at which inverter modulation is carried out results in a high-amplitude output switching ripple, which necessitates the use of an inductor to smoothen the signal. The value of the DC capacitor and inductor coupling is determined by:

1) *Determination of the Value of the DC Capacitor*

$$V_{DC} = \frac{3\sqrt{2}\times V_m}{\pi} = \frac{3\sqrt{2}\times 311}{\pi} = 419.99\text{V} \quad (11)$$

The VDC is set to 500 V for inverter optimization and the quantity of energy that flows in the capacitor can be calculated as:

$$\frac{1}{2}\times C_{DC}\times V_{DC}^2 = P\times T\ , C_{DC} = \frac{2\times P\times T}{V_{DC}^2} = \frac{2\times 4000\times 0.02}{500^2} = 640\mu F \quad (12)$$

The capacitor's efficiency in storing electrical charge is optimized by a larger value of 900μF.

2) *Determination of the Value of Inductor Coupling*

$$F_{max} = \frac{V_{DC}{}^2}{2V_{DC}\times \text{L}\times \Delta \text{I}} \quad (13)$$

$$L = \frac{V_{DC}}{2\times F_S\times \Delta I} = \frac{500}{6\times 40.000\times 0.5} = 12.5 \text{ mH} \quad (14)$$

D. *Hysteresis Current Control (HCC) PWM*

According to [16], the inverter output current is controlled by using the tolerance band control method, which compares the actual inverter output current with the tolerance limit around the reference current, as shown in Figure 7. In the event that the actual current reaches the upper limit, the PWM is modulated to decrease the output current. Conversely, if the actual current reaches the lower limit, the PWM is modified so that the inverter increases the output current. Once the inductor value has been obtained, the hysteresis band width can be determined, and is equivalent to half of the current ripple (ΔI). The hysteresis band is used to limit the current ripple that will be generated by the inverter. When the current error exceeds the upper hysteresis band, a switching pulse is generated for one pair of switches, inducing a drop in the inductor current. Conversely, when the current error exceeds the lower hysteresis band, a switching pulse is generated, resulting in an increase in the inductor current [17].

$$HB = \frac{\Delta \text{I}}{2} = \frac{0.5 \text{ A}}{2} = 0.25\ A \quad (15)$$

The selection of this method was influenced by numerous factors, including its uncomplicated application, its swift dynamic response, its capacity to minimize steady-state error, its reliance on minimal hardware and software, and its independence from system parameters [18].

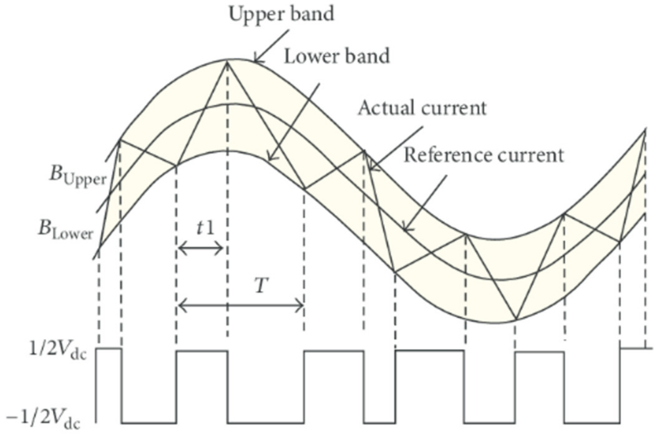

Fig. 7. Working principle of HCC PWM.

III. SIMULATION AND RESULTS

The effectiveness of an active filter is determined by its ability to minimize the current distortion at the source that is subject to a non-linear load. To assess this capability, simulations were conducted using the MATLAB environment, as portrayed in Table III.

TABLE III. SIMULATION PARAMETERS

No	Parameter	Value
1	V_{max}	311 V
2	V_{DC}	500 V
3	C	900 µF
4	L	12.5 mH
5	F_{max}	40 kHz
6	ΔI	0.5 A
7	HB	0.25 A
8	P_L	4 kW
9	L_{line}	0.01 H
10	V_{max}	311 V

The loading circuit causes an imbalance in the shape of the current and voltage, leading to a current distortion, resulting in a non-sinusoidal shape. The installation of an active filter in parallel with the source and load is necessary to restore the current form, as shown in Figure 8.

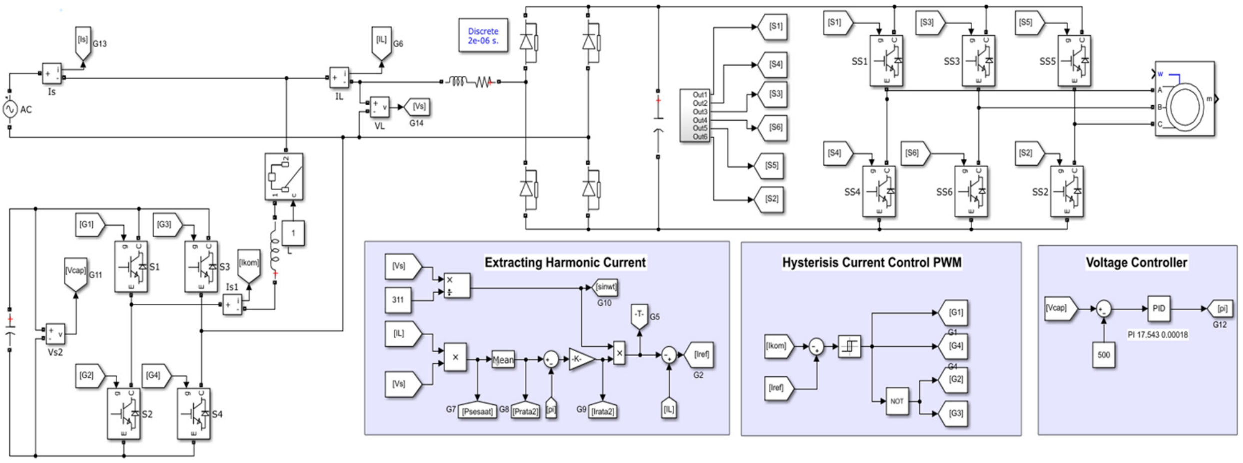

Fig. 8. System circuit.

After the active filter is used, the current waveform exhibits a near-sinusoidal pattern. This observation is supported by a significant decrease in the THD current, which was initially measured at 45.35% and subsequently reduced to 3.57%, aligning with the IEEE 519 - 2014 standard [19-21]. Figure 9 shows the reduction harmonic, while Figure 10 presents the THD-V, and Figure 11 the THD-I. Figure 12 illustrates the distorted source current waveform, the compensating current, and the current after the harmonic reduction. The distorted source current is then integrated with the regulating current, which is defined as the output current of the inverter. Once the filter is integrated into the system, the distorted source current transitions to a nearly sinusoidal form. The objective of this study is to determine the efficacy of a particular method for achieving the desired result. The experimental approach used a DC stability control system for the capacitor bus, which was regulated by a PI controller, as shown in Table IV.

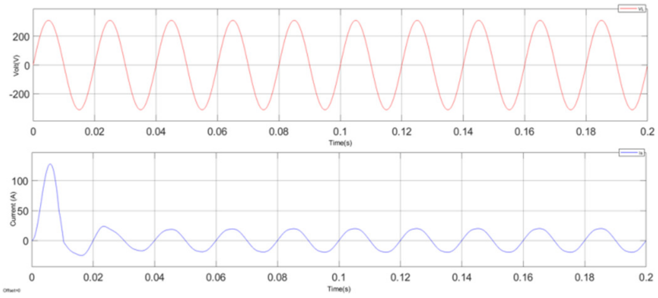

Fig. 9. Result of reduction distortion current reduction.

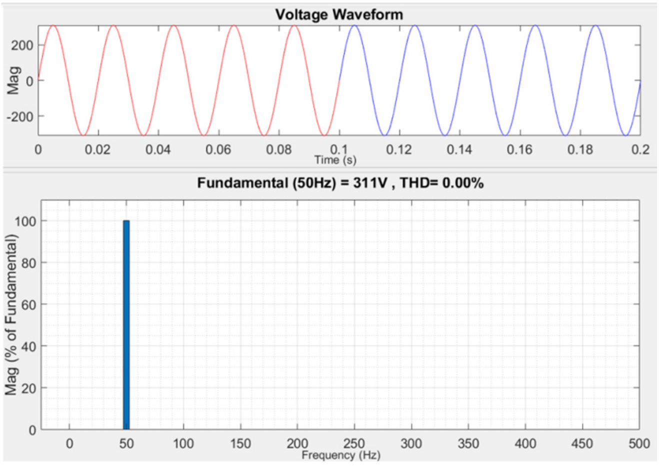

Fig. 10. THD-V after reduction.

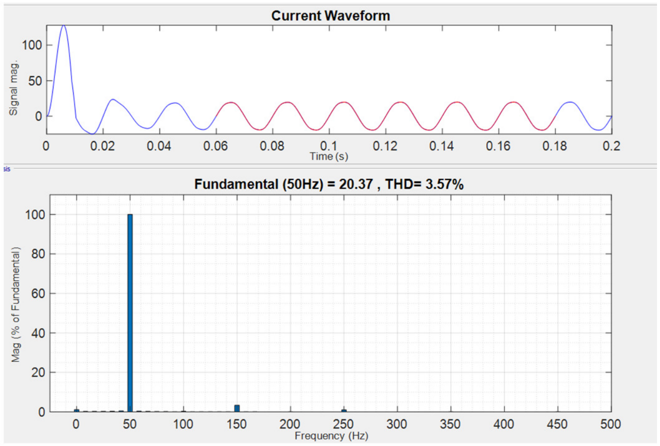

Fig. 11. THD-I after reduction.

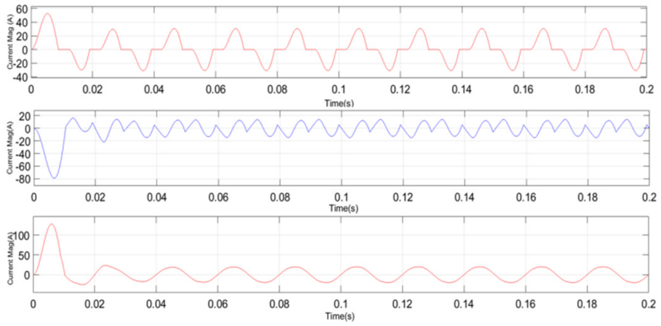

Fig. 12. Current distortion, current compensation, source current.

TABLE IV. CONTROL PARAMETERS

No	Parameter	Value
1	Proportional	17.543
2	Integral	0.00018

Prior to the transfer of the PI control, the DC bus voltage exhibits instability, resulting in a decline from its setpoint, as shown in Figure 13. This phenomenon leads to a reduction in the performance of the harmonic active filter. Consequently, it is important to regulate the capacitor voltage to maintain the V_{DC} value around the setpoint, as presented in Figure 14. This approach allows the harmonic active filter to sustain its capacity to generate a compensation current.

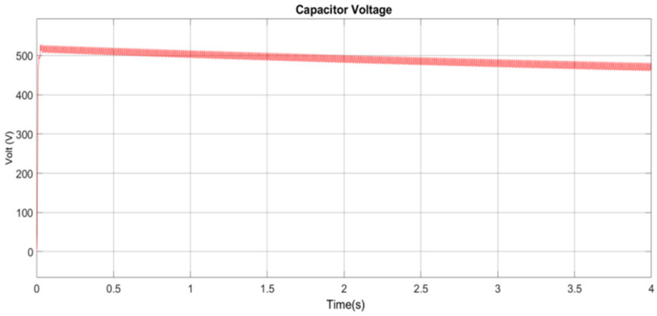

Fig. 13. Capacitor voltage before being controlled.

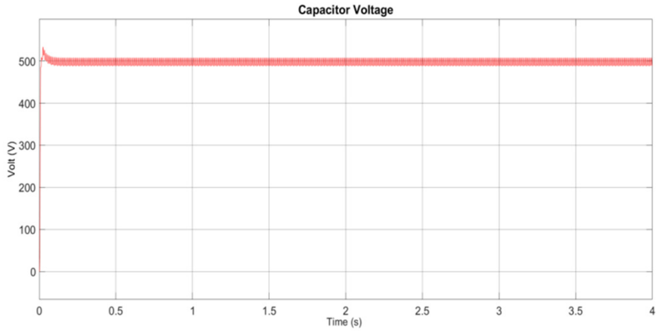

Fig. 14. Capacitor voltage after being controlled.

The results indicate that the voltage value at the capacitor exhibits a range of approximately 500 V, with a standard deviation of approximately 19 V. This variation enables the calculation of the error of the set point:

$$\text{Error} = \frac{19V}{500V} \times 100\% = 3.8\% \tag{16}$$

IV. CONCLUSIONS

In this study, simulations have been conducted to reduce the current distortion in a single-phase source by using the Variable Frequency Drive (VFD), resulting to:

- The usage of VFD for the purpose of speed control functions, in addition to the conversion of single-phase sources to three-phase sources, leads to the distortion of the source current, resulting in an irregular current pattern that deviates from a sinusoidal shape. This irregularity can potentially disrupt the operation of connected equipment, as the current supplied to the load may not be within the nominal range, potentially leading to overheating issues.
- The harmonic current extraction method using multiplication with sine function is advantageous in this research because it is more straightforward to apply in a single-phase system than the d-q transformation extraction method or PQ theory.
- Following the integration of the compensation current into the mesh, a substantial reduction in Total Harmonic

Distortion (THD) was observed, from 45.35% to 3.57%. This outcome aligns with the stringent requirements of the IEEE 519 - 2014 standard, demonstrating the efficacy of the implemented solution.

- In accordance with the potential difference principle, the compensation current induction is only permissible if the Direct Current (DC) side voltage of the inverter exceeds the peak voltage of the mesh. Conversely, in the event that the peak voltage of the mesh exceeds the input DC voltage of the inverter, the current will flow from the mesh to charge the inverter's input capacitor.

- The stability of the DC bus voltage is a critical parameter, and Proportional Integral (PI) control is employed to ensure that the DC bus operates close to the setpoint. Subsequent to the implementation of the requisite controls, the deviation error was 3.8%.

- The Hysteresis Current Control (HCC) Pulse Width Modulation (PWM) ignition method was selected due to its rapid response and ease of use. The principle of error tolerance limits between the reference and output currents, were used to generate the PWM.

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