DESIGN, SIMULATION & ANALYSIS OF POWER ELECTRONICS MODULATORS FOR VARIABLE FREQUENCY DRIVES

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Abstract: AC Motors are largely used in various industrial manufacturing processes due to their simplicity, robustness, and cost-effectiveness compared to DC motors, which are costly and use brushes that limit its efficiency and usage in critical applications. Variable Frequency Drives (VFD) play a crucial role and are extensively used in various critical applications to control the speed of AC motors by varying the voltage and frequency of their power supply. Power Electronics Modulator (PEM) are used in VFD, and they cause stress on the grid due to its switching. Simulation of different converters and inverters used in VFD provides an overview of different converters, their modes of working principles, efficiency, and limitations. In this paper, authors design and simulate the different converter topologies used in VFD to analyze and compare their line current T.H.D. This paper aims to provide a comprehensive comparative analysis of various simulation techniques employed in modelling converters for VFD.

***Index Terms:-* AFE, SPWM, Variable Frequency Drives (VFD), T.H.D, Unipolar Inverter, Scalar Control Method**

I. INTRODUCTION

An Electrical Motor Drive is defined as a form of machine equipment consisting of Electric motors together with its electronic control equipment & energy transmitting links designed to convert electrical energy into mechanical energy and provide electronic control of this process.[1] In a system where the loads fluctuate over time, adding a Variable Frequency Drive (VFD) to a motor-driven system may result in energy savings.[2] Variable speed drives, also known as Adjustable Speed Drives, are a class of machinery that includes VFDs. It is obvious that Variable Speed Drives (VSD) can be electrical or mechanical, whereas VFDs are electrical.[3]

By altering the frequency of the motor supply voltage, a motor connected to a VFD can have a different operating speed. This allows continuous process speed control. VFD coupled to motors provides a reliable and cost-effective solution to many applications including water pumping, fans, conveyors, etc. in industries. In specific applications, a VFD can provide energy conservation benefits and improvements in operational control. [4-5]

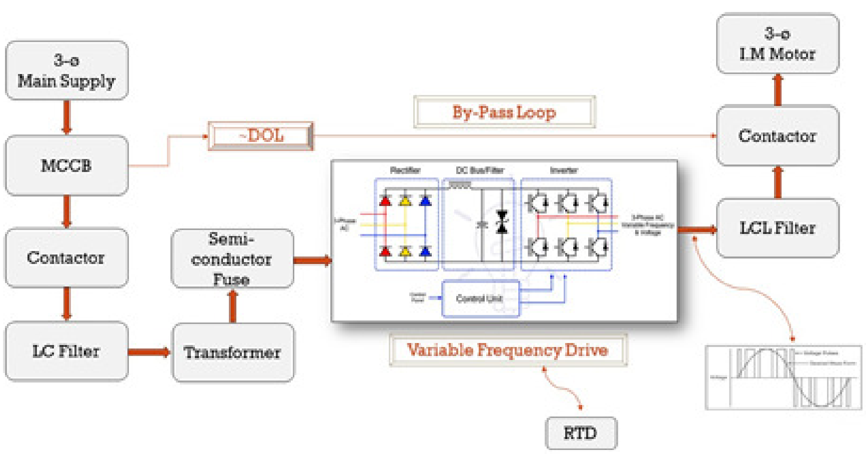


Figure 1 Block Diagram of VFD

A VFD is essentially an electrical circuit that connects a motor to a supply network. The primary function of a VFD is to supply the motor with an AC supply voltage (or AC current) of variable frequency, allowing a variable motor speed and torque, in contrast to a Direct-On-Line (DOL)-operated motor, whose speed is fixed to the frequency of the supplied AC network. The three sections of a modern VFD are usually the rectifier, DC-link, and inverter sections. The rectifier section of the VFD converts the incoming AC network voltage, which is typically 50 or 60 Hz, into a DC voltage (or DC current). The DC voltage (or DC current) is subsequently converted into an AC voltage (or AC current) with variable frequency and amplitude in the inverter section of the VFD Fig. 1.[6] The rectifier converts the AC supply voltage into a DC voltage. This converter may be an uncontrolled rectifier or a controlled rectifier. According to IEEE 519-2022, Standard, the line current THD (Total Harmonic Distortion) will be limited to a permissible range based on the strength of the electrical system at the Point of Common Coupling (PCC) [9].

The uncontrolled six-pulse diode rectifier was the most popular converter, and it does not require any control, but it is one of the non-linear loads and produces about 31.08%-line current T.H.D. It reduces the line power factor, which will necessitate the use of a line reactor and DC link Reactor, which will increase the cost and require more space [7]. Due to the, multi-pulse converters were invented, which reduced the THD to <5% and complies with the IEEE 519-2022 Standards [8]. An 18-pulse diode converter is successfully able to reduce the harmonics but it is one of the more expensive solutions to reduce the T.H.D. because it is typically custom-built and constructed using expensive, large magnetics. The Active Front End Rectifier (AFE), also known as an Active Rectifier, is a preferred choice because it reduces the THD and provides other benefits such as control over the DC voltage and bidirectional power flow. It works by using SVPWM techniques [9]. This paper presents the design and simulations of converters of VFD such as Front-end converters, 12-pulse diode converters, AFE, and SPWM inverters [10].

II. Diode Rectifier

The three-phase diode rectifier is one of the simplest rectifiers. The circuit diagram of the passive rectifier is shown in Fig. 2.

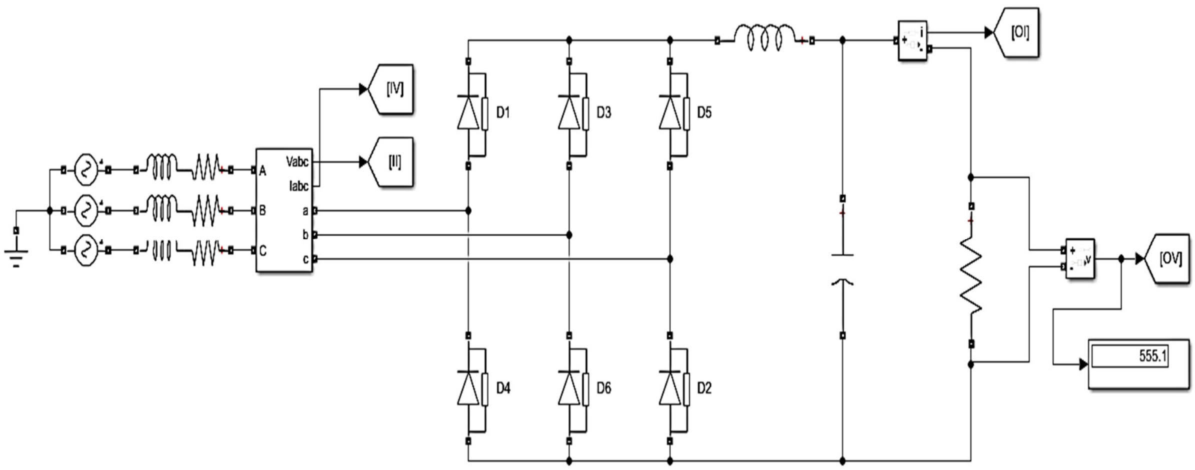
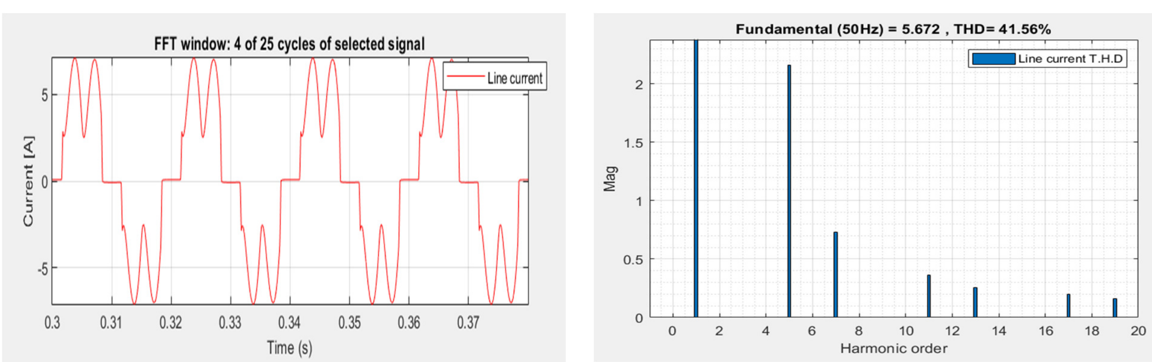


Figure 2 Simulink Model of 3-Ø Uncontrolled Rectifier

It consists of six passive switches, such as diodes, an AC and DC line reactor, and a filter capacitor. It does not require any control technique as the diodes are switched at the grid frequency. It is one of the non-linear loads and does not provide any control over the DC output voltage. It also differs from a linear load in that its impedance varies with the instantaneous applied voltage, resulting in a non-sinusoidal current when the voltage fluctuates. In simpler terms, this type of load doesn't maintain a consistent current-to-voltage relationship throughout the alternating cycle. The basic setup to illustrate a non-linear load is a diode rectifier circuit, which comes in various forms such as full-wave and half-wave rectifiers, as well as single-phase or three-phase configurations. This uncontrolled converter injects about 31.09% of the current THD, which can go up to 40–70% [11]. The working operation of the converter is simulated using MATLAB Simulink [12]. From this, we can observe that the line current is not sinusoidal and has harmonic content (5^{th}, 7^{th},11^{th},13^{th}).

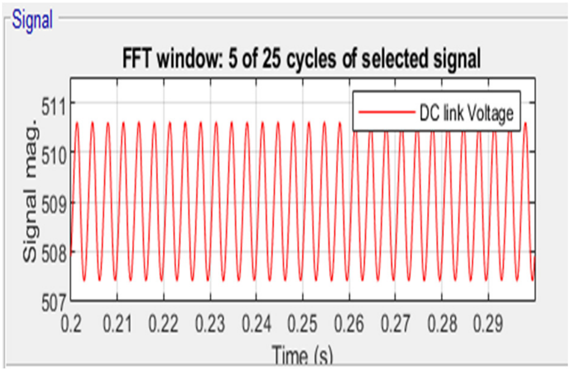


Waveform FFT Analysis

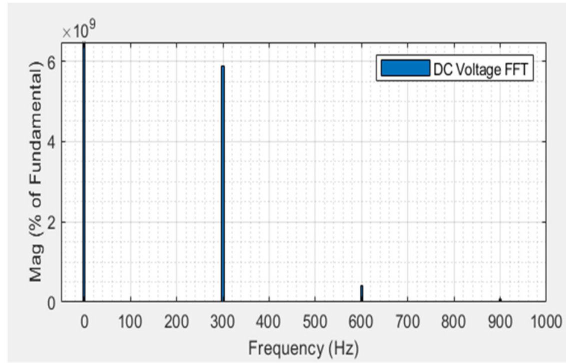
Figure 3 Line Current of Uncontrolled Rectifier

The waveforms of a passive rectifier are shown in Fig. 3. From the above waveform, we can see that the current is not sinusoidal and has a high amplitude of lower-order harmonics such as the 5^{th} and 7^{th} harmonics. The average output DC voltage of the rectifier is 507 VDC and the DC link has a Ripple voltage of 3.29V as shown in Fig. 4. The average output value of the rectifier DC voltage can be calculated by:

$$V_{dc} = \frac{1}{\pi/3}\int_{\frac{\pi}{6}}^{\frac{\pi}{2}} \sqrt{2}\, V_{LL} \sin\left(\omega t + \frac{\pi}{6}\right).d(\omega t) = \frac{3\sqrt{2}}{\pi} V_{LL} \approx 1.35 V_{LL}$$



Waveform



FFT Analysis

Figure 4 Output DC voltage

Reactors (inductors), play a crucial role in power systems by managing current flow and protecting equipment. When placed between electrical equipment and the power system, reactors, particularly line reactors, serve as a barrier against power surges and transients. By limiting the current change rate, they reduce harmonics and safeguard sensitive components such as variable-frequency drives (VFDs).

In this configuration, line reactors shield the entire VFD from potential damage and ensure stable operation. They also reduce the line-current harmonics that the rectifier injects into the grid. Line reactors and DC chokes are employed to mitigate harmonic distortion in the line current. Table 1 presents the results of a study investigating the impact of line reactor impedance on THD. As evident from the table, modifications to the line reactor resistance demonstrably influence the line current THD.[13]

TABLE 1 SUMMARY OF DESIGN PARAMETER AND ANALYSIS OF RECTIFIER

I/P Voltage (VLL) (V)	**I/P Frequency (HZ)**	**Line Reactor**		**DC Choke (mH)**	**Load Resistance (Ohm)**	**Line I T.H.D (%)**	**Line V T.H.D (%)**	**O/P DC Voltage (V)**
		Resistance (Ohm)	**Inductance (mH)**					
415	50	0.5	0.2288	5.35	100	50.61	0.79	551.7
415	50	1	0.2288	5.35	100	49.57	1.09	546.4
415	50	1.5	0.2288	5.35	100	48.85	1.46	541.3
415	50	2	0.2288	5.35	100	47.96	1.84	536.2
415	50	2.5	0.2288	5.35	100	46.95	2.21	531.3
415	50	3	0.2288	5.35	100	45.88	2.56	526.4
415	50	3.5	0.2288	5.35	100	44.77	2.9	521.7
415	50	4	0.2288	5.35	100	43.67	3.22	517
415	50	4.5	0.2288	5.35	100	42.59	3.52	512.4
415	50	5	0.2288	5.35	100	41.56	3.81	507.9

The graphical representation of resistance vs. line voltage and current is shown in Fig. 5. From the graph, it can be observed that as we change the value of line reactor resistance, the values of line voltage and current T.H.D. will also change. As resistance increases, the line current T.H.D. will decrease with the increase in the line voltage T.H.D. The charging of the DC bus capacitor in VFDs results in pulses of current, leading to a non-sinusoidal current flow with a high T.H.D, typically ranging from 90% to 150%.

These harmonics are predominantly at the 5^{th}, 7^{th}, 11^{th}, and 13^{th} frequencies. Introducing a line reactor into the system transforms this discontinuous current into a smoother, continuous waveform. This occurs because the voltage at the VFD terminals becomes more consistent, causing the charging time for the DC bus capacitor to lengthen. Consequently, the width of the current pulses increases, while their peak amplitudes decrease. By utilizing line reactors with around 5% impedance, a significant reduction, approximately 65%, in the THD of the current can be achieved.

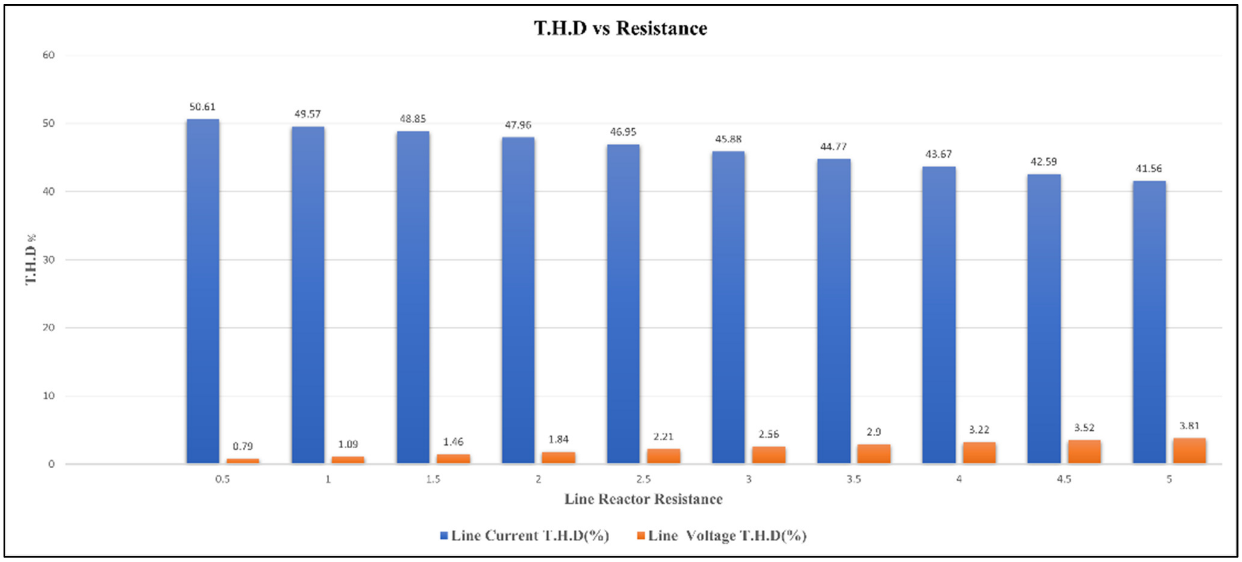


Figure 5 Resistance vs Line Voltage & Current T.H.D

This reduction not only aids in meeting the requirements outlined in the IEEE 519 Standard but also helps in lowering motor operating temperatures and reducing operational noise [14]. A six-pulse diode-bridge fed the Scalar-Controlled Induction Motor Drive (SCIMD) is shown in Fig. 6.

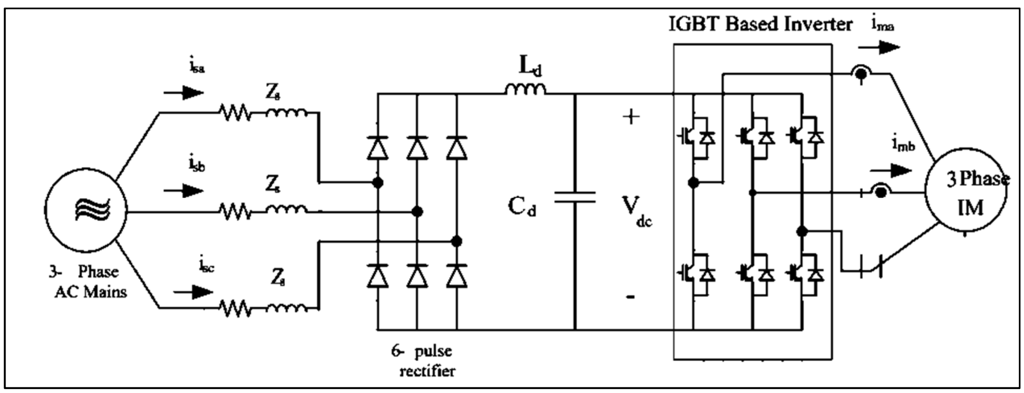
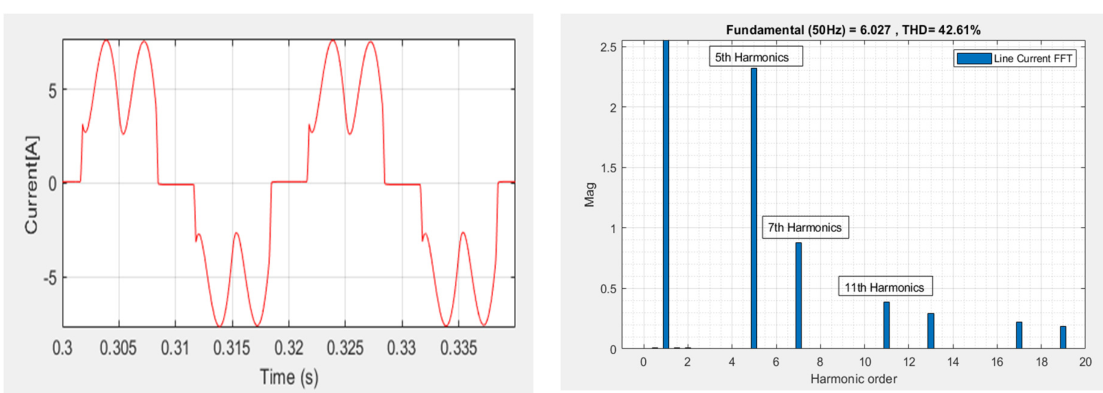


Figure 6 Schematic of VFD

The six-pulse diode rectifier is connected at the front end of the VFD and injects a line current harmonic of about 42.61% into the grid. The supply voltage is about 415V line-to-line, and the 20 HP motor load is connected to the VFD inverter. The current T.H.D. analysis is shown in Fig. 7.



Waveform　　T.H.D Analysis

Figure 7 Line Current of the VFD Rectifier (Six-pulse diode)

III. Multi-Pulse Diode Rectifier [15]

While the basic 6-pulse diode rectifier is reliable and cost-effective, it struggles with fluctuating DC voltage and injects current harmonics back into the grid. Due to these limitations, multi-pulse converters are used, which limit the harmonics to < 5%, as discussed earlier. A Multi-Pulse Converter is made by connecting multiple converters; for example, an 18-pulse converter is made by connecting three six-pulse diode bridge rectifiers, the delta-connected auto-transformer-based 12-pulse converter is shown in Fig 8.

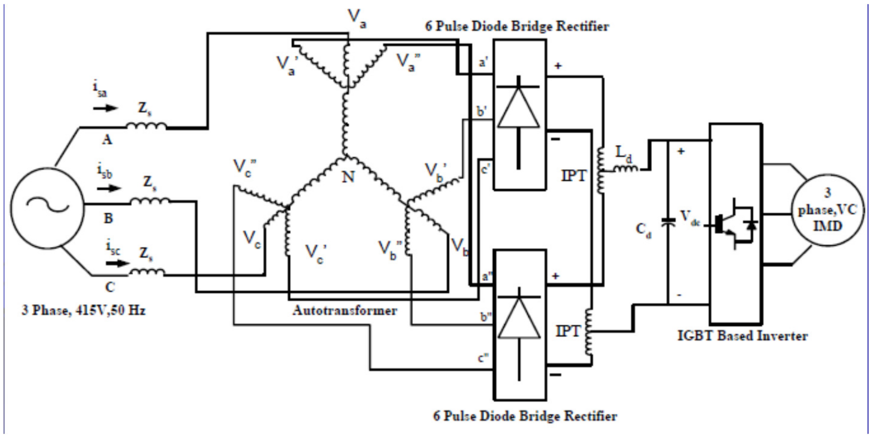


Figure 8 12-pulse Converter

As shown in Fig. 8, the delta-connected autotransformer is used with a 12-pulse diode converter, which provides the phase shift to the passive converter connected in parallel with each other. The winding connection and the phasor diagram are shown in Fig.9.

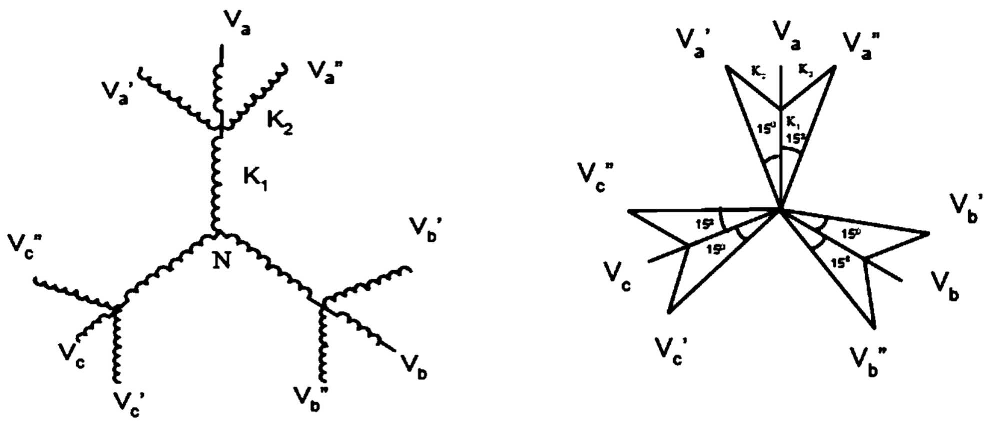


Figure 9 Winding connection & phasor Diagram

The 12-pulse converter, along with the DC bus and IGBT-based inverter, can be referred to as a VFD. The induction motor is connected to the VFD, which acts as a load. The waveform of line current T.H.D. of a 12-pulse diode converter at full load is shown in Fig. 10. Here it is but obvious that the 12-pulse converter provides better performance by reducing the line current T.H.D. to 9.89%. The basic workings of a 12-pulse converter remain the same; however, in order to generate nine phases with a 20º phase displacement, a transformer comprising three additional windings must be used. The drawbacks of these solutions include high transformer weight and volume, efficiency losses, and cost.

While 12-pulse converters offer improved harmonic mitigation, they come with limitations like increased size, complexity, and dependence on bulky transformers. AFE technology addresses these drawbacks. AFEs achieve excellent harmonic reduction with controllable electronic switches instead of diodes in the rectifier stage. This allows for a compact size of the converter and provides other benefits, such as control over the DC voltage and bidirectional power flow. It works by using SVPWM techniques[16], as discussed earlier. Also, introduce complexity in control as AFEs use closed-loop control algorithms.

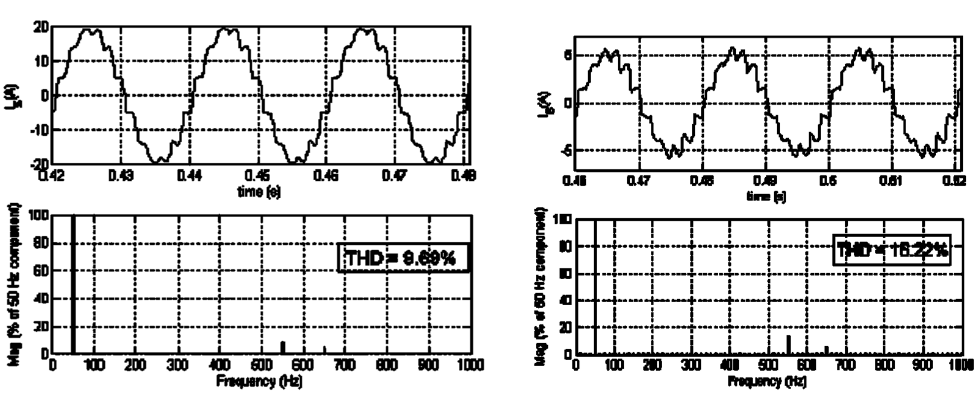


Figure 10 Line current T.H.D of 12-pulse Converter [17]

IV. ACTIVE FRONT END CONVERTER

Due to their versatility, PWM/AFE rectifiers are a favorite choice for powering systems like VFDs and UPS. These advanced rectifiers offer several benefits. Firstly, they can regulate the incoming power from the input, ensuring efficient energy use and minimizing wasted power. Secondly, they help to reduce the distortion in the line current waveform, which can create stress on the connected grid.

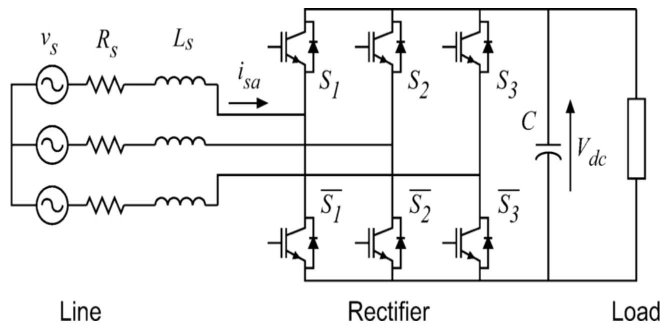
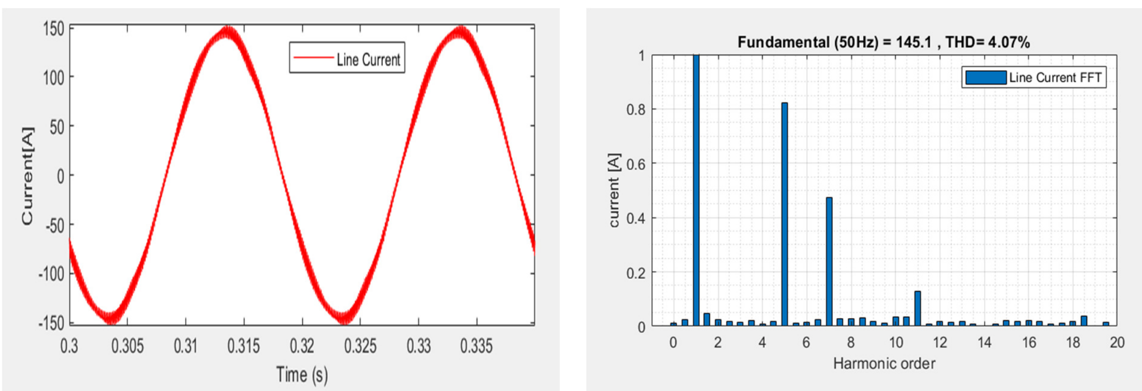


Figure 11 Schematic of AFE

Thirdly, they provide flexibility by allowing power to flow in both directions, making them suitable for specific applications. Finally, PWM/AFE rectifiers offer precise control over the DC voltage output. These features, combined with various control techniques, make them a powerful and efficient solution for many DC power needs.



Waveform

T.H.D Analysis

Figure 12 Line current of the Active Frond End Converter

The AFE also known as an Active rectifier reduces the line current T.H.D to < 5% and is a better solution as compared to a multi-pulse converter as it also provides control over the DC voltage Output. Due to the advantages, AFE has become more popular. Many applications, including VFDs, UPS, and EVs, use AFE due to its lower harmonic distortion in the line current. The circuit diagram of the AFE Converter is shown in Fig.11. It consists of Six Active switches, a line side, and a DC capacitor Filter. A closed-loop controlled AFE fed the Scalar-controlled induction motor drive (SCIMD) is shown in Fig. 13.

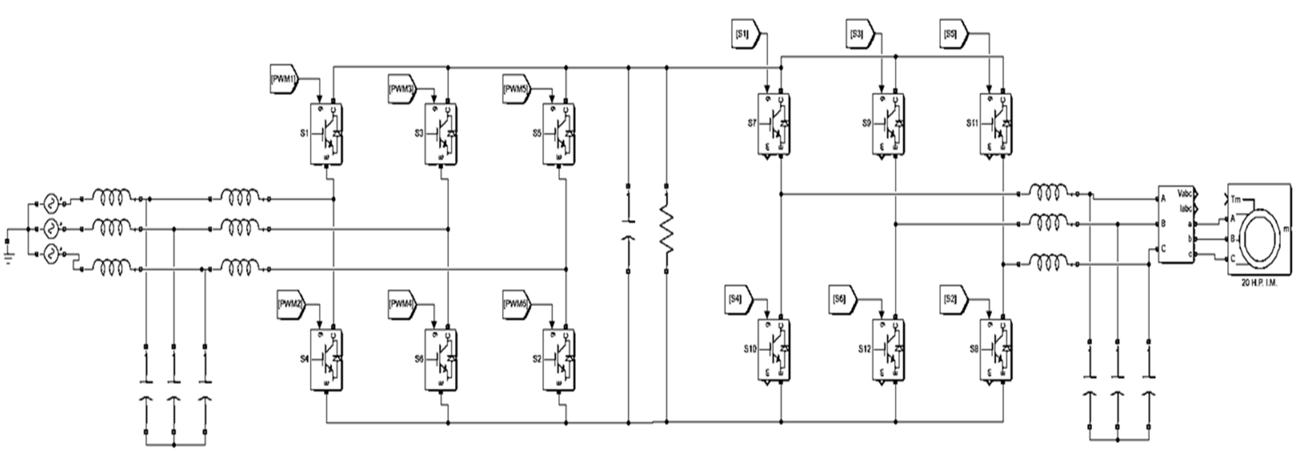
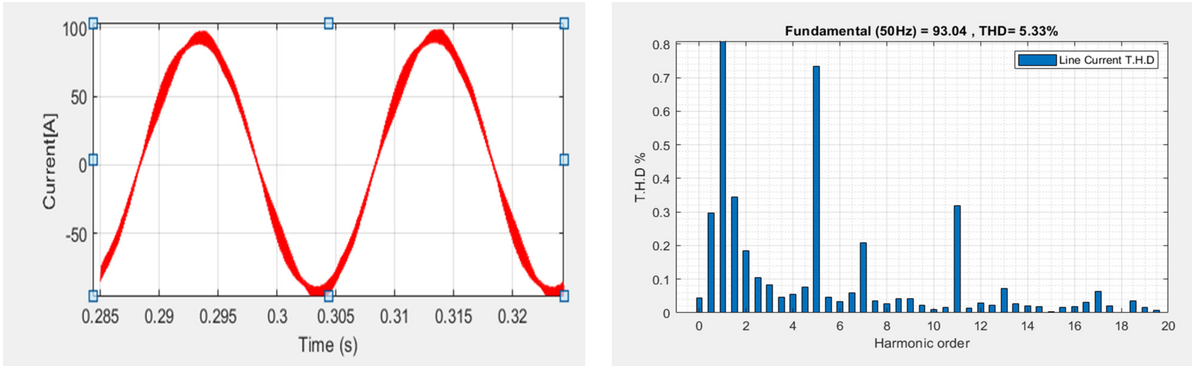


Figure 13 Simulink Model of Active Front End Converter

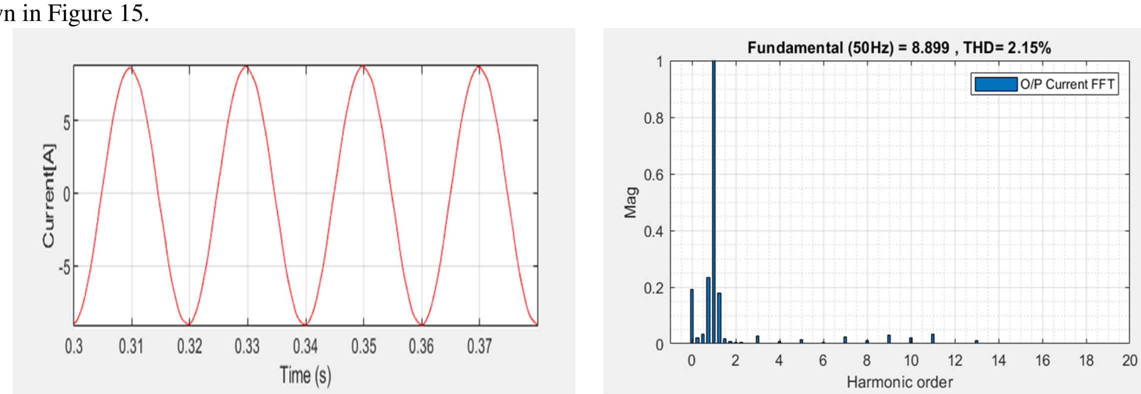
From the simulation, it can be observed that the AFE injects about 5.33% of line current T.H.D. into the grid. The line-to-line voltage is about 415V, the switching frequency is about 4 kHz, and it is loaded with an inverter connected to a 20-hp ACIM load.



Waveform T.H.D Analysis

Figure 14 Line current of the VFD with Active Frond End Rectifier

The output current T.H.D of three three-phase unipolar Inverter Powered from the AFE and connected to a 20 H.P. ACIM load is shown in Figure 15.



Waveform T.H.D Analysis

Figure 15 Output current of VFD Inverter

From the waveform, it is observed that the T.H.D. of the output current is about 2.15%, which is within the permissible limit of IEEE Standards.

V. Three-Phase Unipolar PWM Inverter

Three-phase PWM inverters are commonly used in a wide range of Power Electronics (PE) applications, including VFDs, UPS, renewable energy systems, and EVs. It is one of the most important PE converters.[18] PWM Inverters Use different PWM techniques, such as SPWM, SVPWM, etc. In VFD, when open-loop scalar control is required, three-phase PWM inverters use SPWM control techniques, and when vector control is required, it use SVPWM control techniques. 3-Phase PWM Inverter consists of Six Active switches such as IGBT, MOSFET, etc. The Converter is simulated [19] using MATLAB Simulink the Input DC voltage is about 400 V, the switching frequency is 4 KHz and a Motor Load is connected to the Inverter Fig.16.

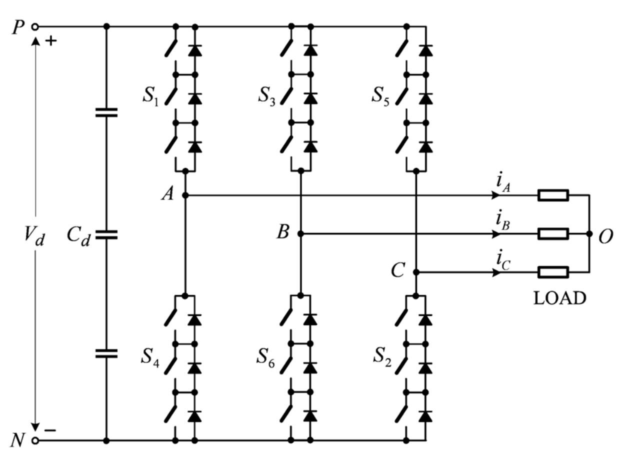


Figure 16 3-∅ PWM Inverter

It is controlled by using the SPWM technique[20], in which a sin wave is compared with carrier waves (unipolar PWM), and from which the gating signal is generated to control the active switches of the inverter. By using an amplitude modulation index, the fundamental frequency component of the inverter output voltage can be adjusted by:

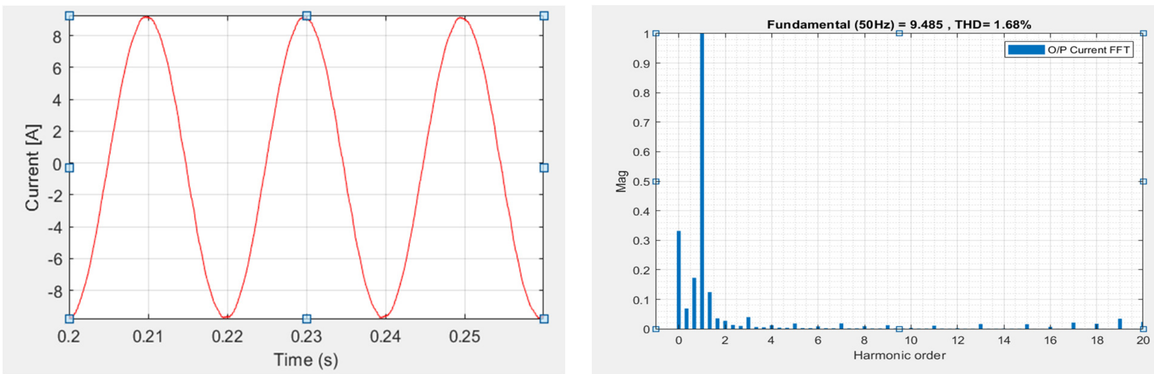
$$M_a = \frac{V_m}{V_{cr}}$$

Where

V_m = the amplitude of the modulating Signal

V_{cr} = the amplitude of the Carrier wave

The amplitude modulation index ma is usually adjusted by varying V_m while keeping V_{cr} fixed. Switches S_1 to S_6 turn on and off based on how a control signal (modulating wave)[21] interacts with a high-frequency signal (carrier wave). If the modulation wave voltage (V_m) exceeds the carrier wave voltage (V_{cr}), the upper switch (S_1) in inverter leg A is activated while the lower switch (S_4) operates inversely, being deactivated. Consequently, the resulting voltage at inverter terminal VAN, relative to the negative DC bus N, matches the Direct Current (DC) voltage V [8]. The inverter produces about 1.68% O/P T.H.D. when loaded with a 20 H.P. motor load. The simulated waveform of a three-phase SPWM inverter is shown in Fig. 17.



Waveform T.H.D Analysis

Figure 17 Output Current of 3-∅ phase Unipolar Inverter

A simulation-based comparative analysis of different converters used at the front end of the VFD is shown in Table 2. The comparison table highlights key parameters of different rectifier topologies and an active front-end (AFE) system. The six-pulse diode rectifier, while offering low cost, exhibits high line current THD and lacks control. In contrast, the 18-pulse rectifier significantly reduces THD, but at a higher cost and complexity due to the increased number of diodes and increase in magnetics. The AFE system, with controlled operation and bidirectional power flow capability, offers intermediate THD levels, requires fewer switches, and has an average cost. Each topology has different performance, complexity, and cost.[24]

Table 2 COMPARISION OF THREE PHASE RECTIFIERS

Parameters	Six-pulse Diode Rectifier [23]	Multi-pulse Rectifier (12-pulse) [17]	AFE [22]
Grid Voltage	415 V_{LL}	415 V_{LL}	415 V_{LL}
Grid Frequency	50Hz		
DC O/P Voltage	560V	560V	600V
Switching Frequency of Rectifier	Switched at the Grid Frequency	Switched at the Grid Frequency	20KHz
Switching Frequency of Inverter	4 KHz		
Load	Inverter Connected to a 20 H.P. ACIM		
Line I T.H. D	42.61%	9.89 % - with Full load 15.22 % with 20% Load	5.33% (reduces at full load)
Controlled	Uncontrolled	Uncontrolled	Controlled
Bidirectional Power flow	Not Possible	Not Possible	Possible
No. of Switches	6 (Diodes)	12 (Diodes)	6 (IGBT)
Cost	Low	High	Moderate

CONCLUSION

From four simulations realized above, three are about the front-end converter used in VFD. It can be observed that the six-pulse diode rectifier is the simplest and has a lower cost, but it can inject about 42.61%-line current distortion into the grid. The 12-pulse converter on the other side can only inject about 9.89%-line current T.H.D with full load and 15.22% - line current THD with 20 % of the load, but the multi-pulse converter requires large magnetics because nine phases are needed for three different rectifier bridges with a 20-degree phase displacement, which increases the size and overall cost of the circuit. The AFE converter reduces the harmonic distortion to 5.33%, which can be further reduced by designing an appropriate input LCL filter, provides control over DC voltage, and has a compact size. From the above results, it can be concluded that the AFE converter is the most suitable option for VFD applications demanding a balance between performance, size, and cost.

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