Comparative Analysis of Bipolar and Unipolar SPWM Techniques in PIC-Based Pure Sine Wave Single-Phase Inverters

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ABSTRACT

This paper provides a comparative analysis of bipolar versus unipolar Sinusoidal Pulse Width Modulation (SPWM) in DC-AC inverters, focusing on Total Harmonic Distortion (THD) across modulation indices and the latter's effects on the R-L loads. Using the PIC18F2431 microcontroller for its efficiency, a single-phase inverter accomplished to deliver a high-fidelity sine wave. This study discovered that while both SPWM methods reduce harmonics, the unipolar approach yields more uniform THD reduction and superior performance, particularly noticeable in RL load conditions, where minimal harmonic distortion is crucial. The bipolar inverter, despite a higher initial THD, shows a considerable improvement at higher indices, significantly enhanced by an LC low-pass filter. This filter is a key component in achieving sub-1% THD levels at full modulation, ensuring optimal sine wave quality. The findings highlight the operational differences between the SPWM techniques and the importance of the LC filters in ameliorating the inverter output for various power applications.

Keywords-single phase inverter; bipolar SPWM; unipolar SPWM; THD; PIC18F2431

I. INTRODUCTION

The profound impact of semiconductor technology on electronic power systems has revolutionized power conversion and control [1]. The advent of transistors, with their compact size, reliability, and efficiency, revolutionized electronic circuits, as they became the foundational building blocks. Their role as effective switches and amplifiers facilitated more compact and efficient designs across various electronic applications, including those in power systems [2, 3]. As semiconductor technology progressed, it ushered in an era of even more advanced capabilities and applications. The development of Integrated Circuits (ICs) represented a monumental stride, further miniaturizing electronic systems and amplifying their performance. This miniaturization, coupled with the ability for rapid information development, played a pivotal role in the burgeoning field of power electronics, which focuses on the conversion and control of electrical power through electronic devices. A significant landmark in this evolutionary path was the emergence of the Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) and subsequently, the Insulated Gate Bipolar Transistor (IGBT) [4, 5]. These devices revolutionized power converter designs with their capability for rapid switching and minimal power losses, making them indispensable in medium to high-power applications, including motor drives, electric vehicles, and renewable energy systems' grid-tied inverters.

During the next evolution stage, modern inverters, especially pure sine wave inverters, achieved unprecedented efficiency with minimal losses. These inverters are engineered to produce an alternating current (AC) output that meticulously replicates the smooth sinusoidal waveform of grid electricity, crucial for powering sensitive electronic equipment. The advancement of these inverters has been propelled by the progression in semiconductor technology and sophisticated control techniques. Unlike their predecessors, pure sine wave inverters utilize complex mechanisms to precisely emulate the characteristics of grid-supplied AC power. This is vital across a spectrum of applications, from residential solar power systems to critical medical equipment. The control strategies employed in these inverters are pivotal to their performance, with Pulse Width Modulation (PWM) being a predominant technique. PWM involves the modulation of pulse durations using high-frequency switching devices like IGBTs or MOSFETs, efficiently managing output voltage and frequency to achieve low harmonic distortion. Further advancements in control methods, including Space Vector PWM (SVPWM), Digital Signal Processing (DSP), and microcontroller-based controls, have enhanced the precision in waveform generation. In the realm of inverter control, Bipolar and Unipolar SPWM stand out as two distinct methods, each with unique advantages and specific applications. Bipolar SPWM, known for producing waveforms that closely mimic a natural sine wave with lower harmonic distortion, is ideal for high-quality power applications [6, 7]. However, the constant polarity shifts can impose increased stress on switching devices. Contrastingly, Unipolar SPWM, which switches the output voltage between a Direct Current (DC) rail and zero, offers greater efficiency and component longevity but at the cost of higher harmonic distortion. The choice between these methods hinges on the specific requirements of power quality, system efficiency, and component durability. While Bipolar SPWM is preferred where power quality is non-negotiable, Unipolar SPWM is favored in scenarios prioritizing component lifespan and system efficiency. Continuous advancements in semiconductor technology and control algorithms are further refining both techniques, optimizing their performance for diverse inverter applications. This evolution was completed through the integration of PIC Microcontrollers, developed by Microchip Technology, in controlling single-phase inverters through SPWM [8]. These microcontrollers, acknowledged for their efficiency and versatility, are pivotal in converting DC to high-quality AC power. Their rapid computational abilities enable real-time pulse width adjustments in response to varying loads or input conditions, ensuring consistent power quality. This adaptability is especially valuable in systems with fluctuating input conditions, such as solar inverters. The integration of PIC microcontrollers not only renders inverters cost-effective and compact, but also enables customization and advanced features like remote monitoring and intelligent power management to take place, thus enhancing efficiency, reliability, and user convenience [9, 10].

II. BIPOLAR AND UNIPOLAR SPWM CONTROL

The concepts of Bipolar and Unipolar Sinusoidal Pulse Width Modulation (SPWM) represent two pivotal control strategies in the realm of power electronics, particularly in the context of inverter design and operation. Both methods aim to modulate the output of an inverter to closely emulate a sine wave, which is essential for converting DC to a smooth AC. However, they differ in their operational principles, advantages, and suitability for various applications [11].

A. Bipolar SPWM

Bipolar SPWM involves alternating the output voltage of the inverter between the positive and negative values of the DC supply voltage as illustrated in Figure 1. This results in an output waveform that oscillates above and below the zero-voltage line, closely mimicking a true sine wave. The primary advantage of Bipolar SPWM lies in its ability to produce a high-quality output with lower harmonic distortion. This makes it particularly suitable for applications where power quality is critical, such as in sensitive medical equipment, precision laboratory instruments, or audio systems where signal integrity is paramount [11, 12]. In Bipolar SPWM, the switching devices within the inverter (such as IGBTs or MOSFETs) are controlled to rapidly switch between the positive and negative voltage rails, effectively carving out a waveform that resembles a sine wave. The challenge in this method is the higher stress on the switching devices due to the frequent switching between positive and negative voltages. This can lead to an increased wear and tear on the components, potentially reducing the lifespan of the inverter. Furthermore, the rapid switching can also lead to higher electromagnetic interference (EMI), which may require additional filtering or shielding in sensitive applications.

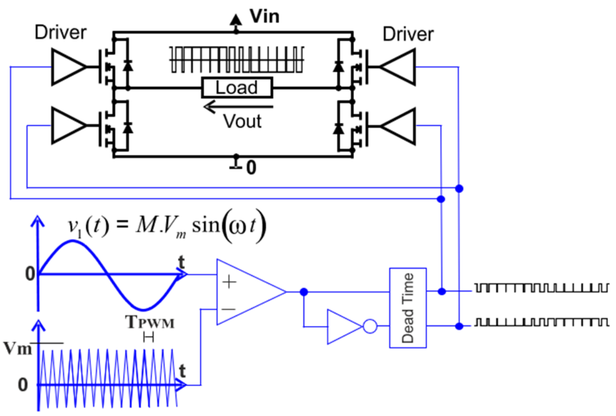

Fig. 1. Bipolar SPWM inverter.

B. Unipolar SPWM

Unipolar SPWM, in contrast, switches the output voltage between a single polarity (positive or negative) and zero. Unlike Bipolar SPWM, the waveform in Unipolar SPWM does not cross the zero-voltage line. It either stays above zero, switching between the positive peak and zero, or below zero, switching between the negative peak and zero. The major advantage of Unipolar SPWM is the reduced stress on the switching devices, as the voltage does not swing between the positive and negative extremes. This reduced stress can lead to increased efficiency and potentially longer component lifespan. However, the drawback of the Unipolar SPWM is a typically higher harmonic distortion in the output waveform compared to the Bipolar SPWM. While this may not be critical in some applications, it is a significant consideration in the instance that the quality of the AC power is crucial. Unipolar SPWM is often used in applications where efficiency and longevity of the inverter are more critical than the absolute fidelity of the output waveform, such as in certain types of industrial equipment or in cost-sensitive consumer applications [13, 14].

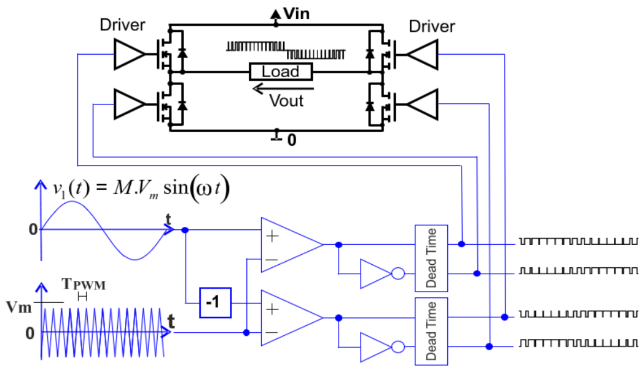

Fig. 2. Unipolar SPWM.

The distinctions between Bipolar and Unipolar SPWM are pivotal for the nuanced design and operational dynamics of inverters. Each method exhibits specific characteristics that significantly influence efficiency, harmonic distortion, and applicability in various domains. When comparing Bipolar and Unipolar SPWM techniques, several key differences emerge. Bipolar SPWM alternates the output voltage between positive and negative values of the DC supply, leading to higher waveform quality with lower harmonic distortion. However, this approach places higher stress on switching devices due to frequent changes in voltage polarity, which could result in potentially lower efficiency due to rapid switching and associated losses. It is typically preferred in applications where high power quality is crucial, such as medical equipment and precision instruments, though it may lead to potentially higher EMI and reduced component longevity due to increased wear and tear. On the other hand, Unipolar SPWM switches the output voltage between a single polarity and zero, which simplifies the stress on components as the voltage does not swing between extremes. This method tends to result in higher harmonic distortion compared to Bipolar SPWM but offers potentially higher efficiency due to reduced stress and switching losses. Unipolar SPWM is suitable for applications where efficiency and component longevity are prioritized, such as industrial equipment and cost-sensitive consumer applications, benefiting from lower EMI and potentially increased component longevity due to lower operational stress [14].

III. LC LOW-PASS FILTER

The LC low-pass filter transforms the output waveform towards a sinusoidal shape by attenuating frequencies higher than its cutoff frequency while allowing lower frequencies to pass. When an inverter outputs a waveform that includes the desired fundamental frequency along with higher frequency harmonics, the LC filter will reduce the amplitude of these harmonics based on the filter's frequency response [15].

A. Transfer Function of the LC Filter

The transfer function $H(s)$ of a second-order low-pass LC filter is given by:

$$H(s) = \frac{1}{s^2LC + sRC + 1} \quad (1)$$

where s is the complex frequency variable in the Laplace domain, L is the inductance, C is the capacitance, and R is the resistance. For an ideal LC filter, R approaches 0, which simplifies the transfer function to:

$$H(s) = \frac{1}{s^2LC + 1} \quad (2)$$

B. The Cutoff Frequency

The cutoff frequency (f_c) where the filter begins to attenuate signals can be found by:

$$f_c = \frac{1}{2\pi\sqrt{LC}} \quad (3)$$

C. Attenuation of Harmonics

For each harmonic frequency (f_n), the filter's attenuation can be described by the magnitude of the transfer function $|H(j\omega)|$ at that frequency:

$$|H(j\omega)| = \frac{1}{\sqrt{\left(1-\left(\frac{\omega}{\omega_c}\right)^2\right)^2 + \left(2\xi\frac{\omega}{\omega_c}\right)^2}} \quad (4)$$

where $\omega = 2\pi f_n$ is the angular frequency of the n^{th} harmonic, $\omega_c = 2\pi f_c$ is the angular cutoff frequency, and ξ is the damping factor of the filter, which is minimal for an ideal LC filter.

D. Output Waveform

The output waveform $V_{out}(t)$ after the LC filter is a sum of the fundamental frequency and the attenuated harmonics:

$$V_{out}(t) = V_1 \sin(2\pi f_1 t) + \sum_{n=2}^{\infty} V_n |H(j2\pi f_n)| \sin(2\pi f_n t + \phi_n) \quad (5)$$

where V_1 is the amplitude of the fundamental frequency, V_n is the amplitude of the n^{th} harmonic before filtering, f_1 is the fundamental frequency, f_n is the frequency of the n^{th} harmonic, and Φ_n is the phase of the n^{th} harmonic.

By attenuating the harmonics more than the fundamental frequency, the LC low-pass filter effectively 'cleans up' the output waveform, making it more sinusoidal. The degree of sinusoidality will depend on the filter design, specifically on how sharply it attenuates frequencies above f_c and the harmonic content of the input waveform.

IV. SIMULATION RESULTS AND DISCUSSION

This simulation was performed using the ISIS software. The PIC18F2431 microcontroller is adept at generating SPWM signals. The former operates deploying an 8 MHz crystal, which is effectively quadrupled to 32 MHz by the microcontroller's internal Phase Locked Loop (PLL) [16]. This acceleration allows the microcontroller to execute operations at a rate of 8 Million Instructions Per Second (MIPS), ensuring efficient performance.

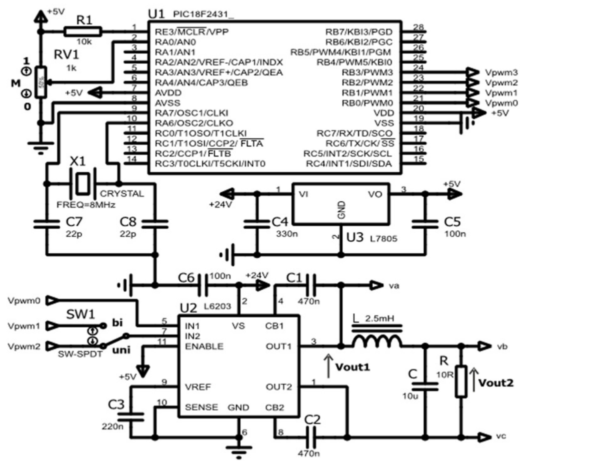

Fig. 3. Electronic circuit of the sinewave single phase inverter under ISIS.

The L7805, a robust linear voltage regulator delivering a stable 5V output at up to 1.5 A, is suitable for various applications. Capacitor C_5 (100 nF) ascertains the stability of the voltage output, even in the absence of a load. Capacitor C_4 (330 nF) is essential when the regulator is situated at a significant distance from the power supply filter, as it mitigates the effects of line impedance. For motor control, the L6203 full-bridge driver is employed. This specific driver is notable for its compatibility with supply voltages reaching up to 48 V, its capability to handle total RMS currents up to 4 A, and its low on-state resistance, typically just 0.3 Ω at 25 °C, which enhances the overall efficiency.

The inverter's output voltage spectrum is characterized by a fundamental sinusoidal frequency of 50 Hz, along with harmonics starting at a minimum frequency of 10 kHz. To refine this output into a clean sinusoidal voltage, a low-pass filter with a cutoff frequency strategically set at 1 kHz, which is high above the fundamental frequency, yet below the harmonics, is introduced. The filter design, featuring an inductance of 2.5 mH and a capacitance of 10 μF, effectively smooths the output while preserving the desired 50 Hz signal.

Figure 4 demonstrates the inverter's output voltage waveforms and frequency spectra at various modulation indices, both before and after the integration of an LC filter. It is evident that the post-filter waveforms more closely resemble a pure sinusoidal shape, indicative of significant attenuation of higher-frequency components. This attenuation becomes more pronounced as the modulation index rises, suggesting that the filter's ability to smooth the waveform improves with increased modulation. Such a trend not only substantiates the efficacy of the LC filter in enhancing the power quality by reducing harmonic distortion, but also highlights the filter's role in maintaining waveform integrity across a range of operational conditions. This behavior underscores the critical impact of the filter in achieving a cleaner AC output, which is particularly beneficial for sensitive electronic devices that require high-quality power inputs.

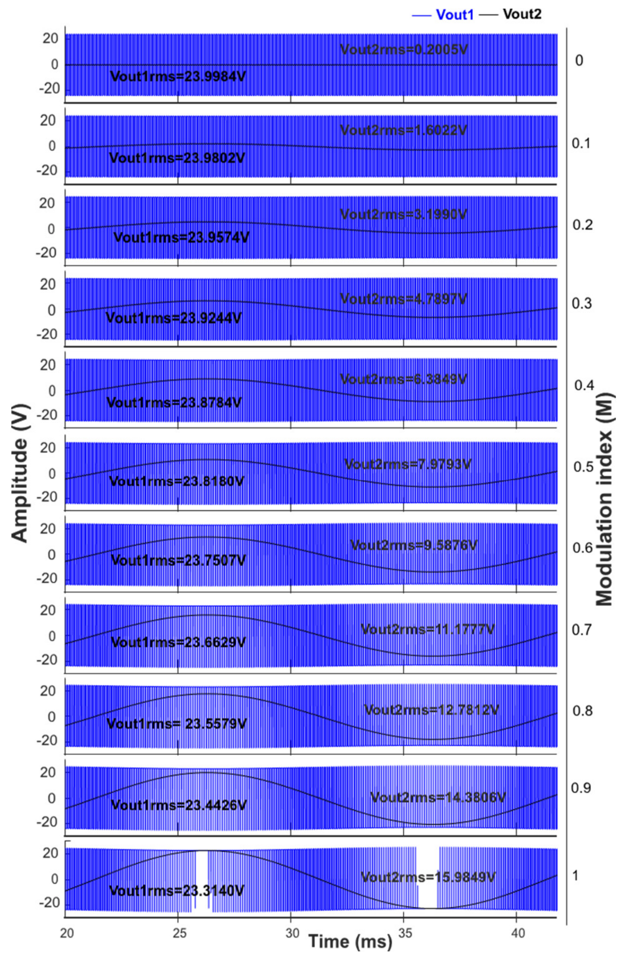

Fig. 4. Bipolar SPWM inverter output Voltage waveforms at various modulation indices before and after LC filter application.

Integrating the observations from Figures 5 and 6, the spectral analysis of the bipolar SPWM inverter output is enhanced by comparing the THD levels for V_{out1} and V_{out2} at different modulation indices. The THD for V_{out1}, which reflects the output before the LC filter application, exhibits a substantial decrease from an exceedingly high 1481.6% at a modulation index of 0.1 to a much lower but still significant 106.02% at a modulation index of 1. This suggests that the inverter's inherent modulation strategy may already contribute to a harmonic reduction as the modulation index increases. When the LC filter is introduced, as displayed by V_{out2}, there is an even more significant reduction in THD. The THD values for V_{out2} start at 12.562% at a modulation index of 0.1 and decrease to a minimal 0.741% at a modulation index of 1, indicating the filter's high effectiveness across the full range of modulation indices. The lower THD values for Vout2 across the board confirm the filter's critical role in improving the output quality by attenuating unwanted harmonics, certifying that the inverter's output is closer to the desired sinusoidal waveform, and that the power quality is suitable for sensitive and high-fidelity applications.

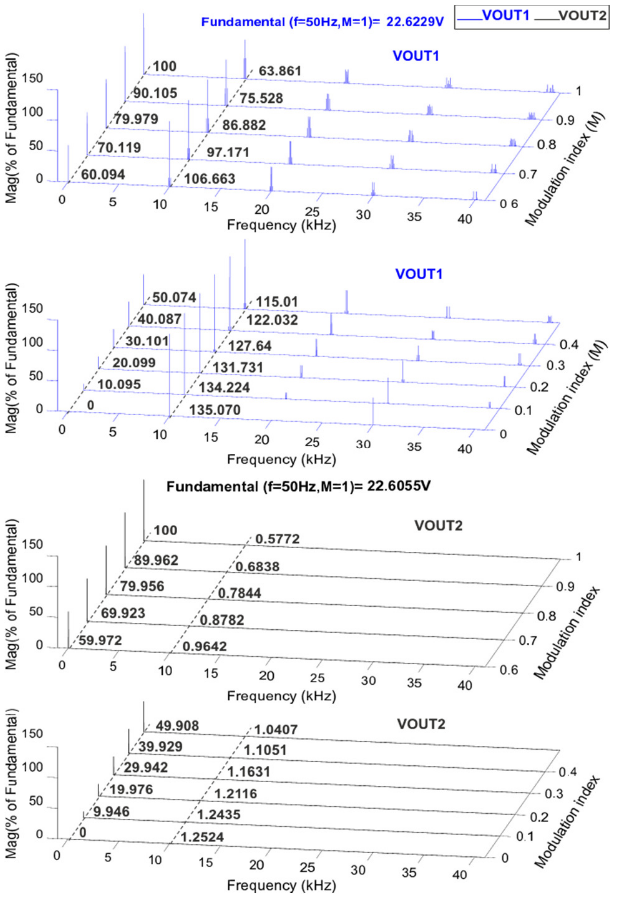

Fig. 5. Bipolar SPWM inverter output harmonics at various modulation indices before and after LC filter application.

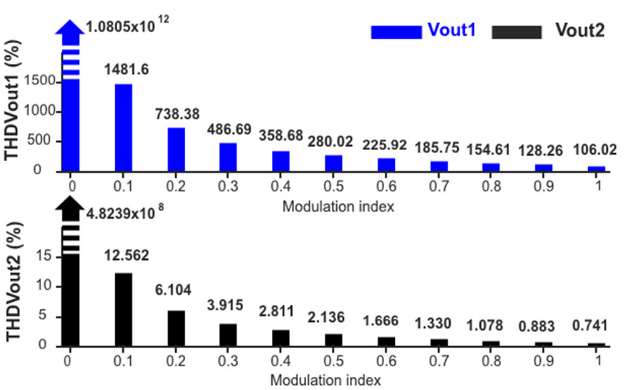

Fig. 6. Bipolar SPWM inverter THD at various modulation indices before and after LC filter application.

Figure 7 illustrates the performance of a unipolar SPWM inverter with and without the application of an LC filter across a range of modulation indices. It manifests that Vout1rms, the RMS voltage before the filter application, linearly increases from 0 V to 18.2839 V as the modulation index progresses from 0 to 1, which aligns with the expected behavior of unipolar SPWM inverters where higher modulation indices yield higher RMS voltages. Upon the application of the LC filter, $V_{out2rms}$ also demonstrates an increase in RMS voltage with the modulation index, but peaks at a slightly lower voltage of 15.9916 V, illustrating the filter's impact in attenuating higher frequency components and resulting in smoother waveforms. The consistency and uniformity in the shape of $V_{out2rms}$ waveforms across different modulation indices reinforce the LC filter's role in sustaining waveform integrity and in mitigating high-frequency noise. Visually, $V_{out2rms}$ waveforms are notably smoother compared to Vout1rms, especially at lower modulation indices, which implies effective harmonic reduction by the filter. This harmonic attenuation is less pronounced as the modulation index reaches its maximum, where the filtered and unfiltered outputs begin to converge, suggesting the filter's varying efficiency across the modulation spectrum.

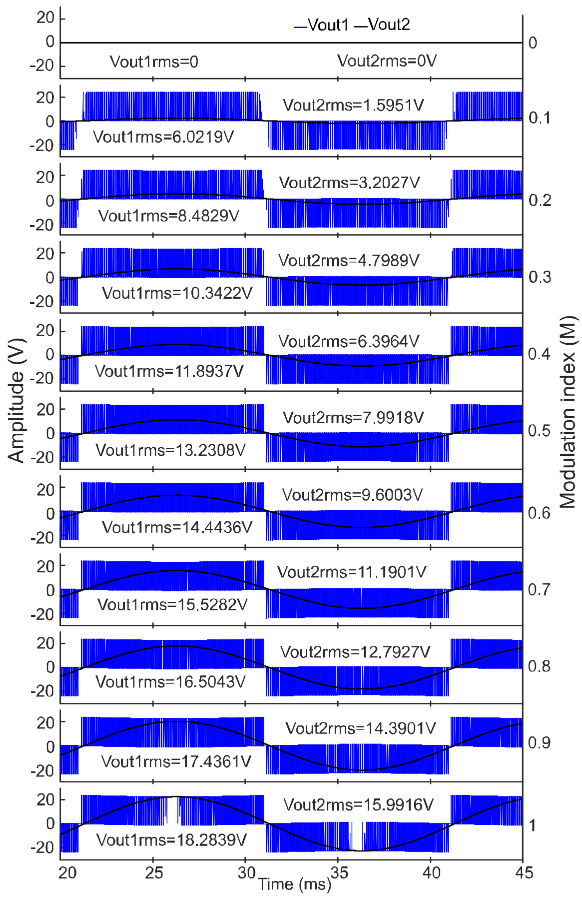

Fig. 7. Unipolar SPWM inverter output Voltage waveforms at various modulation indices before and after LC filter application.

Figure 8 depicts the spectral distribution of the inverter's output voltage (V_{out1}) before the application of the LC filter.

The spectrum is characterized by a significant fundamental frequency component at 50 Hz, with its magnitude maintained constant, and a series of higher-order harmonics, whose magnitudes vary across the modulation indices. Figure 9 complements the previous by providing a detailed view of the THD levels for the inverter output before (V_{out1}) and after (V_{out2}) the introduction of the LC filter. For V_{out1}, the THD starts at extremely high values at lower modulation indices, which is typical for unipolar SPWM inverters without filtering, and decreases as the modulation index increases. However, once the LC filter is applied, the THD values for Vout2 are significantly lower, indicating an effective harmonic suppression. This is illustrated by the sharp decrease in THD, for example, from 359.24% to 1.035% at a modulation index of 0.1, which further drops to 0.142% at a modulation index of 1.These observations underscore the LC filter's critical role in reducing harmonic distortion, thereby enhancing the quality of the power output from the inverter.

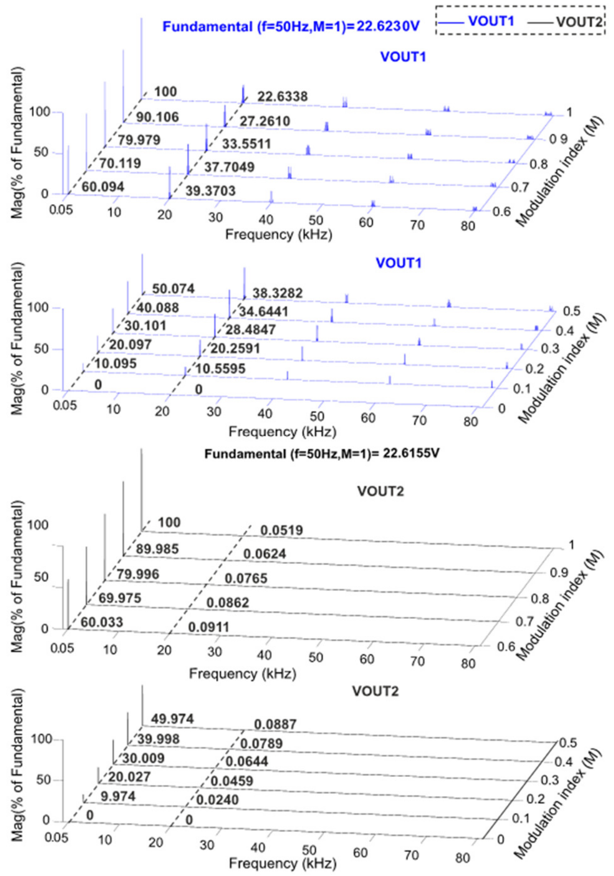

Fig. 8. Unipolar SPWM inverter output harmonics at various modulation indices before and after LC filter application.

Table I and Figures 10 and 11 present a comparison between Bipolar and Unipolar PWM techniques in terms of their impact on a load consisting of a resistance (*R*) and an inductance (*L*).

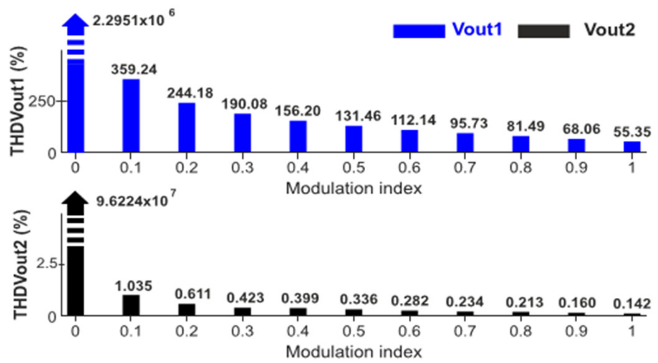

Fig. 9. Unipolar SPWM inverter THD at various modulation indices before and after LC filter application.

- Bipolar PWM: The current THD is 4.28%, which is considered low, whereas the Voltage THD is very high at 84.38%. This high voltage THD implies that the voltage waveform is significantly distorted from a pure sinusoidal wave.
- Unipolar PWM: The current THD is extremely low at 0.05%, indicating a very clean current waveform with minimal harmonic distortion. The Voltage THD is low at 5.23%, which is much better compared to the Bipolar PWM.

TABLE I. BIPOLAR VS. UNIPOLAR PWM: IMPACTS ON THD CURRENT AND VOLTAGE IN *R-L* LOADS

	Bipolar PWM	Unipolar PWM
Load (*R*,*L*)	*R* =10 Ω and *L*= 10 mH	
Current THD	1.384%(Low)	0.373%(Very Low)
Voltage THD	105.51%(Very High)	55.08% (High)

Figures 10 and 11 are exhibiting the current and voltage waveforms of both PWM techniques. In Figure 10, the top waveform represents the current, exhibiting a sinusoidal pattern indicative of a relatively low THD. The bottom waveform depicts the voltage, characterized by a sequence of alternating positive and negative pulses, which is associated with a high THD.

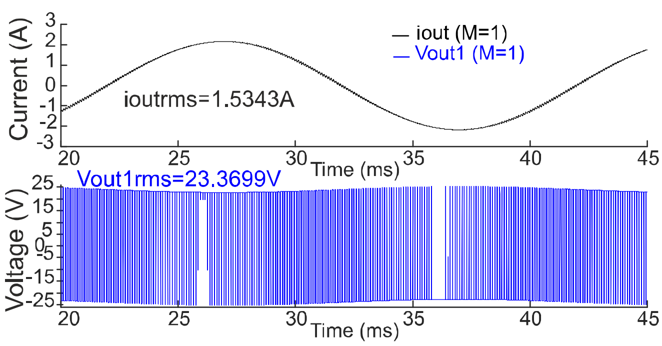

Fig. 10. Bipolar PWM inverter control with an R-L load connection.

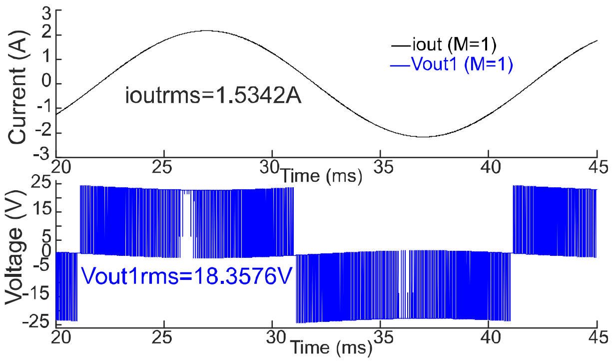

Fig. 11. Unipolar PWM inverter control with an *R-L* load connection.

In Figure 11, the top waveform represents the current, displaying a clean sinusoidal shape that aligns with the very low THD value. The bottom waveform, manifesting the voltage, consists of a series of positive pulses only, accounting for the reduced voltage THD when compared to Bipolar PWM.

The Unipolar PWM is superior in terms of harmonic distortion, resulting in cleaner current and voltage waveforms when juxtaposed to Bipolar PWM. This makes Unipolar PWM a more desirable choice for applications requiring minimal distortion, like in sensitive electronic equipment or precision control systems.

V. CONCLUSION

This study conducts a detailed comparative analysis of bipolar and unipolar SPWM inverters, with a focus on their THD performance at various modulation indices. The current study discovers that bipolar inverters exhibit higher THD at lower indices, indicating significant harmonic distortion, which diminishes as the modulation index increases. In contrast, unipolar inverters demonstrate a more consistent THD reduction across the modulation spectrum. The deployment of an LC filter effectively lowers THD in both configurations, especially in bipolar inverters, significantly reducing their initially high THD. At full modulation, both types of inverters achieve THD levels below 1%, with the unipolar model recording a particularly low THD of 0.142%, versus 0.741% for the bipolar model, underscoring the importance of filtering. The enhanced THD performance of the unipolar inverter, mainly under RL load conditions, underscores its suitability for applications requiring minimal harmonic distortion. Future research should consider the adoption of an LCL filter to potentially achieve even greater THD reduction, possibly offering benefits beyond those of the LC filter. Moreover, applying these PWM techniques to grid-connected inverters could yield valuable insights into their efficacy within more complex power systems.

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