Investigation of DC-AC converter control techniques with enhanced MOSFET gate driver

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ABSTRACT

To promote the use of photovoltaic (PV) systems and reduce costs, it is crucial to develop innovative approaches for grid integration, thereby contributing to global power generation. This article presents the development of an integrated power circuit using the TOSHIBA-TLP350 as a gate driver for the implementation of a single-phase H-bridge inverter, combined with inductor–capacitor–inductor (LCL) filters. This circuit was designed and controlled using a high-frequency pulse width modulation (PWM) signal generated by an ATmega328P microcontroller board, with a predefined program, to facilitate the filtration and reduction of both current and voltage harmonics present at the output of the filters. The study primarily focuses on a grid-connected mode of operation but also demonstrates adaptability to the islanded mode. The proposed application in this article can be adapted to other renewable energy conversion systems. The effectiveness of this achievement is demonstrated through detailed experimental results, highlighting the potential benefits for cost reduction and performance improvement of photovoltaic systems.

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1. INTRODUCTION

Sustainability is at the heart of our time when it comes to excessive consumption of electricity worldwide. Renewable energy sources, such as hydropower, wind, and solar (photovoltaic) [1], are essential for this transition. Solar photovoltaic energy is growing rapidly worldwide, marked by a significant increase in installed capacity compared to previous years [2]. Originally designed to power remote areas, photovoltaic technology has become a crucial solution for energy challenges. These systems convert solar radiation directly into electricity through solar cells [3]. Many studies have focused on photovoltaic energy conversion and the integration of these systems into the power grid, ensuring compliance with current and voltage injection standards at the point of common coupling (PCC), in line with IEEE 519 and IEC regulations [4]-[6].

This work discusses the design and implementation of a DC/AC converter, focusing on improvements to its switching control techniques [7]-[10]. Particular attention was given to the switching control circuit using the TOSHIBA-TLP350, which improves the performance of control methods such as PI and PR control by enhancing switching accuracy, reducing delays, and ensuring better overall system stability and efficiency [11], [12]. Various control techniques for DC/AC converters, including full-wave, shift, and pulse width modulation (PWM) control, are explored, with PWM control being the most prominent [13]. The research aims to introduce a new PWM control strategy using an ATmega328P microcontroller, designed to optimize filtering and reduce current and voltage harmonics at the filter output [14]-[17].

The work is organized as follows: Section 1 provides an overview of DC-AC converters and related research. Section 2 covers the PV system connected to the grid, including the modeling and simulation of key elements like the DC/AC converter, converter switch control, and the TOSHIBA-TLP350 MOSFET gate driver. The many DC/AC converter management techniques, such as PWM, which play an essential role in controlling the switching of the DC/AC converter, allowing for precise control over the output waveform. By modulating the width of the pulses, PWM helps to minimize harmonic distortion and smooth the output current, which enhances the effectiveness of the filtering process. Section 3 presents experimental and simulation results, showcasing MOSFET gate driver enhancements, the H-bridge DC/AC converter, and a detailed analysis of the PWM control strategy. The findings confirm the strategy's effectiveness in harmonic reduction, representing a significant improvement in photovoltaic energy conversion systems.

2. DESCRIPTION OF THE SYSTEM

A typical setup of a solar PV system connected to the electrical grid is shown in Figure 1. This configuration includes an inductor–capacitor–inductor (LCL) filter after a static DC/AC converter transforms the DC power from the solar PV model into AC electricity [18]. Two MOSFET drivers have been designed to make it easier to control the inverter switches with a microcontroller ATmega328P control board.

2.1. DC/AC converter

The single-phase inverter in Figure 2 illustrates the H-bridge configuration with four complementary MOSFET switches (S1, S2, S3, S4) [19], [20], controlled by a TOSHIBA-TLP350 driver and an ATmega328P microcontroller. Through the proper microcontroller ATmega328P coordination, the H-bridge converts the DC from single-phase systems into AC, which is essential for various applications such as renewable energy [21]. Table 1 presents the switch configurations for the H-bridge inverter circuit. Where +VCC is the positive supply voltage and –VCC is the negative supply voltage.

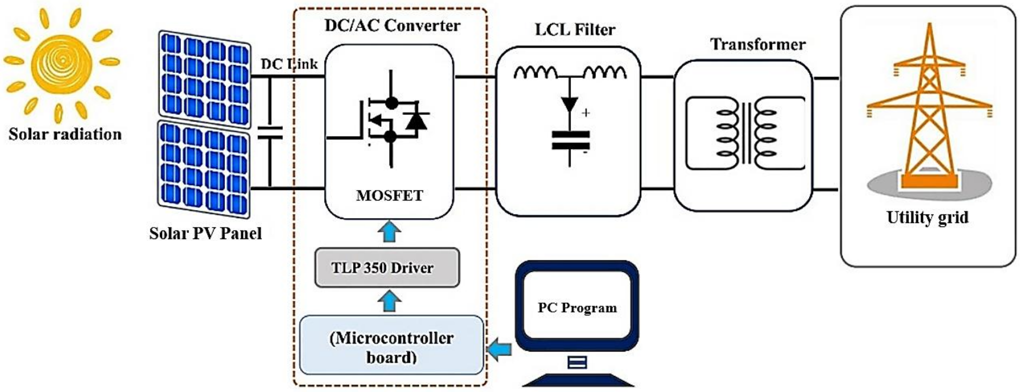


Figure 1. The proposed PV system's grid-connected components

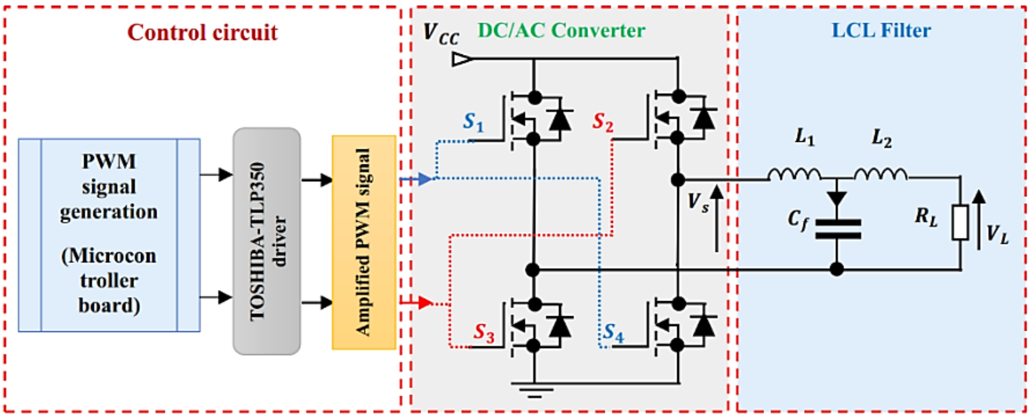


Figure 2. Circuit diagram for the H-bridge inverter with an LCL filter

Table 1. Switch configurations for H-bridge inverter circuit

S.L.	Switch configurations	Voltage Vs at converter output
1	S_1, S_2, S_3, and S_4 are open	$V_S = 0$ V
2	S_1, S_4 are closed and S_2, S_3 are open	$V_S = +VCC$
3	S_2, S_3 are closed and S_1, S_4 are open	$V_S = -VCC$
4	S_1, S_3 are closed and S_2, S_4 are open	Short-circuit load
5	S_2, S_4 are closed and S_1, S_3 are open	Short-circuit load

2.2. Converter switches control strategy

To prevent simultaneous activation of both MOSFETs in the same arm of the converter, complementary signals with a time delay are generated, ensuring one switch is off while the other is on. A PWM control strategy was developed to achieve this [22]. This section details the generation of inverter switch control signals using PWM, which creates square waves with modulated duty cycles tailored to regulate the H-bridge power circuit. The principle involves comparing a triangular carrier wave with a sinusoidal modulating signal, incorporating a 3 µs delay through the "on delay" block in MATLAB/Simulink [23]-[25]. Figure 3 provides a visual representation of this strategy.

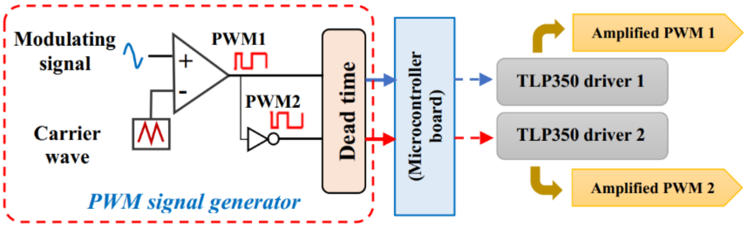


Figure 3. PWM control scheme with elaborate dead time

2.3. Proposed MOSFET gate driver development

To address the challenges in controlling our H-bridge inverter, we made significant improvements to the TOSHIBA-TLP350 integrated circuit to better suit our specific requirements [26]. The modifications to the circuit include the addition of a 0.1 µF ceramic bypass capacitor between VCC and GND, which stabilizes the linear operation of the TOSHIBA-TLP350 and enhances its reliability in our application. Additionally, we adjusted the input signal V_F, generated by the ATmega328P microcontroller, to control the output state. It is crucial that the ground of this signal is connected to the GND pin of the control board, and the ground of the TOSHIBA-TLP350 and the load are referenced to the power supply's ground, as shown in Figure 4.

The current I_F at the LED input is approximately 20 mA, with the TOSHIBA-TLP350 controlled by a 5 V amplitude signal from the ATmega328P, while the LED voltage is 0.8 V. Accordingly, we adjusted the resistance R_{1min} using (1).

$$R_{1min} = \frac{V_F - 0{,}8}{I_F} \quad (1)$$

These upgrades have been crucial to guaranteeing the TLP350's accurate and dependable operation, which has increased our H-bridge inverter's total efficiency. The adaptations made to the TLP350 allowed it to optimally meet our specific MOSFET transistor control needs while minimizing energy losses and ensuring system safety [27].

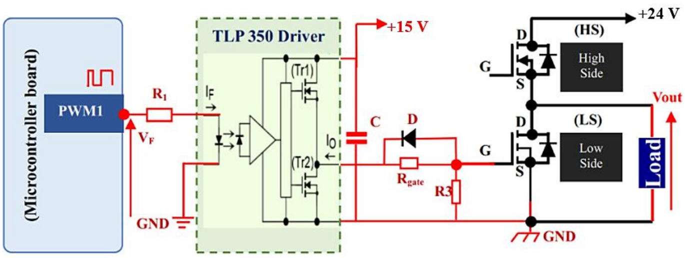


Figure 4. Developed diagram of the MOSFET gate driver circuit

3. RESULTS AND DISCUSSION

3.1. Simulation results

In this section, we present the simulation results of our previously described system, which includes a single-phase H-bridge inverter with an LCL filter. The system is specifically designed for grid-connected operation, and the load in the simulations represents the electrical grid. It is important to note that replacing the load with the grid directly is not feasible without adjustments to the control strategy and system parameters. For our simulations in MATLAB/Simulink, we replaced the photovoltaic (PV) module with a DC voltage source. Figures 5 and 6 highlight the main components of our system.

At the core of this schematic, we find the four MOSFETs of the H-bridge, which form a DC/AC converter. Their role is crucial for energy conversion. Furthermore, both figures mainly focus on the signal generation blocks for a full wave or high-frequency PWM control, designed and modeled in MATLAB/Simulink. It is essential to note that these two schematics in Figures 5 and 6 do not explicitly represent the presence of two gate drivers, one for each arm of the H-bridge. These gate drivers are essential components of our system, playing a key role in amplifying power signals. Their main function is to ensure that the four MOSFETs (two for each arm of the H-bridge) operate in perfect harmony. When one MOSFET in an arm is activated to allow current flow, the other MOSFET in the same arm is deactivated to block current. This precise coordination is vital for generating a stable sinusoidal alternating voltage.

The gate drivers are controlled by a microcontroller ATmega328P board, which serves as the interface between the software (MATLAB/Simulink) and the hardware part of our system. This microcontroller ATmega328p board emits the necessary control signals to activate or deactivate the MOSFETs in synchronization with the PWM signals generated by the software part. By combining these elements, the system ensures the precise operation of the H-bridge inverter and guarantees the production of a stable and regulated sinusoidal electrical output.

This study involved simulating two H-bridge inverter configurations with four MOSFET transistors in MATLAB/Simulink, requiring advanced control structures for optimal switching. We generated two control signals for the simulation: full-wave control and PWM. Full-wave control activates each arm of the inverter for half the time, while PWM offers finer control by adjusting the pulse width. The PWM signal is created by comparing a triangular carrier signal with a sinusoidal reference, as shown in Figure 6.

Figure 7 presents the results of our simulation conducted using MATLAB/Simulink. The PWM1 signal was generated using a sinusoidal-triangular comparison method. To control the other two switches and prevent short circuits, a complementary PWM2 signal with a dead time was introduced. The dead time was precisely set to 3 microseconds (μs) using Simulink's "on delay" block. This configuration and these parameters ensure precise and secure control of the inverter switches, ensuring operation in compliance with technical and safety requirements.

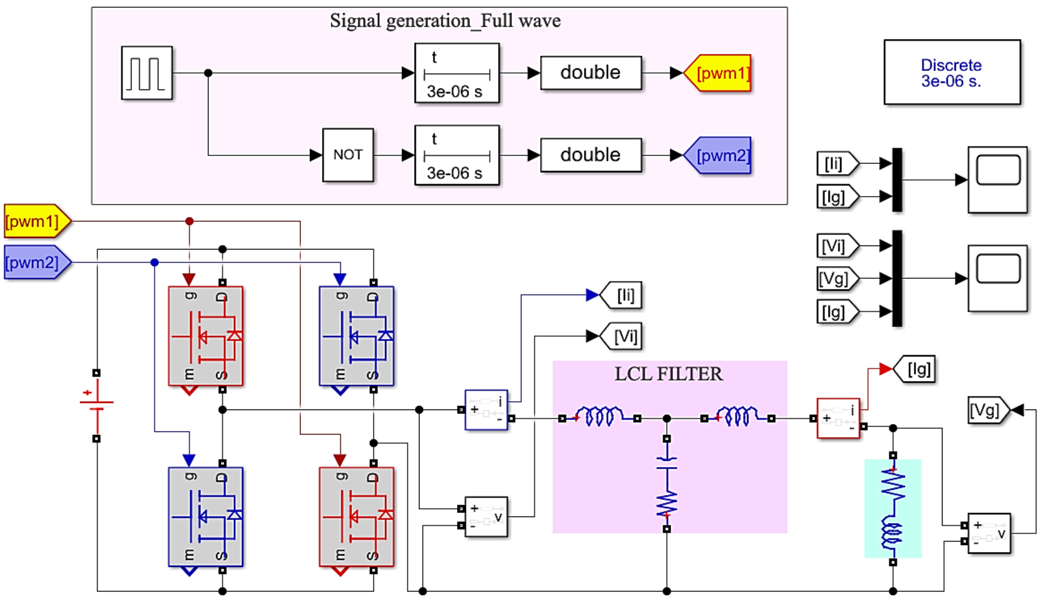


Figure 5. Circuit diagram showing complementary full-wave signals with dead time in MATLAB/Simulink

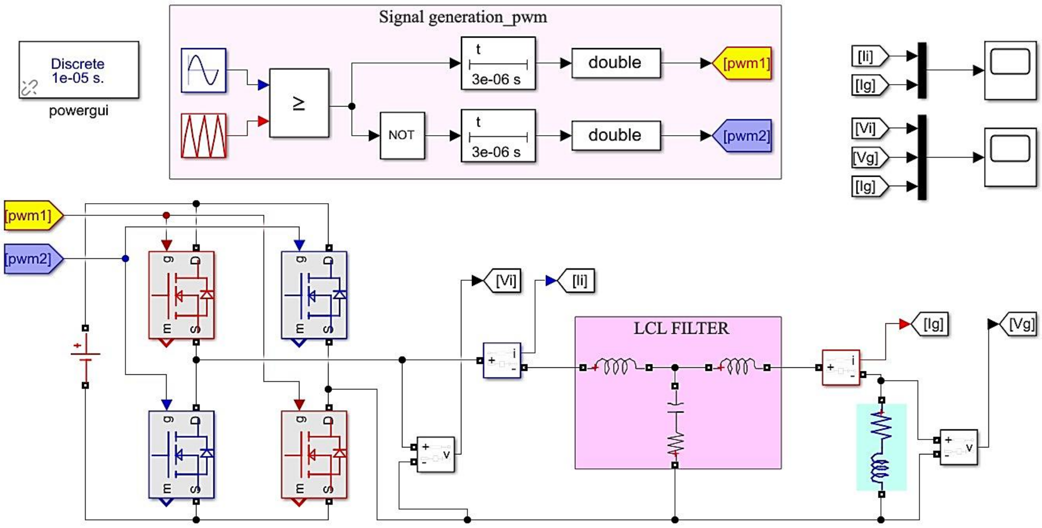


Figure 6. Circuit diagram illustrating complementary PWM signals with dead time in MATLAB/Simulink

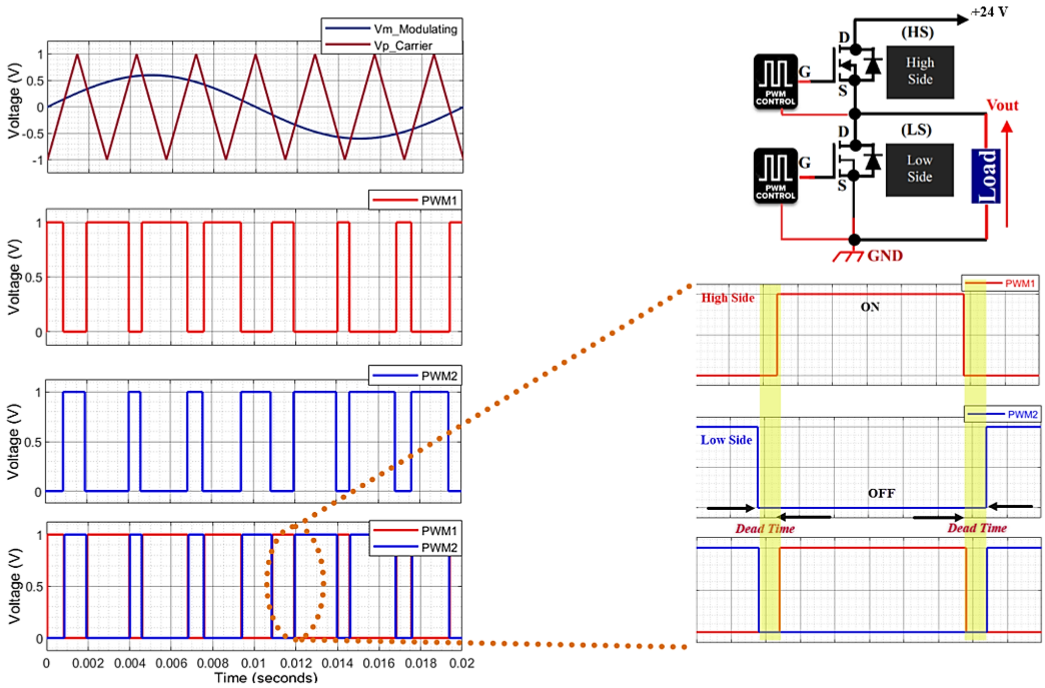
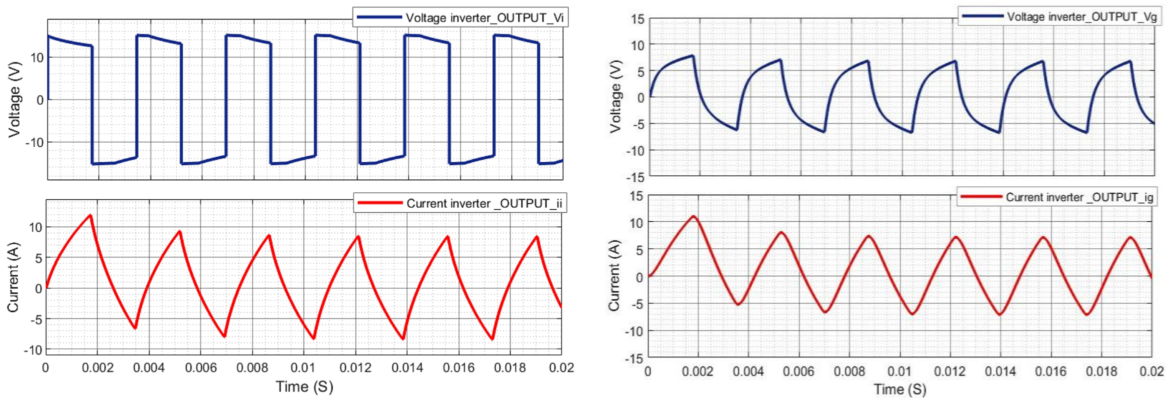


Figure 7. Simulation results in MATLAB/Simulink for complementary signals and dead time

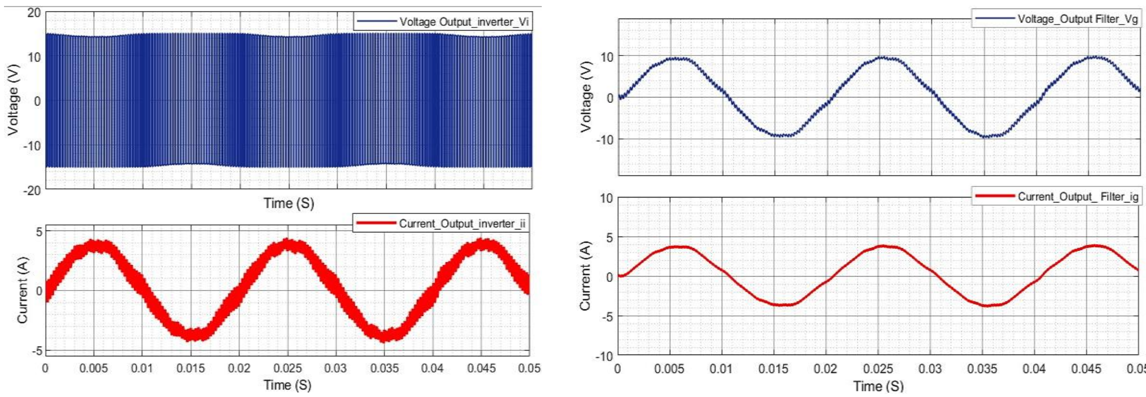
Our work's main objective is to examine the inverter's output waveform in both configurations and evaluate its quality by calculating its total harmonic distortion (THD). The THD must be kept below 5% in accordance with International Electrotechnical Commission (IEC) guidelines [28]. By comparing the results of these two control patterns, we can better understand how the full-wave control differs from the PWM control in terms of the quality of the output of the inverter and its ability to maintain THD within the limits required by international standards. The simulation results for both inverter control strategies are depicted in Figures 8 and 9. Furthermore, Figure 10 provides an overview of the THD in % for each current at the output of the LCL filter.

To assess the THD, a comparative simulation was conducted between two control methods (full-wave control and PWM control). This simulation demonstrated a significant reduction in THD when using PWM control, decreasing from 684.11% to 4.72% compared to full-wave control. This is depicted in Figures 10(a) and 10(b). In essence, the proposed PWM control enables the generation of an electrical signal with substantially reduced distortion, which can be advantageous across various applications.



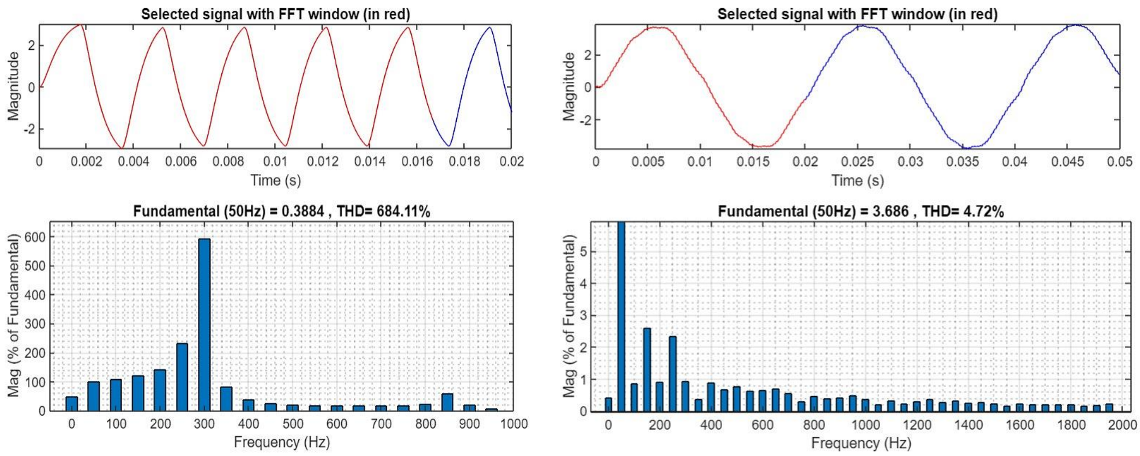
(a) (b)

Figure 8. Simulation results of the full wave inverter: (a) output voltage and current without filter LCL and (b) voltage and current with filter LCL



(a) (b)

Figure 9. Simulation results of the PWM inverter: (a) output voltage and current without filter LCL and (b) voltage and current with filter LCL



(a) (b)

Figure 10. FFT analysis of the filtered voltage: (a) full-wave control inverter output and (b) PWM control inverter output

3.2. Hardware implementation results

3.2.1. Optimizing dead time in experimental PWM control

To prevent real-time short circuits, a dead time delay between full MOSFET switches must be introduced in the experimental setting [29]. Based on the location where the two curves from the previous simulation intersected, a pre-calculated program was created using a microcontroller ATmega328p to address this issue, as shown in Figure 7. As seen graphically in Figure 11, this method enables accurate measurement of PWM1 signal driving and blocking timings. By preventing undesired short circuits and guaranteeing ideal MOSFET switch synchronization, this technique enhances system performance.

3.2.2. Equipment ensemble for experimental validation

A set of essential equipment was utilized for experimental validation, as depicted in Figure 12. This ensemble included a computer for programming the microcontroller ATmega328p and running MATLAB/Simulink. This board played a central role in system coordination. A pivotal aspect of this experiment involved enhancing the TLP350 integrated circuit, a vital component for amplifying the control signals of MOSFET transistors. Furthermore, we engineered a DC/AC converter using four MOSFET transistors to ensure precise electric energy conversion. To maintain system stability, a dedicated power supply was employed, delivering constant voltage and current. Lastly, an oscilloscope monitored real-time signals, providing crucial data for performance assessment and confirming its effectiveness under real-world conditions.

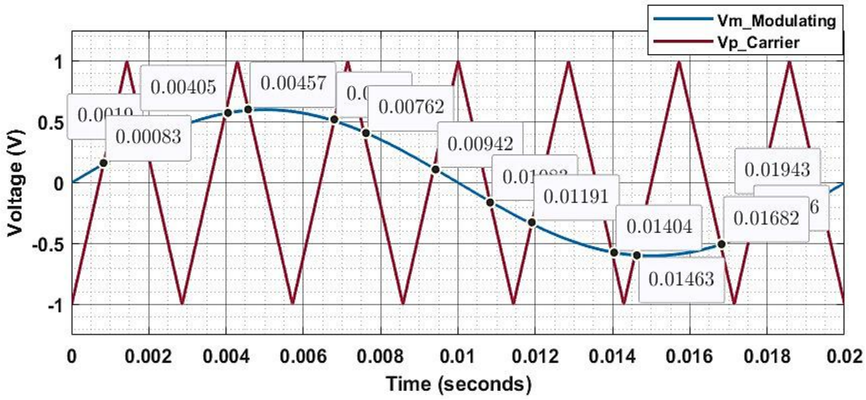


Figure 11. Intersection points of the two signals

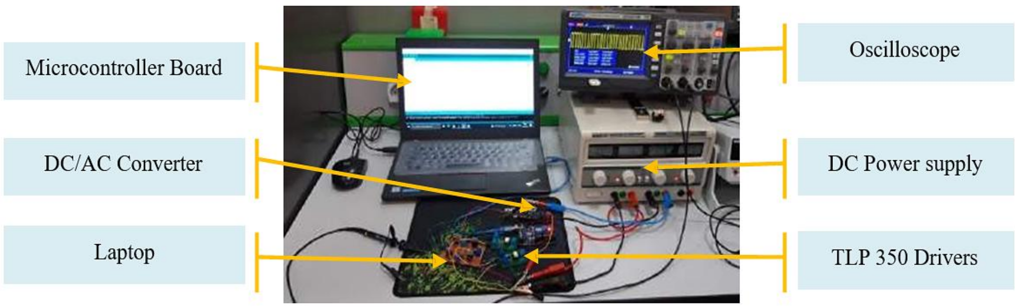


Figure 12. PWM H-bridge inverter control experimental validation

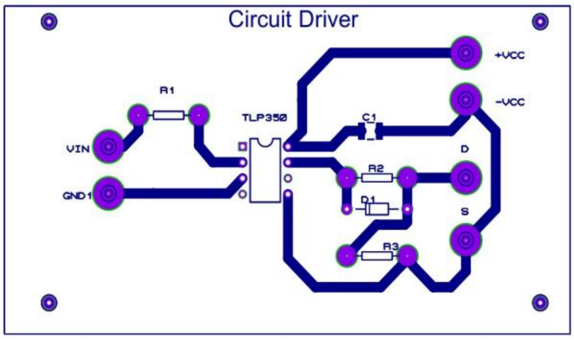
3.2.3. Design of TLP350 driver circuit for H-bridge inverter

The gate driver control circuit for four MOSFETs was carefully designed to enhance the TLP350 integrated circuit. Several significant steps were taken in this complex procedure. Firstly, the circuit diagram was designed with great care to ensure accuracy and appropriateness for the intended application. The printed circuit board (PCB), as illustrated in Figure 13(a), was carefully arranged to optimize performance.

The following steps were involved in assembling the PCB for the gate driver control circuit: i) preparing and inspecting all components, ii) designing and verifying the PCB layout, iii) placing components onto the PCB, iv) soldering components securely, and v) testing the assembled PCB. This thorough procedure, detailed in Figure 13(b), ensured all necessary parts were integrated to achieve precise control over the MOSFET transistors' gates. These actions demonstrate the diligent efforts made to improve the TLP350 integrated circuit.

3.2.4. Design of H-bridge inverter

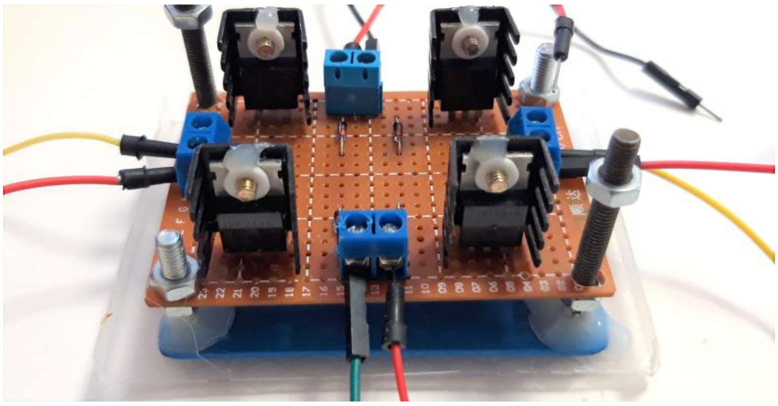
Our experimental single-phase H-bridge inverter is shown in Figure 14 and was built following the diagram in Figure 2. Two PWM signals, our careful design and manufacturing guarantee a precise fit to our specifications. The inverter's essential position in our study is strengthened using this gadget, which enables us to objectively assess its performance.



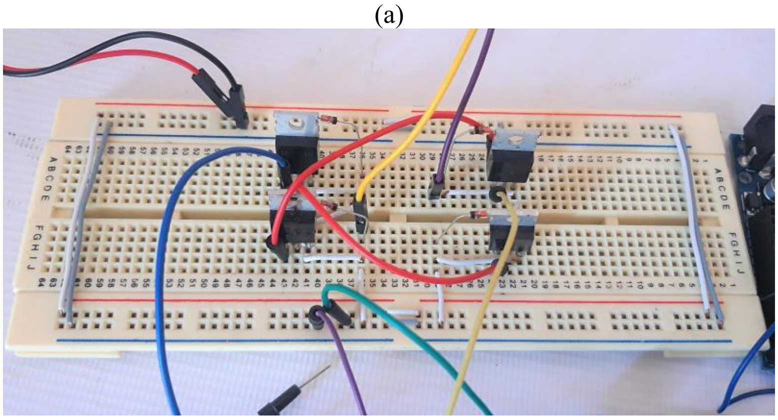
(a)

(b)

Figure 13. Design of MOSFET drivers: (a) PCB face component and (b) real circuit of driver



(a)



(b)

Figure 14. Single-phase H-bridge inverter design: (a) prototype and (b) experimental setup

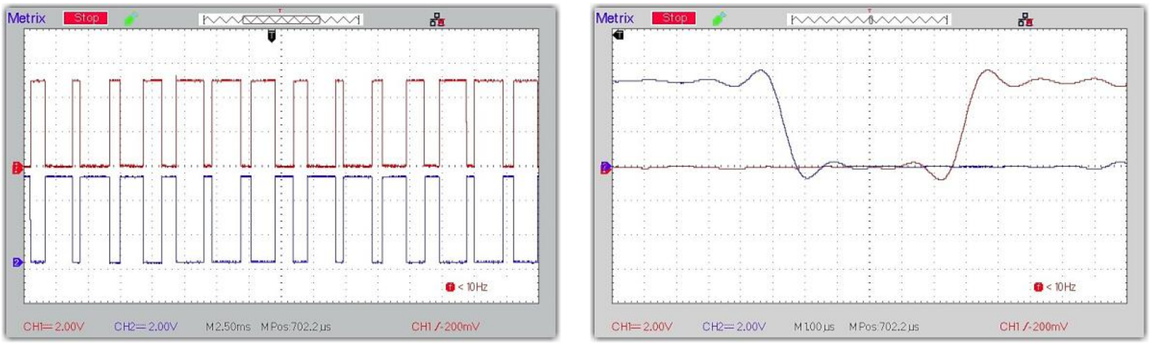
3.2.5. Experimental findings and data analysis

The complementary PWM signals, which are essential to the operation of our inverter, were obtained at the output of the microcontroller ATmega328P and are detailed in Figure 15(a). These signals are precisely generated to control the 4 MOSFET transistors of the H-bridge. One of the most important aspects of this configuration is the presence of a precisely calculated dead time to avoid any potential short circuit between MOSFETs.

Figure 15(b) provides a zoom on a crucial segment of the PWM signals for a more in-depth analysis of this dead time. The precise duration of the dead time is highlighted in this focus, confirming its adequacy to ensure the correct operation of the system safely and minimize the risks of malfunction due to short circuits between the arms of the H-bridge. These signals are essential to ensuring stable and efficient electrical conversion.

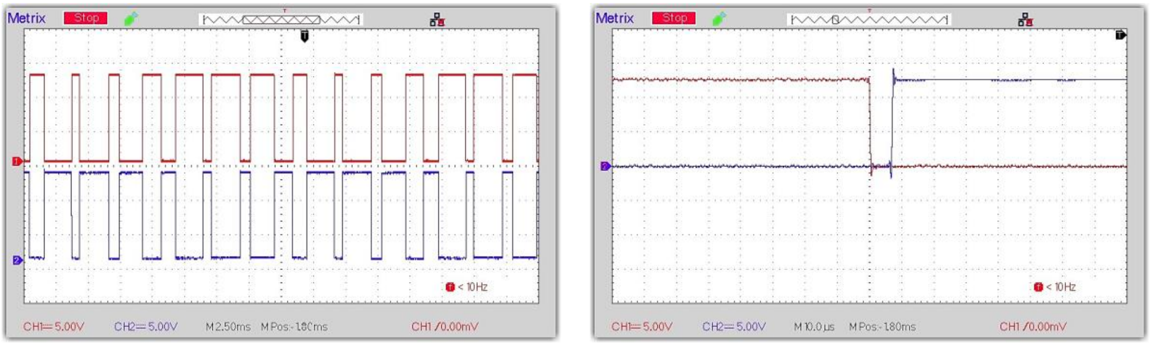
As seen in Figure 16(a), MOSFET drivers produce PWM1 and PWM2 signals with complimentary forms that are similar to those produced by the microcontroller. As seen in Figure 16(b), these signals use optimum amplitudes and a predetermined dead time to regulate the MOSFET gates. The oscilloscope screenshots that are accessible in the earlier pictures serve as an example of the experimental setup of this technology. These outcomes demonstrate the substantial extent of our efforts to enhance the TLP350 drivers and the precision of the collected data.

Figure 17(a) displays a screenshot from the oscilloscope, highlighting the characteristics of the voltage signal obtained experimentally at the output of our inverter designed without the use of the LCL filter. This signal appears as a square wave, demonstrating the proper operation of both arms of our H-bridge, consisting of 4 MOSFET transistors. It maintains the amplitude and frequency of the PWM1 and PWM2 signals generated by the TLP350 drivers developed in the previous circuit. Conversely, Figure 17(b) presents an oscilloscope screenshot taken after applying the LCL filter. This screenshot reveals that the output voltage signal is closer to a sinusoidal waveform at the appropriate frequency, thereby demonstrating the effectiveness of the filtering and underscoring the significance of PWM control over other control methods for improving output quality.



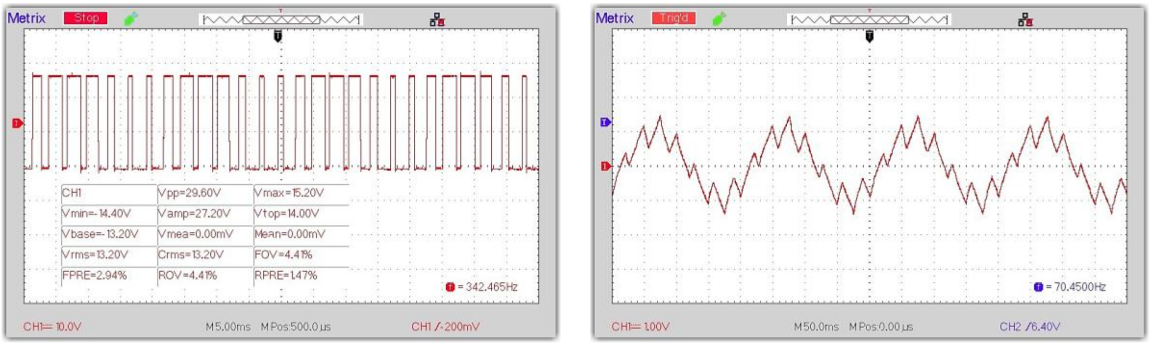
(a) (b)

Figure 15. Signals generated by the ATmega328P microcontroller: (a) complementary PWM signals and (b) captured dead time for safe operation



(a) (b)

Figure 16. Signals generated by the drivers TLP350: (a) complementary PWM signals and (b) captured dead time for safe operation



(a) (b)

Figure 17. Oscilloscope screenshots of the H-bridge inverter output voltage: (a) without LCL filter and (b) after applying the LCL filter

4. CONCLUSION

This article investigates the control techniques with enhanced MOSFET gate driver. Through MATLAB/Simulink simulations and experimental validations, we highlight the advantages of using pulse width modulation (PWM) control over traditional full-wave control methods. A critical aspect of our approach is the precise generation of control signals facilitated by an ATmega328P microcontroller, which efficiently bridges the gap between hardware and the MATLAB/Simulink environment for real-time coordination.

The control of MOSFET transistors is greatly improved by the TOSHIBA-TLP350 drivers, which leads to more effective electrical conversion. Additionally, by lowering voltage harmonics, an LCL filter significantly improves the output voltage's quality. Total harmonic distortion (THD) was significantly reduced from 684.11% to 4.72% in a comparative simulation between full-wave and PWM control, confirming the suggested control method's efficacy in enhancing output signal quality.

These findings contribute to a deeper understanding of inverter control, with promising implications for renewable energy systems. Looking ahead, future research could explore advanced control strategies, such as predictive control or artificial intelligence-based techniques, to optimize inverter performance even further. Additionally, the integration of energy storage systems and grid-tied configurations will improve the reliability and stability of power systems. Overcoming challenges related to scalability and cost-effectiveness in real-world applications will be essential for the widespread adoption of these technologies.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Akaaboune Jalil	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	
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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

The datasets used and/or analyzed during the current study available from the corresponding author, [EB], on reasonable requests.

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