

Design and Implementation of a Photovoltaic-Fed Inverter System with LC Filtering for Sinusoidal AC Output

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Abstract— This work presents the design and implementation of a 300 W photovoltaic power supply system capable of converting the DC voltage generated by a solar panel into a 50 Hz, pure sine-wave AC output. The proposed system consists of a DC-DC buck converter followed by a single-phase inverter to ensure efficient power conversion and output voltage regulation. A central aspect of this study is the investigation of the inverter's control loop, where we propose and compare a classical PI regulator with an adaptive fuzzy-like PI controller. The comparative evaluation, implemented in real-time via a dSPACE DS1104 platform, assesses both controllers in terms of steady-state error, overshoot, and response time, demonstrating the superior adaptability of the fuzzy-like approach under transient conditions. In addition, a monitoring system is integrated to supervise key operating parameters, including input and output voltages as well as power switch temperatures, thereby enhancing system reliability and protection. Due to the broad scope of photovoltaic energy conversion systems, this paper primarily focuses on the design and implementation of the power electronics stage.

Keywords— Solar power, DC-DC converter, DC-AC conversion, dSPACE 1104.

I. INTRODUCTION

Economic and technological progress is accelerating the consumption of fossil fuels, making the transition to renewable energies essential to reducing pollution. Since most electronic devices require alternating current (AC), a major research focus is on converting renewable sources into usable alternating current. DC-AC converters are widely used in applications such as electric vehicles (EVs) [1], [2], motor speed controllers [3], and renewable energy systems [4]. They utilize power electronic components and their operation typically relies on pulse-width modulation (PWM) to control the converters. The growing demand for clean and sustainable energy has driven significant interest in photovoltaic (PV) systems as an alternative to conventional fossil-fuel-based power generation. Solar energy is one of the most abundant renewable energy resources and offers several advantages, including environmental sustainability, low operating costs, widespread availability, and compatibility with energy storage systems, which enable the storage of excess energy for later use and improve overall system reliability[5]. Photovoltaic technology enables the direct conversion of solar radiation

into electrical energy without producing greenhouse gas emissions or noise pollution. However, the output power generated by PV panels is inherently variable, as it depends on solar irradiance, temperature, and weather conditions. To ensure a stable and reliable power supply, PV systems are often combined with power electronic converters and battery energy storage systems. Power converters regulate and condition the generated electrical energy, while batteries store excess energy and provide power during periods of low solar irradiation. Consequently, the integration of photovoltaic generation, energy storage, and advanced power electronics has become a key solution for delivering high-quality electrical power in both standalone and grid-connected applications [6], [7], [8].

DC-DC converters play an increasingly crucial role in electrical engineering. Their presence is essential due to their high efficiency, compact size, light weight, and low cost. They consist of capacitors, inductors, and static switches. They consume little energy and achieve very high efficiency. They have become essential components in power supplies for laptops, mobile phones, household appliances, and renewable

energy sources such as photovoltaic solar panels and wind turbines, even at low power levels [1], [9], [10].

Solar energy, captured by PV panels, offers a viable and sustainable alternative for electricity production. It is a clean, virtually unlimited resource with minimal risk. Its potential to meet global energy needs is considerable. Furthermore, solar energy is widely available worldwide, which enhances its universal appeal. With the decreasing cost of PV modules and the rising price of fossil fuels, investing in solar energy systems has become both economically viable and profitable [6], [11]. Although simulation tools provide a cost-effective and efficient means for analysing and validating power electronic systems, they cannot fully represent the behaviour of real-world implementations. Simulation models are often based on ideal assumptions and may neglect several practical factors, such as component tolerances, switching losses, electromagnetic interference, temperature variations, sensor inaccuracies, and measurement noise [12]. Consequently, the performance predicted through simulation may differ from that observed in experimental operation. For this reason, hardware implementation and real-time testing are essential to verify system performance, evaluate controller robustness, and identify practical challenges that are difficult to capture in a purely simulated environment. The development of a laboratory prototype therefore constitutes a crucial step toward validating the feasibility and reliability of the proposed solar power supply system [13], [14].

This work aims to develop a solar power system capable of generating a sinusoidal output signal, an essential requirement for most electrical equipment. The study will examine the technical implementation of this system as well as the advantages of solar energy and its potential environmental benefits.

The study and implementation of solar power systems is an important topic in the field of renewable energy. Solar energy is gaining popularity due to its environmental benefits and cost-effectiveness, but one of the main challenges is

converting the direct current (DC) produced by solar panels into alternating current (AC) usable in homes and businesses. The primary focus of this research is directed toward the design, implementation, and experimental validation of the power conversion system, specifically the buck converter and inverter stages, rather than the optimization of photovoltaic energy extraction or the detailed evaluation of power quality metrics. Consequently, maximum power point tracking (MPPT) functionalities and comprehensive harmonic analyses have been deliberately excluded from the present scope to maintain a clear and concentrated investigation of the control and power stage performance. However, it is worth acknowledging that both MPPT and harmonic mitigation are critical for maximizing the efficiency and output quality of photovoltaic systems. As such, they constitute natural and highly relevant extensions of this work, offering clear pathways for future research and development to further enhance the system's overall performance and grid compatibility.

The remainder of this paper is organized as follows. Section II describes the proposed solar power supply system. Section III presents the modelling and simulation of the photovoltaic generator. Sections IV and V detail the output voltage control of the Buck converter and the control strategy of the single-phase inverter, respectively. Sections VI and VII present and discuss the simulation and experimental results. Finally, Section VIII concludes the paper and outlines directions for future work.

II. DESCRIPTIONS SOLAR POWER SUPPLY

Figure 1 shows the block diagram of the proposed solar power supply system, which comprises a photovoltaic (PV) generator, a DC-DC Buck converter, a single-phase DC-AC inverter, LC Filter and a 12 V/220 V transformer. Both the Buck converter and the inverter are controlled using PI-based control strategies to ensure proper voltage regulation and sinusoidal output generation.

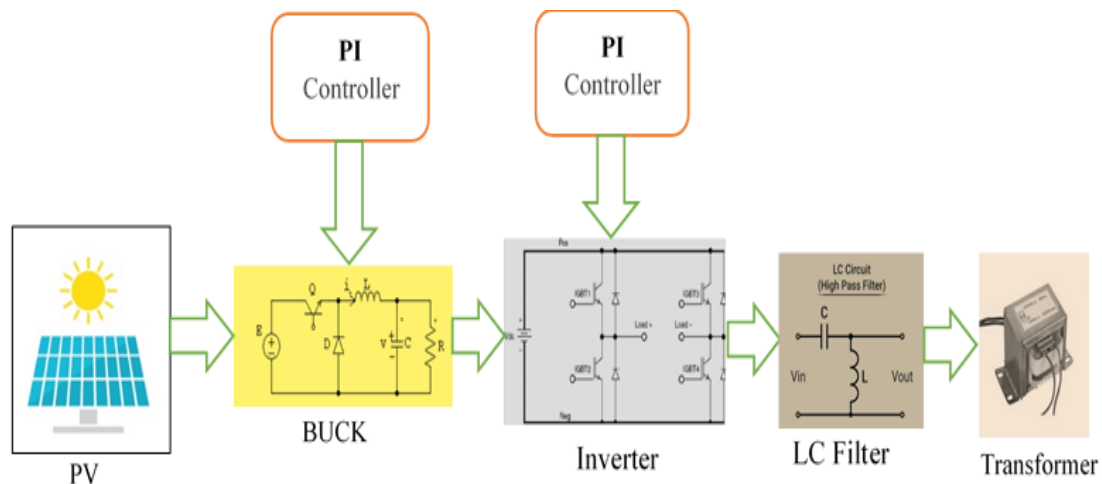


Fig. 1. Block Diagram of the Proposed System.

III. PHOTOVOLTAIC GENERATOR SIMULATION

Figure 2 shows the representation block of the photovoltaic generator (PVG), which can be used with different power supply circuits in Simulink. The PVG's inputs are irradiance

(G_n) and temperature (T_n), while its outputs are voltage and current [4], [15].

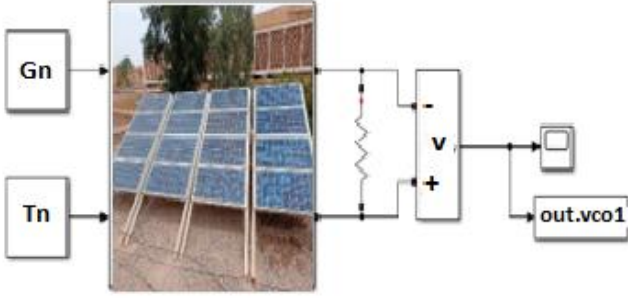


Fig. 2. PV Generator Module Simulation

TABLE I. CHARACTERISTICS OF THE PWX500 PV PANEL

Parameter	Value
$P_{max} (W)$	50
$I_{nom} (A)$	2.78
$V_{nom} (V)$	17.10
$I_{cc} (A)$	3.11
$V_{co} (V)$	21.9
$R_{series} (\Omega)$	0.55
Efficiency [%]	10.19

Figure 3 presents the power–voltage (P-V) characteristics of the photovoltaic panel for various temperatures while maintaining a constant irradiance level. Temperature is a key factor affecting photovoltaic system performance, since the electrical behaviour of semiconductor devices is strongly dependent on thermal conditions. As the cell temperature varies, the output voltage and maximum power point shift accordingly, influencing the energy conversion efficiency of the PV panel.

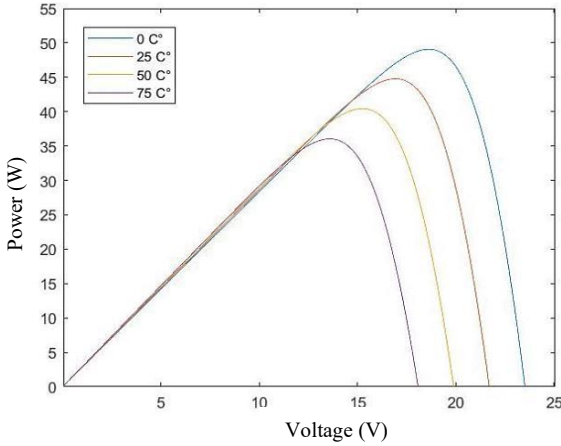


Fig. 3. The Temperature impact on the P(V) characteristic.

Figure 4 shows the power-voltage (P-V) characteristic of a solar photovoltaic panel as a function of light intensity, at constant temperature and constant ambient airflow velocity.

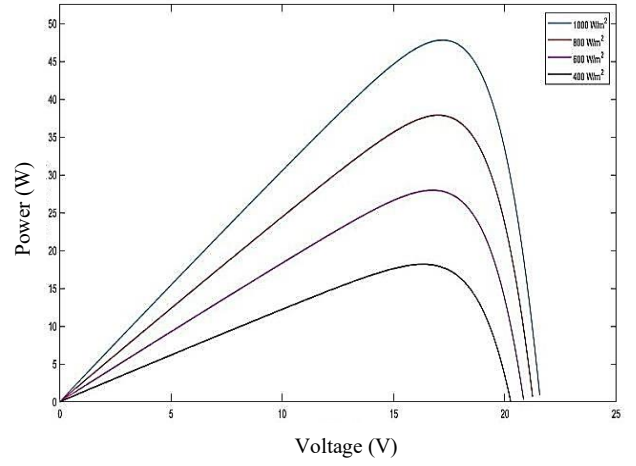


Fig. 4. Effect of Solar Irradiance on the Power-Voltage (P-V) Characteristic of the Photovoltaic Panel.

IV. CONTROL OF THE BUCK CONVERTER'S OUTPUT VOLTAGE

Although modern control techniques have evolved, the PI controller remains the most widely used in industrial applications due to its simple structure and reliability. The primary objective in designing a PI controller is to determine its parameters to ensure optimal operation under all circumstances. However, with fixed parameters, it is very difficult to cover a wide range of operating conditions [8], [16].

The mathematical model of the PI controller is given by equations (1)-(3), following the standard formulation reported in [8], [16]:

$$u(t) = k_p \left[e(t) + \frac{1}{\tau_i} \int_0^t e(t) dt \right] \quad (1)$$

$$u(t) = k_p \cdot e(t) + k_i \int_0^t e(t) dt \quad (2)$$

$$\begin{cases} k_i = k_p / \tau_i \\ e(t) = w_r^*(t) - w(t) \end{cases} \quad (3)$$

Where $e(t)$ is the error of the system controller, k_p is the proportional gain, and τ_i is the integral time constant.

The tuning problem consists of determining the values of these two parameters (k_p et τ_i) to satisfy the control specifications, such as tracking performance and robustness to model uncertainties. The PI controller parameters (k_p et τ_i) can be obtained using classical methods. Numerous PI tuning methods have been described in the literature, such as the pole placement technique.

The representative diagram of the DC-DC converter regulation loop with unity feedback using a PI controller is shown in figure 5 [8].

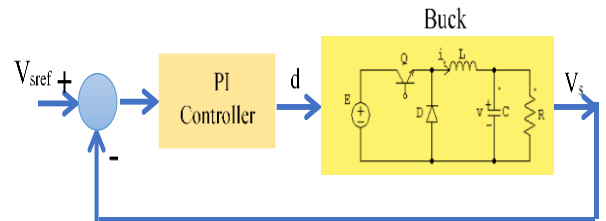


Fig. 5. Direct Duty Cycle Control Diagram.

The variable to be regulated (usually the output voltage) is compared to a reference value. The error signal is then processed and compared to a sawtooth waveform to generate the control signal. Figure 6 Shows the experimental Buck converter prototype used in the laboratory.

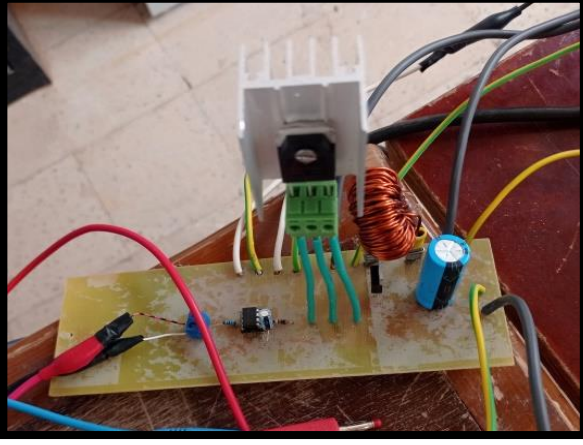


Fig. 6. The experimental Buck converter.

V. SINGLE PHASE INVERTER CONTROL

Inverter control consists of regulating the switching instants of the power semiconductor devices to generate an AC output voltage that accurately follows a desired reference waveform. The objectives of the control strategy are to ensure high-quality output voltage generation, reduce harmonic distortion, and achieve effective utilization of the DC-link voltage [17]. The selection of an inverter control technique depends primarily on the required output voltage characteristics, the desired dynamic performance, and the switching frequency limitations of the power semiconductor devices. Among the most widely used control methods are Pulse Width Modulation (PWM) and hysteresis control [17].

For the proposed system, a PI (Proportional-Integral) controller, illustrated in Figure 7, is employed to regulate the inverter output voltage. The controller consists of a proportional gain, (K_p), and an integral gain, (K_i). The proportional action improves the dynamic response and reduces the tracking error, while the integral action eliminates steady-state error and enhances output voltage accuracy. Although increasing (K_p) can improve the response speed, excessively large values may lead to oscillations and reduced system stability. The PI controller offers a simple and effective solution for linear systems, providing satisfactory voltage regulation and tracking performance. More advanced control structures, such as the PID (Proportional-Integral-Derivative) controller, can be obtained by incorporating an additional derivative term proportional to the rate of change of the error signal [8], [16].

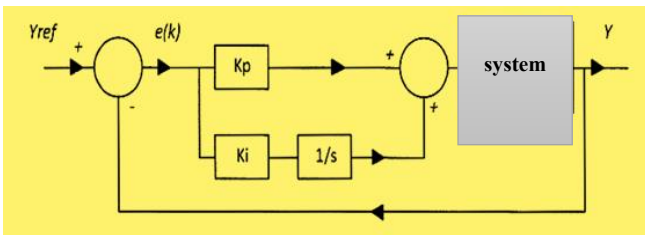


Fig. 7. Structure of a PI Regulator

VI. FUZZY-LIKE PI CONTROLLER FOR INVERTER OUTPUT REGULATION

While classical PI controllers offer simplicity and reliable performance for linear systems, their fixed gains limit adaptability under varying operating conditions, such as load changes, input voltage fluctuations, and parameter variations inherent in photovoltaic systems. To address these limitations, this study proposes a fuzzy-like PI controller that dynamically adjusts the proportional and integral gains based on the system's state [18], [19]. The fuzzy-like PI controller retains the fundamental structure of a conventional PI regulator but introduces adaptive gain scheduling through a fuzzy inference mechanism. This approach combines the simplicity of PI control with the flexibility of fuzzy logic, enabling improved transient response, reduced overshoot, and enhanced disturbance rejection without requiring complex mathematical models of the system [20].

VII. STRUCTURE OF THE FUZZY-LIKE PI CONTROLLER

The proposed fuzzy-like PI controller, illustrated in Figure 8, consists of two main components: a conventional PI regulator and a fuzzy gain scheduler. The controller inputs are the error signal $e(t)$ and its derivative $\dot{e}(t)$, defined as:

$$\begin{aligned} e(t) &= V_{ref} - V_{out} \\ \dot{e}(t) &= \dot{V}_{ref} - \dot{V}_{out} \end{aligned} \quad (4)$$

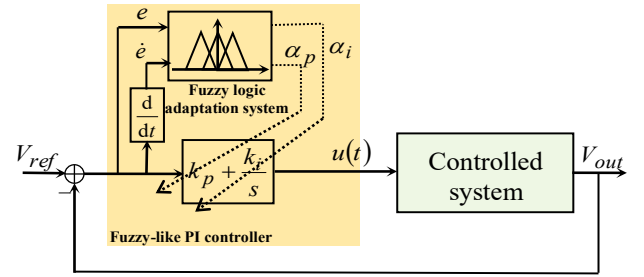


Fig. 8. Structure of the fuzzy-like PI controller for voltage control loop of the single-phase inverter

The fuzzy inference system examines these inputs to generate scaling factors α_p and α_i , which dynamically adjust the proportional and integral gains according to:

$$k_p^{fuzzy} = \alpha_p \cdot k_p^{nom} \quad (5)$$

$$k_i^{fuzzy} = \alpha_i \cdot k_i^{nom} \quad (6)$$

where k_p^{nom} and k_i^{nom} are the nominal gains obtained through classical tuning methods [16].

The control law for the fuzzy-like PI controller is then expressed as:

$$u(t) = k_i^{fuzzy} \cdot e + k_p^{fuzzy} \int e \cdot dt \quad (7)$$

The fuzzy inference system employs a Mamdani-type architecture using the error and its time derivative $\dot{e}(t)$ as inputs and tuning factors, α_p and α_i , as output variables. Each input has a normalised universe of discourse in the range [-1, 1], with five linguistic membership functions: Negative Big (NB), Negative Small (NS), Zero (ZE), Positive Small (PS), and Positive Big (PB). However, the tuning factors of the integral and the proportional gains

are designed with universe of discourse of $[0.5, 1.8]$ and three membership functions: Small (S), Medium (M), Big (B).

The membership functions of the two inputs, $e(t)$ and $\dot{e}(t)$, are depicted in Figure 9, whereas the output membership functions of tuning factors, α_p and α_i , are depicted in Figure 10. Finally, the rule base inference system, which groups the rules governing the online tuning of both parameters, α_p and α_i , is shown in Table 1 and Table 2, respectively. The rule base is designed to achieve fast response with minimal overshoot while maintaining steady-state accuracy.

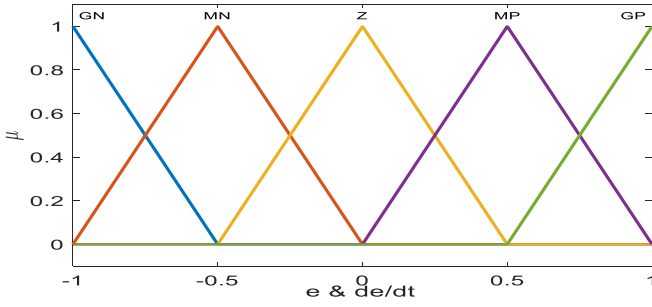


Fig. 9. Membership function of the inputs e and $\dot{e}$

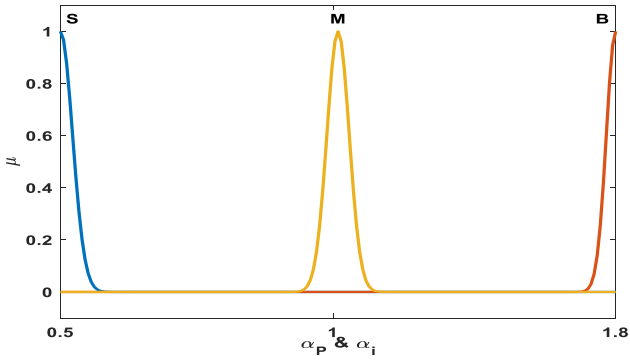


Fig. 10. Membership function of the output α_p and α_i

The fuzzy-like PI controller is implemented in the voltage control loop of the single-phase inverter. The controller receives the error between the reference sinusoidal voltage and the measured output voltage after the LC filter. The fuzzy gain scheduler dynamically adjusts the PI-controller parameters based on the error and its derivative, ensuring optimal performance across different operating conditions.

The integration of the fuzzy-like PI controller with the SPWM generation block enables real-time adjustment of the modulation index, resulting in improved output voltage quality and reduced harmonic distortion. The LC filter attenuates high-frequency switching harmonics, and the

adaptive PI controller compensates for filter parameter variations and load changes

TABLE II. FUZZY RULES OF THE SCALING OUTPUT α_p

		e				
		BN	MN	Z	MP	BP
$\dot{e}$	BN	B	B	M	M	S
	MN	B	B	S	M	S
	Z	M	M	S	M	M
	MP	M	M	S	M	M
	BP	S	S	M	B	B

TABLE III. FUZZY RULES OF THE SCALING OUTPUT α_i

		e				
		BN	MN	Z	MP	BP
$\dot{e}$	BN	S	S	M	M	B
	MN	S	S	B	M	B
	Z	M	M	B	M	M
	MP	M	M	B	M	M
	BP	B	B	M	S	S

The inference mechanism uses the min-max composition method, and defuzzification is performed using the center of gravity (CoG) method to obtain crisp values for α_p and α_i .

VIII. SIMULATION RESULTS

The simulation results of the complete photovoltaic power supply system, incorporating PI-controlled voltage regulation for both the Buck converter and the inverter, are presented in Figure 11 under standard operating conditions of solar irradiance $E = 1000 \text{ W/m}^2$ and temperature $T = 25^\circ\text{C}$. The figure illustrates the Simulink model developed for the proposed system. To evaluate the dynamic performance and robustness of the control strategy, a load variation was introduced between 10.5 s and 12.5 s. The obtained results demonstrate the ability of the system to maintain stable operation and satisfactory voltage regulation despite changes in load conditions.

Figures 12-16 present the photovoltaic generator voltage, the output voltage of the Buck converter, and the voltage and current waveforms at the inverter and transformer outputs. The results show that the Buck converter effectively regulates the DC voltage to the desired level, providing a lower output voltage than that supplied by the photovoltaic source. In addition, the inverter successfully generates a sinusoidal AC waveform, while the transformer delivers the required output voltage. The results also demonstrate stable system operation and satisfactory performance under the considered operating conditions.

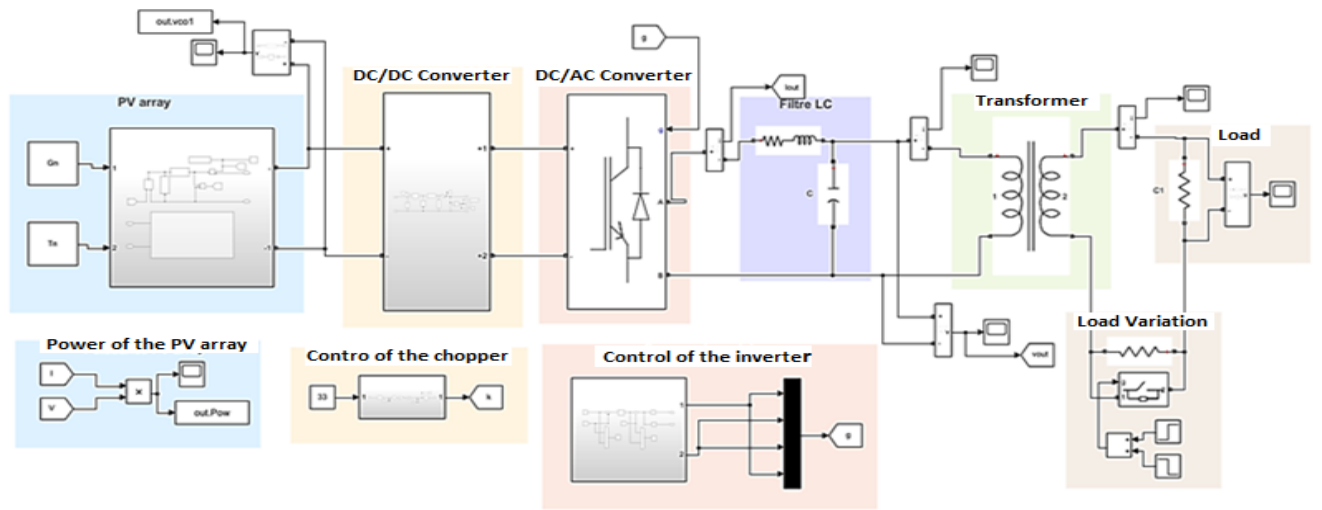


Fig. 11. Simulink Model of the Proposed System under Load Variation.

To further validate the advantages of the proposed control strategy, comparative simulations were conducted under identical operating conditions. Figure 17 presents the inverter output voltage waveforms obtained with the classical PI and fuzzy-like PI controllers, under steady-state conditions. While both controllers successfully generate a sinusoidal output voltage, the fuzzy-like PI controller exhibits slightly better tracking of the reference waveform with a minimal error (see Figure 17). The results demonstrate that the fuzzy-like PI controller provides superior dynamic performance, reduced

harmonic distortion, and better voltage regulation compared to the classical PI controller. The adaptive gain scheduling effectively handles non-linearities and parameter variations, making it particularly suitable for photovoltaic applications where operating conditions are subject to continuous change. These simulation results, however, remain to be validated experimentally in future work, as the current experimental implementation focuses on the classical PI controller to demonstrate the fundamental feasibility of the proposed photovoltaic power supply system.

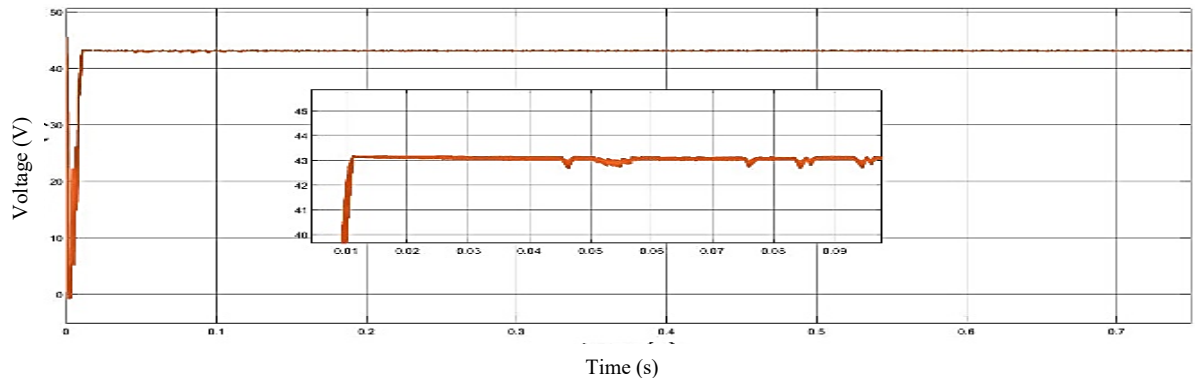


Fig. 12. Voltage of the PV.

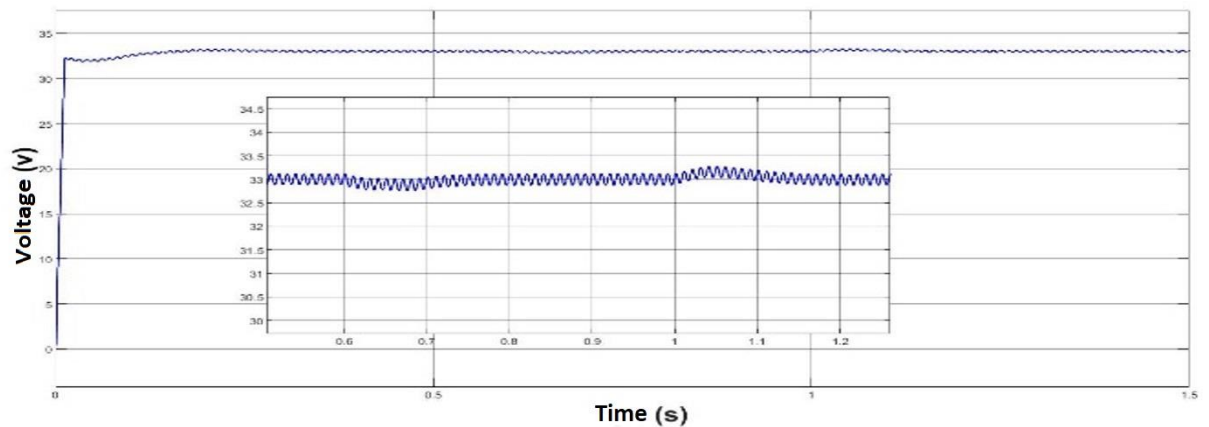


Fig. 13. Output Voltage of the Buck converter

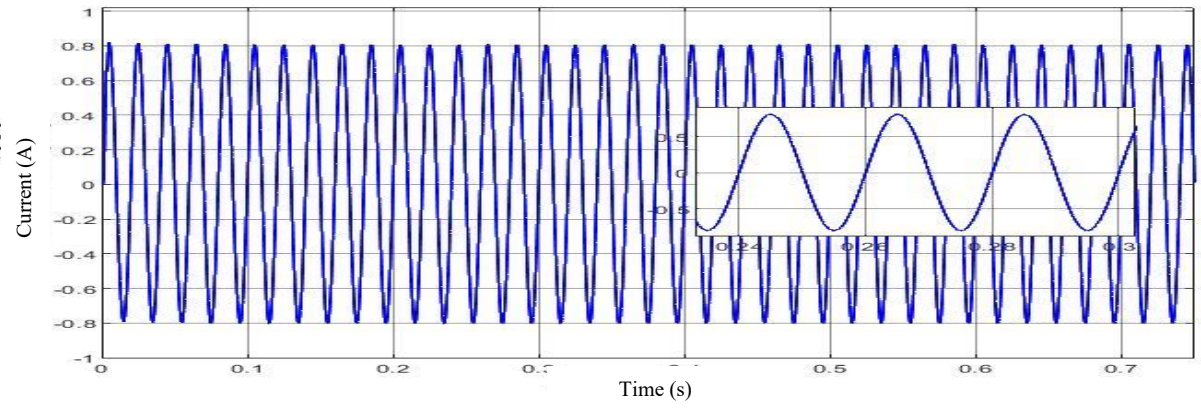


Fig. 14. Output current of the Inverter after Filtering

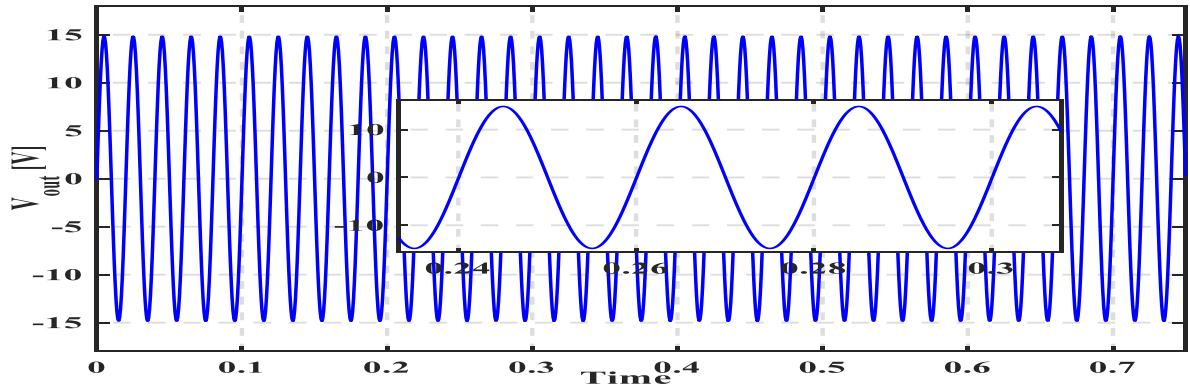


Fig. 15. Output Voltage of the Inverter after Filtering.

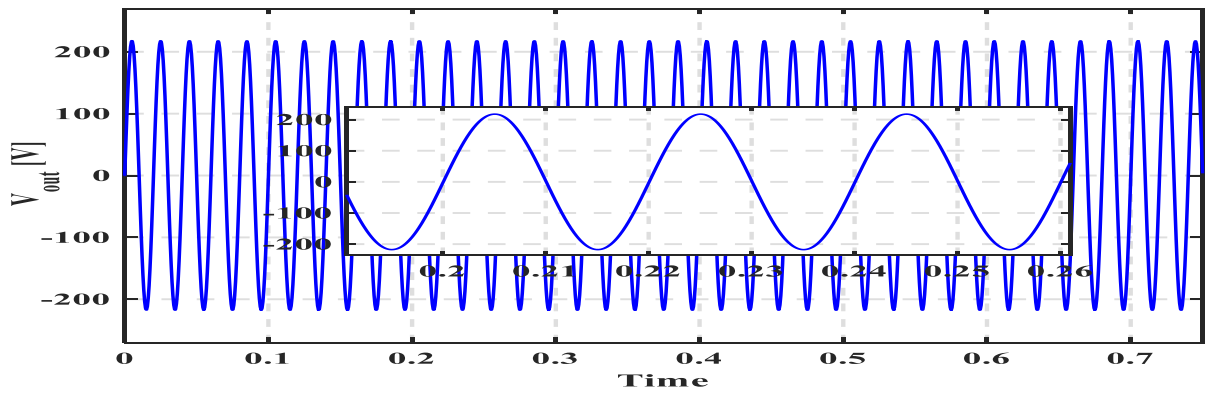


Fig. 16. Output voltage of the transformer

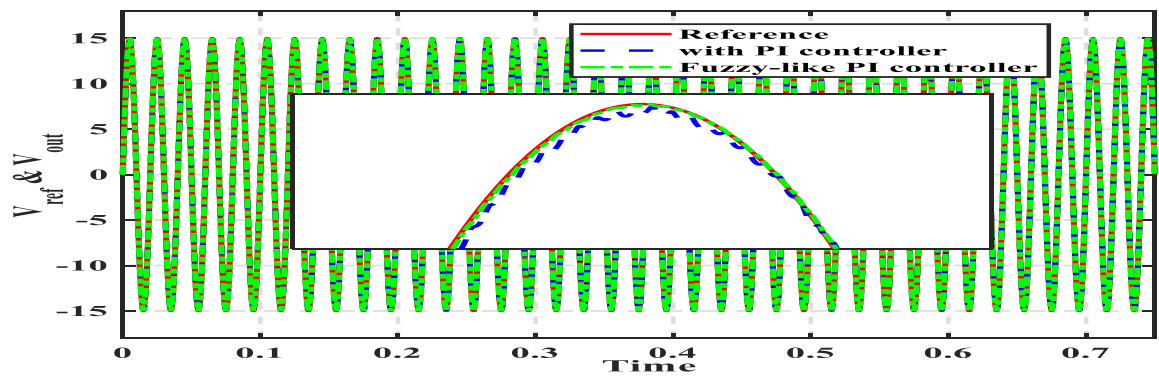


Fig. 17. Comparative results between PI controller and fuzzy-like PI controller

IX. EXPERIMENTAL RESULTS

In this section, the proposed system is implemented using a dSPACE DS1104 real-time control board. This high-performance PCI-based platform interfaces directly with a host PC and incorporates dual processors, a comprehensive set of analog and digital input/output channels, and incremental encoder interfaces, making it particularly suitable for real-time control applications.

The experimental setup, shown in Figure 18, utilizes ControlDesk software as the main interface for the dSPACE DS1104 real-time control board presented in Figure 19. The software enables real-time system monitoring, parameter adjustment, data acquisition, and control, thereby facilitating the implementation and evaluation of the proposed system.

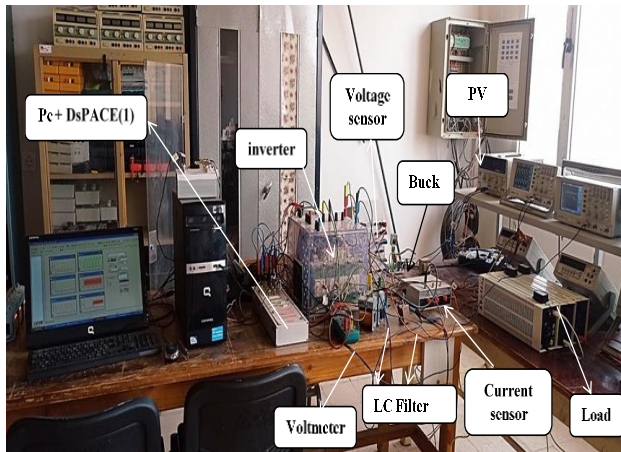


Fig. 18. The experimental test bench

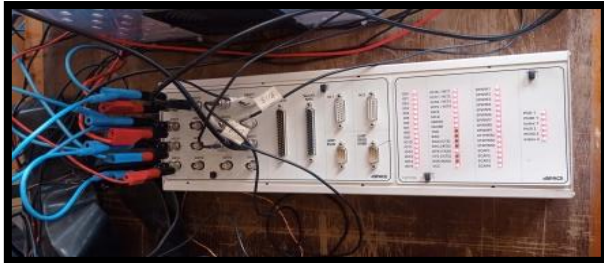


Fig. 19. Dspace 1104 control board.

The experimental results presented in Figures 20-23 illustrate the performance of the proposed system under real operating conditions. Figure 20 shows the inverter input voltage, which is regulated at approximately 33 V by the Buck converter. Figure 21 presents the inverter output current, with a measured value of approximately 0.9 A. The inverter output voltage waveform is depicted in Figure 22, demonstrating the successful generation of an AC voltage. Then, Figure 23 shows the transformer output voltage under load variations, confirming the ability of the system to maintain a stable output voltage despite changes in load conditions.

These results validate the effectiveness of the proposed power conversion system and its control strategy. Finally, the spectrum of the output voltage waveform is shown in Figure 24. To draw this spectrum, experimental data were captured in real-time via the dSPACE DS1104 controller board using ControlDesk software. The acquired signals were stored and later imported into MATLAB/Simulink. The Powergui (FFT Analysis) tool was then used to compute the THD and

visualize the frequency spectrum of the output voltage, enabling a direct comparison with simulation results. It is clear that the THD of the output voltage is very low, 2.39%, which confirm the effectiveness and the usefulness of proposed AC power supply based on PV and the associated single-phase inverter with LC filter.

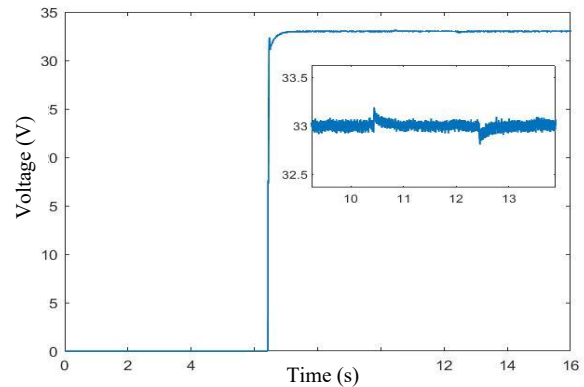


Fig. 20. Input voltage of the Inverter under Load Variations.

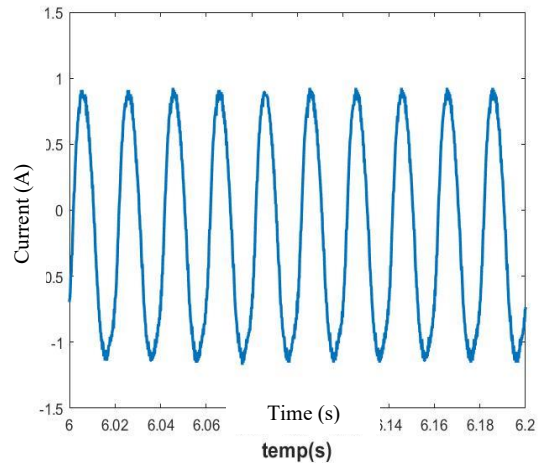


Fig. 21. Output Current of the Inverter under Load Variations.

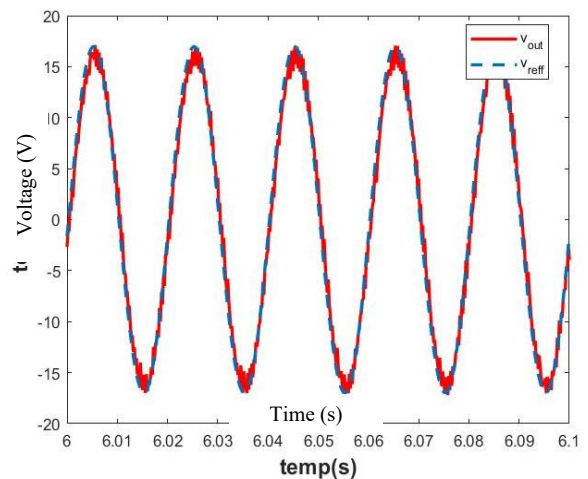


Fig. 22. Output voltage of the Inverter with load variation

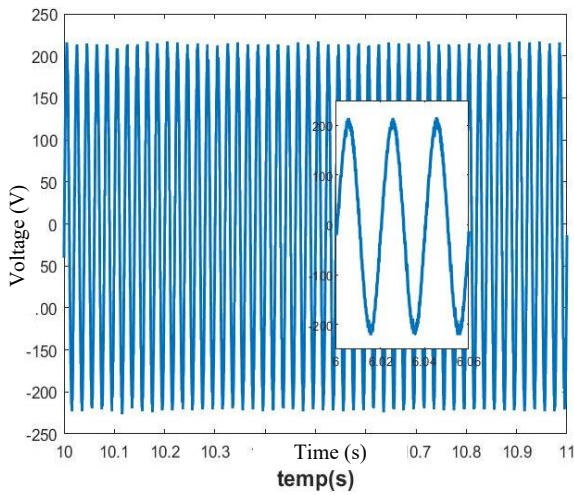


Fig. 23. Output voltage of the transformer with load variation

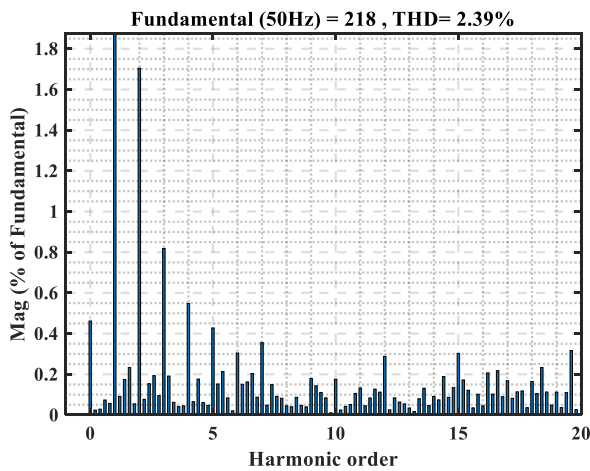


Fig. 24. Output voltage spectrum

VII. 1 PRESENTATION OF A SOLAR POWER SUPPLY GENERATING SINUSOIDAL OUTPUT

Figure 25 shows the experimental solar power supply generating a sinusoidal output with an output power of approximately 300 W. The system operates from a photovoltaic source with an input voltage of 18 VDC and delivers a 230 VAC, 50 Hz pure sine-wave output.

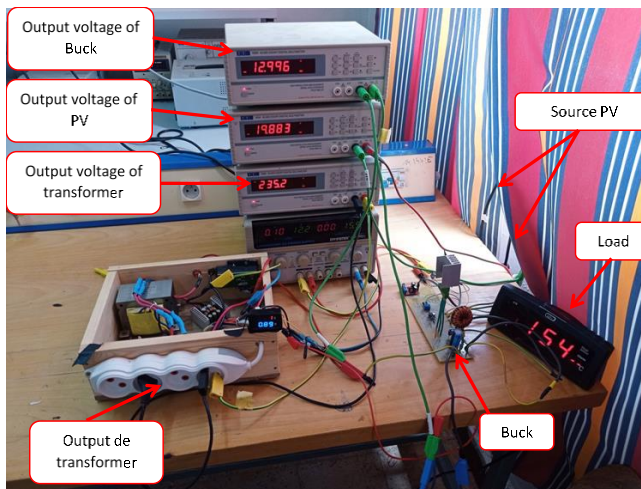


Fig. 25. Solar power supply generating a sinusoidal signal

X. CONCLUSION

This paper presented the study and implementation of a photovoltaic power supply capable of generating a 230 VAC, 50 Hz sinusoidal output from a low-voltage DC photovoltaic source. The proposed system is based on a Buck converter for DC voltage regulation and a single-phase SPWM inverter for DC-AC power conversion. The control strategy was implemented and validated in real time using a dSPACE DS1104 platform, demonstrating the feasibility and effectiveness of the proposed architecture.

The experimental results confirmed the proper operation of the power conversion stages, including DC voltage regulation, sinusoidal voltage generation, and stable operation under load variations. The developed prototype delivered an output power of approximately 300 W, producing a sinusoidal AC waveform suitable for low-power standalone applications. Furthermore, the important contribution of this work lies in the comparative investigation of the inverter's control loop between a classical PI regulator and an adaptive fuzzy-like PI controller. The finding results, assessed in terms of steady-state error, overshoot, and response time, demonstrate that the fuzzy-like approach offers superior adaptability under transient conditions while maintaining comparable steady-state performance. These findings highlight the potential of adaptive, rule-based control techniques to improve the dynamic behaviour of inverter systems without significantly increasing computational complexity.

It should be noted that the objective of this work was to focus on the design, implementation, and experimental validation of the power conversion system rather than on photovoltaic energy optimization or advanced power-quality assessment. Consequently, MPPT functionality and detailed harmonic analyses were not considered within the scope of the present study. Nevertheless, these features represent valuable extensions that could further improve system efficiency and output power quality.

Future work will therefore focus on the integration of MPPT algorithms, comprehensive harmonic and spectral analyses, and the investigation of advanced control strategies to further enhance the performance and efficiency of photovoltaic power supply systems.

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