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Development of MPPT-Enabled Boost Converter for Solar Power Applications

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***Abstract:* -** This study presents the modeling, simulation, and practical implementation of a photovoltaic (PV) system, focusing on two control mechanisms applied to a DC-DC boost converter: Maximum Power Point Tracking (**MPPT**) and output voltage regulation. Photovoltaic systems exhibit power fluctuations due to changing weather conditions, and they seldom operate at the maximum power output capacity of the photovoltaic (**PV**) generator. Therefore, an MPPT control strategy is essential to enhance efficiency by maximizing power output. Two MPPT algorithms, incremental conductance and perturb-and-observe, are utilized in this work for their simplicity, requiring only voltage and current measurements from the PV panel. Additionally, a classic PI regulator with anti-windup is used for output voltage regulation, implemented on an STM32F429 microcontroller. Preliminary MATLAB Simulink simulations validate the mathematical models of the PV generator, boost converter, and load. Practical results confirm the obtained simulation results.

***Keywords**: Constant Voltage Algorithm, Constant Current Algorithm, Perturb and Observe, Incremental Conductance, MPPT, Simulation.*

1. Introduction

Renewable energy has emerged as a cornerstone for achieving sustainable development in the face of growing energy demands and environmental challenges. Unlike fossil fuels, renewable energy sources such as solar, wind, hydro, geothermal, and biomass are naturally replenished and have minimal environmental impact. These energy solutions not only reduce greenhouse gas emissions but also contribute to energy security, economic growth, and the preservation of natural resources. The increasing adoption of renewable energy is driven by advancements in technology, declining costs, and the global shift toward decarbonization to combat climate change. Solar panels, wind turbines, and other renewable systems are being integrated into electricity grids, transportation, and industrial processes, offering cleaner and more efficient alternatives to traditional energy sources.

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In addition, innovations in energy storage and smart grid technology have enhanced the reliability and scalability of renewables, making them a viable solution to meet the world's energy needs. As countries and industries transition to renewable energy, the benefits extend beyond environmental protection. The use of renewables fosters job creation, reduces dependence on finite resources, and promotes energy independence. This paradigm shift represents a crucial step toward a sustainable future, where energy is abundant, accessible, and environmentally responsible.

Solar energy has become one of the most promising and widely adopted sources of renewable energy in the modern world. Harnessed directly from sunlight through photovoltaic (PV) panels or solar thermal systems, it provides a clean, abundant, and sustainable alternative to fossil fuels. As global energy demands rise and the effects of climate change intensify, solar energy offers an environmentally friendly solution that reduces greenhouse gas emissions and helps combat global warming.

One of the primary reasons to use solar energy is its sustainability. The sun is an inexhaustible resource, providing more energy in a single hour than the entire world consumes in a year. Additionally, solar energy systems are highly adaptable, capable of powering anything from small homes to large industrial facilities. Advances in technology have also made solar energy more affordable and efficient, with declining installation costs and improved energy conversion rates making it accessible to both individuals and businesses.

Beyond environmental benefits, solar energy offers economic advantages. It reduces reliance on non-renewable energy sources, lowers electricity bills, and provides opportunities for energy independence. In regions with abundant sunlight, solar energy can also play a crucial role in improving access to electricity, particularly in remote or underdeveloped areas. With its environmental, economic, and technological advantages, solar energy is not just a viable choice but a necessary one for addressing the challenges of modern energy consumption and environmental degradation.

Technologies such as Maximum Power Point Trackers (MPPT) play a crucial role in boosting the efficiency of photovoltaic (PV) systems. MPPT ensures that the PV system operates at its optimal power output by continuously tracking the maximum power point, which varies with changes in factors like sunlight intensity and temperature. By dynamically adjusting the system's operating conditions, MPPT minimizes energy losses and ensures efficient energy recovery, even under suboptimal weather conditions. This technology not only enhances the overall performance of PV systems but also improves their reliability and economic viability, making solar energy a more effective and sustainable solution for meeting energy demands.

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This paper provides a comprehensive study on the boost converter to optimize solar energy extraction. The converter is regulated by an STM32F429 microcontroller, allowing precise control of the output voltage.

This paper is structured into five distinct sections, each addressing a key aspect of photovoltaic (PV) system design and optimization. Section 2 provides an extensive literature review on PV systems, exploring their diverse applications, key characteristics, and various configurations. This section aims to offer a comprehensive understanding of the current state of PV technology and its integration into different energy systems. Section 3 is dedicated to the design and simulation of an autonomous PV conversion system, utilizing MATLAB/Simulink for modeling and analysis. This section highlights the simulation setup, design considerations, and key parameters used in developing an efficient and reliable PV system. Section 4 focuses on the implementation and optimization of the converter control system, with a particular emphasis on Maximum Power Point Tracking (MPPT) and the use of a Proportional-Integral (PI) regulator. It details the optimization techniques applied to enhance the performance of the entire PV system, including the boost converter, MPPT algorithm, and output voltage regulation. Furthermore, it explores the interactions between these components to achieve a stable and efficient energy conversion process. Lastly, Section 5 concludes the paper by summarizing the findings and offering insights into potential areas for future research and development, suggesting ways to further enhance PV system efficiency, scalability, and integration into modern energy grids.

2. Review of Existing Literature and Research Goals

Over the past decades, significant research has been conducted in photovoltaic system optimization, particularly focusing on Maximum Power Point Tracking (MPPT) strategies and power converter design [1], [2], [3]. Many researchers conducted a comprehensive comparison of MPPT techniques, identifying Perturb and Observe (P&O) and Incremental Conductance (INC) as predominant methods due to their implementation simplicity and effectiveness [4], [5], [6]. Building on this foundation, others work enhanced the P&O algorithm by optimizing its parameters to minimize steady-state oscillations while preserving rapid tracking capabilities. In parallel, significant advances were made in DC-DC converter design. In fact, the authors in [7] provided in-depth analysis of converter operations across different modes. Recent trends have shifted toward intelligent control implementation, hybrid MPPT techniques, and energy storage integration, while addressing practical challenges such as temperature effects, component degradation, and system efficiency optimization. These developments collectively contribute to the ongoing evolution of more efficient and reliable photovoltaic systems.

A. *Solar Photovoltaic (PV) Systems*

Photovoltaic (PV) systems come in various complexities, primarily categorized into stand-alone (off-grid) systems and grid-connected systems. Stand-alone systems are designed to be the sole power source for applications like homes or water pumps. They can operate with or

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without battery backup; for instance, remote water pumps often work without batteries, storing pumped water for later use. In contrast, home power systems typically use batteries to store energy generated during the day for nighttime use. These stand-alone systems are often more cost-effective than alternatives like utility line extensions.

Grid-connected systems supplement existing utility power. When a grid-connected PV system generates excess energy, it can be exported to the utility, effectively running the customer's electric meter backward. Conversely, should the PV system does not generate enough power, the customer can draw power from the utility. In this arrangement, the monthly utility bill reflects only the net energy consumed. Both system types require specific components beyond PV modules, including inverters for generating AC power. The overall cost of a PV system depends on the size of the PV array and the necessary components for the intended application [8].

In conclusion, PV systems are highly versatile and can be categorized into three main types based on their configuration and application:

- **Hybrid Systems:** These systems integrate solar energy with conventional power sources, such as the grid or diesel generators, to ensure a consistent and reliable power supply. By combining solar energy with traditional sources, hybrid systems mitigate the intermittency and variability of solar power, making them ideal for areas with fluctuating sunlight or high energy demands.

- **Stand-alone Systems:** Operating independently from the electrical grid, stand-alone PV systems are self-sufficient and can be equipped with energy storage solutions, such as batteries, to store excess energy for later use. These systems are particularly useful in remote or off-grid locations, where direct energy is provided to power loads such as lighting or other small appliances during periods of sufficient sunlight (as illustrated in Figure 1).

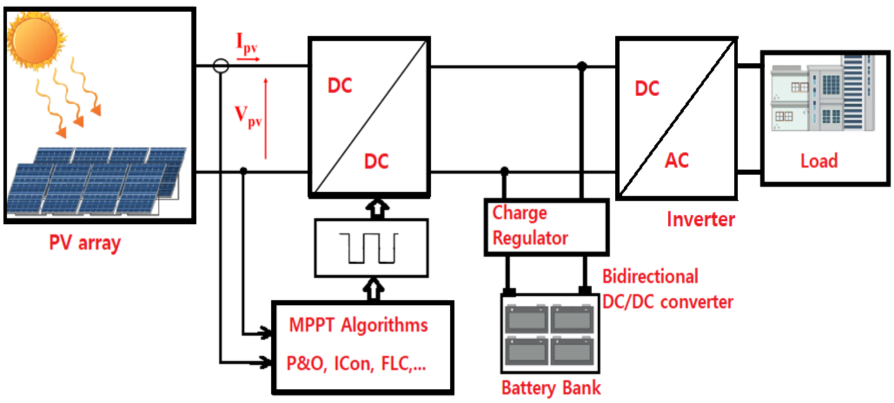

Figure 1: Photovoltaic Systems in Isolated Sites

- **Grid-connected Systems:** These systems are linked to the electrical grid and allow surplus energy generated by the PV modules to be fed back into the grid. This not only

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enhances the overall efficiency of energy use but also provides the potential for grid operators to manage energy demand more effectively by utilizing renewable energy when available.

Each of these PV system types plays a crucial role in advancing sustainable energy solutions and can be selected based on specific energy needs, geographic location, and environmental conditions.

B. *Advantages and Disadvantages of PV Energy Systems*

The following table displays the advantages and disadvantages of the PV systems

TABLE I. SUMMARY OF PV SYSTEMS ADVANTAGES AND ADVANTAGES

Advantages	Disadvantages
Abundant and free energy source.	High manufacturing costs due to advanced technology.
Environmentally friendly with no emissions.	Relatively low energy conversion efficiency (15-22%).
Modular design suitable for diverse applications.	Dependence on weather conditions.
Low maintenance costs	Energy storage requirements for autonomous systems.
Potential to power the entire planet using a small	Environmental impacts associated with manufacturing, installation, and disposal.

The following is the summary of literature findings, recommendations and references:

- PV system efficiency depends on technology and optimization methods, particularly MPPT (Maximum Power Point Tracking) algorithms [9].
- Energy storage solutions, typically batteries, are essential for autonomous PV systems; grid-connected systems can rely on the grid for energy management [10].
- Hybrid systems are particularly beneficial in remote areas, while stand-alone systems can operate independently without infrastructure [11],[12].
- Grid-connected systems improve energy balance, allowing surplus energy to be fed back into the grid.
- Advantages of PV energy include being free, low maintenance, and modular, whereas disadvantages include high initial costs and reliance on weather conditions [13], [14].
- Power converters, such as DC-DC (MPPT) and DC-AC converters, are crucial for adapting PV output to load requirements [15], [16], [17].

The primary objectives of this work focus on optimizing the utilization of solar energy and addressing the challenges associated with photovoltaic (PV) systems. The study aims to develop a PV system capable of efficiently extracting and utilizing solar energy, even under fluctuating weather conditions.

To achieve this, the research incorporates Maximum Power Point Tracking (MPPT) algorithms, specifically Incremental Conductance and Perturb-and-Observe, ensuring the system operates at its maximum power point to maximize energy output. Furthermore, a Proportional-Integral (PI) regulator with anti-windup action is employed to enhance the

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regulation of output voltage, improving the reliability and performance of the DC-DC boost converter. The work also involves modeling and simulating the PV generator, boost converter, and load using MATLAB/Simulink to validate the mathematical models prior to practical implementation.

Additionally, a physical MPPT-enabled boost converter is constructed and tested, with control strategies implemented on an STM32F429 microcontroller to verify the system's performance in real-time conditions. By addressing challenges such as high equipment costs, low energy conversion efficiency, and variability in sunlight, this research aims to make solar energy systems more efficient, reliable, and practical for diverse applications.

3. Methods and experimental measurements

In this part, the realization of an MPPT converter, the implementation of the algorithms (P&O and INC) and the regulation of the output voltage of the boost converter shown in Figure 2 are described. This converter was chosen to design and realize a digital MPPT converter because it has the below advantages:

- Compact number of components, therefore less space constraint, lower cost and weight.
- The values of discrete components change according to the temperature and the operating time.
- Low power consumption of the control card.
- Simplicity of design and control.

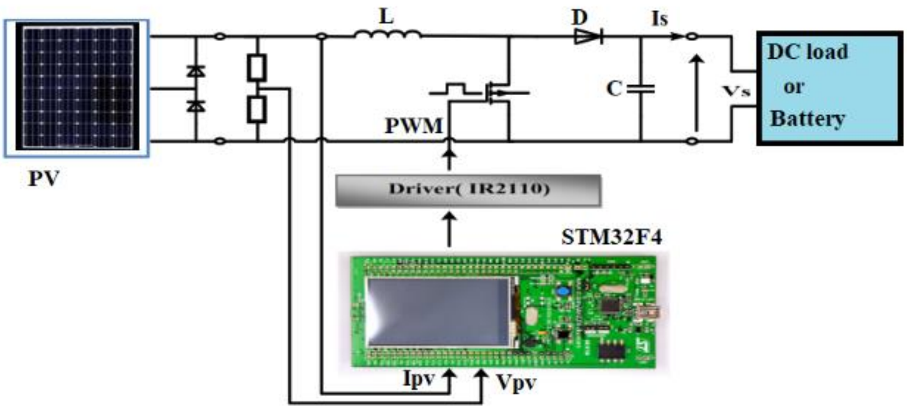

FIGURE 2. MPPT CONVERTER TEST BED

4. Results

A. *MPPT Simulation Results*

To deliver their maximum power, the solar panels it is necessitate the association of the MPPT (Maximum Power Point Tracking) control with the Boost chopper circuit. Indeed, this control always imposes an optimal duty cycle to optimize the energy withdrawn from the solar field even if the load varies.

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TABLE II. POWER VARIATION WITH RESPECT TO LOAD (WITHOUT MPPT)

Load [Ω]	Output current [A]	Output voltage [V]	Output Power [W]
50	0.39	19.58	7.63
20	0.96	19.25	18.48
10	1.86	18.65	34.68
8	2.28	18.32	40.26
6	3.00	16.90	50.70

TABLE III. INCREMENTAL CONDUCTANCE ALGORITHM (20Ω)

Quantity	V_{PV} (V)	I_{PV} (A)	P_{PV} (W)	P_S (W)	V_S (V)	I_S (A)	η (%)
P&O Algorithm	15.08	2.91	44.00	40.30	29.00	1.39	91.90
INC Algorithm	15,56	3.00	48.00	44.70	30.00	1.49	93.10

TABLE IV. INCREMENTAL CONDUCTANCE ALGORITHM (40Ω)

Quantity	V_{PV} (V)	I_{PV} (A)	P_{PV} (W)	P_S (W)	V_S (V)	I_S (A)	η (%)
P&O Algorithm	15.08	2.91	44.00	35.00	35.00	1.00	79.00
INC Algorithm	15.56	3.00	48.00	38.50	42.00	0.91	80.00

From the above results of the MPPT simulations, it is obvious that there is no regulation of the output voltage of the DC-DC converter. To have a fixed voltage (48V) capable of charging the battery, we studied an approach for regulating the output voltage of the chopper aiming for better performance. This approach was synthesized in the time domain and uses a classic PI regulator with an anti-windup action. This PI regulator allowed to have better performance than the system without regulation.

Table 5 illustrates the open circuit voltages and short circuit currents of our solar panel, as well as the maximum powers for a direct connection with a resistive load for different irradiation levels. It is noted that the power extracted from the PV generator connected directly to a load is often very far from the maximum power that the PV generator can deliver.

TABLE V. TABLE OF MEASUREMENTS (V_{CO}, I_{CC}, V_{PMAX}, I_{PMAX}, P_{MAX})

Irradiation	1030W/m²	850W/m²	630W/m²
Vco (V)	17.6	16.8	16.8
Icc (A)	3.48	2.6	1.86
Vpvmax (V)	13	12.8	12.2
Ipvmax (A)	3.1	2.35	1.74
Ppvmax (W)	42.16	30.08	21.22

Through these tests, we can show the limits of the direct connection on the production losses that it causes, hence the optimizing solution is to add an adaptation stage which is in our case a DC-DC Boost type converter.

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B. Realization of the MPPT converter

Determining the real values of these components requires widely extended study on the parameters imposed by the SM50 solar panel, or its characteristics in standard conditions (1000W/m2; area mass: AM1.5; Cell temperature: 25°C). The sizing of the chopper has not been fixed by the specifications; the values of the chopper components are therefore studied according to the value of the chopper output voltage. This voltage is generally the voltage of a battery Vs=48V.

C. Components Selection

Determining the characteristics of the power card is an important and critical step in the development of the MPPT. Of course, any unsuitable component can logically prevent optimal operation of this power card. In all the calculations that follow, the extreme case will be considered. We will assume that the conduction is continuous (the inductor current never vanishes) and the converter losses are negligible. The final design is shown in Figure 3.

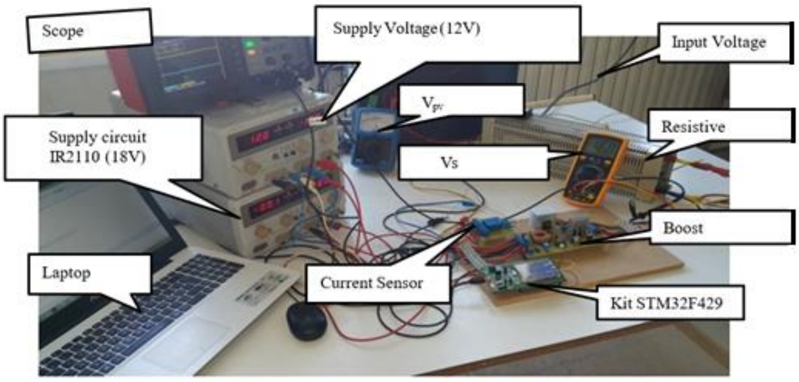

FIGURE 3. HARDWARE TESTBED OF THE DIGITAL MPPT IMPLEMENTATION

D. Performance during load variation

The results obtained by the P&O algorithm under the conditions (Radiation=635W/m² at temperature T=19°C). These tests are performed to know the behavior of the system during a load variation. The results are illustrated in Table 6.

TABLE VI. INCREMENTAL CONDUCTANCE ALGORITHM (40 Ω)

Load Rch[Ω]	Panel voltage Vpv [V]	Panel power Ppv [W]	Converter output power Ps [W]	Output voltage Vs [V]	Output current Is [A]
100	15.5	27	25.50	34	0.75
63	15.0	27	22.80	38	0.60
50	15.0	27	17.64	42	0.42
20	16.0	27	20.00	20	1.00

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Once the load varies, the power of the panel always remains stable, and the algorithm changes the value of the duty cycle to catch up with the MPP. As the load varies, the panel power always remains stable as the algorithm changes the duty cycle value to catch up with the MPP.

5. Discussion

The obtained results demonstrate the effectiveness of the proposed methodologies for enhancing photovoltaic (PV) system performance through the integration of Maximum Power Point Tracking (MPPT) algorithms and output voltage regulation. The Incremental Conductance (INC) algorithm outperformed the Perturb-and-Observe (P&O) algorithm with a slightly higher efficiency of 93.1% compared to 91.9%, showcasing its superior ability to adapt to rapid variations in irradiance and temperature. The addition of a Proportional-Integral (PI) regulator with anti-windup action ensured a stable output voltage of 48V, critical for applications requiring consistent voltage levels, such as battery charging. Experimental results validated the simulation findings, with the MPPT-enabled boost converter achieving stable and efficient operation under varying loads and environmental conditions, as confirmed by the hardware implementation using an STM32F429 microcontroller. The system demonstrated significant improvements in power extraction and energy transfer efficiency compared to direct load connections, reducing energy losses and ensuring reliability. However, challenges such as the impact of environmental conditions and component degradation remain, necessitating further optimization of both hardware and control algorithms.

6. Conclusion

This study demonstrates the importance of effective control strategies in addressing the challenges faced by photovoltaic (PV) systems, such as high costs, low efficiency, and intermittent output due to varying weather conditions. By implementing maximum power point tracking (MPPT) and output voltage regulation, we enhanced the efficiency and reliability of a PV system using a DC-DC boost converter. This work lays a strong foundation for future advancements, including the incorporation of intelligent control techniques like fuzzy logic and neural networks. Additionally, expanding to hybrid configurations with diesel generators and storage systems could provide a more reliable, sustainable power source. This research sets a foundation for optimizing solar energy applications, making them more efficient and adaptable for diverse energy needs.

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