Power Extraction in Photovoltaic Systems using P&O-Based MPPT with DC-DC Buck Converter Integration

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Abstract: - Solar energy is an abundant, renewable resource that offers a sustainable alternative to fossil fuels. Photovoltaic (PV) systems, which convert sunlight into electricity, have gained global prominence due to technological advancements and decreasing costs. A typical PV system consists of solar panels, inverters, and energy storage. However, the efficiency of these systems is affected by variable sunlight and temperature conditions. Maximum Power Point Tracking technology works as an optimization tool for solar panel operations by finding their maximum operational efficiency. The research examines solar panel modeling together with MPPT algorithms and buck converter implementation for energy management between solar panels and storage systems. Simulations based on MATLAB/Simulink evaluated the performance output of a two-stage PV system which integrated an MPPT-controlled buck converter for performance assessment. The system evaluation results demonstrate its analysis of maximum power point while monitoring various conditions that optimize energy efficiency through irradiance and temperature variations. Off-grid and hybrid systems require energy storage according to research findings which demonstrates both lead-acid and lithium-ion batteries as options. The paper explores solar energy integration challenges alongside methods to use advanced energy conversion systems and smart grid systems for enhancing future performance. The study highlights solar energy promising potential to be a key player in the global shift toward renewable energy. The simulation results further validate the system's strong performance, confirming its effectiveness in supporting this transition.

Key-Words: - Photovoltaic (PV) systems, Maximum Power Point Tracking (MPPT), Photovoltaic (PV), DC-DC, converters, buck converter, Battery.

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1 Introduction

Solar energy is one of the most obtainable renewable energy sources available to humans since it is in ample supply and is capable of producing energy ad infinitum with a small quantity of Greenhouse gases that are needed to help combat climate change. In the last years, the use of sun cell (PV) setups has grown a lot. This is due to better tech, lower prices, and a bigger world push for green energy fixes. Sun PV setups change sun rays to power, making them very important in moving to an Earth-friendly energy road ahead, [1], [2].

The ongoing global energy transition is motivated by several factors, including the need for environmentally friendly alternatives to fossil fuels, the growing demand for electricity, and the pressing challenge of addressing climate change. The most rousing attributes of solar energy are that it is widely available, inherently stable, and can be supplied at all levels whether residential or utility, [3].

This paper discusses the elements of the solar photovoltaic system including solar panels, investors, and more so energy storage systems. It also goes to understand the functionality of the

Maximum Power Point Tracking (MPPT) Technology and its types of solar charge controllers, energy storage products, and application of the DC-DC converters such as Buck converters necessary for proficient energy generation and energy storage.

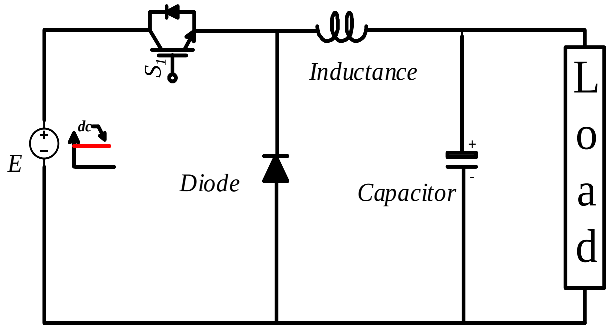

Fig. 1: Buck converter

In addition, the paper reveals the problems and prospects of integration of solar energy into the wider electricity grid, and the future of solar energy in the process of transition, [4], [5]. A typical solar photovoltaic system comprises several key components: modules, investors, and batteries for solar energy applications. These systems are composed of light capturing and converting technologies, energy storage, and distributing technologies, [6]. Solar panels are the central component of any PV system that is composed of photovoltaic cells that produce electrical current once in contact with sunlight. This electrical energy is Direct Current (DC) electrical energy which can be directly supplied to loads or stored in batteries for later usage or converted to Alternating Current (AC) to suit the normal electrical grid systems,[7], [8]. There are steady advancements Thus, growth in PV technology has been driven by advancements in semiconductor materials that have improved efficiency and durability of solar cells. The current photovoltaic solar panels can produce electricity from the sun at rates higher than they were in the past hence more rate of conversion from surface area. Also, over the years there has been a reduction in the cost of PV modules which has favored customers, corporations, and governments all around the world for solar electricity, [9].

The power of the solar panel varies; its output depends on the amount of light reaching the panel the level of heat and the condition around it. Another advantage of the shown mathematics of a solar panel is that reading panel power-voltage characteristics is not constant, but reads a maximum power at a specific point. The peak efficiency power that we discussed above is the maximum power point (MPP) which changes with the sun's position and illumination level. To maximize energy generation thus, it is important that a solar PV system gets to the MPP and this brings us to the understanding of MPPT technology, [10]. In the effectiveness of a solar PV system, it is anticipated that the system operates at the Maximum Power Point tracking the voltage and the current version power density. However, because of the variations in shading, the amount of light intensity on the panel, and variation in temperatures among others the MPP is variable. Rather, it varies from morning to evening hence the need to employ a tracking system to control the operations of the solar panel in real time for optimization, [11].

MPPT technology that serves as the means to achieve that makes sure the solar PV system operates with utmost efficiency in all circumstances, at or close to the Maximum Power Point. Apart from the use of the MPP tracking algorithms, the power output of a PV system is constantly checked and the voltage and currents of the panels are adjusted to that of the MPP. This dynamic tracking is advantageous when harvesting energy since solar radiation changes, especially in areas with cloud cover or partial solar cover, [12]. Despite this, if MPPT is not utilized, the solar panels are likely to operate at a voltage and current level that is remote from the optimum level, causing huge energy losses. For example, with the increased temperature of the solar cells, the MPP is moved to a different voltage and the corresponding current and hence the operating point of the system has to be changed. Likewise in the case when radiation intensity reduces because of cloud inclusion, the MPP changes once more. As it is, these transitions are sensed by MPPT systems, and, in turn, the load is managed to guarantee that the PV array operates at maximal power, [13], [14].

The role of MPPT becomes even more crucial in energy storage devices for example in solar battery charging circuits. These systems need to deliver the right amounts of Voltage and Current to charge the battery without overcharging or deep discharging that harms the battery and decreases the battery's life cycle. The successful operation of photovoltaic systems in the long term depends on proper MPPT deployment with charging controllers according to [15]. Standalone solar photovoltaic power and combined solar and other power systems demand battery storage because they must provide continuous power when the available light is insufficient. He noted that energy storage systems such as batteries hold the excess energy produced from the solar panels during the day for use at night or when there is little sunlight. Lead-acid batteries have been the most popular battery technology used in energy storage in solar applications because of their low cost and reliability, [16], [17]. However, the advances in battery technology, including the lithium-ion type of battery, have brought new opportunities in energy storage systems. Lithium-ion batteries in turn have compact structure, high energy density, long cycle life, high electrochemical efficiency, and better safety compared to lead-acid batteries. However, these events make lead-acid batteries popular in solar energy projects, especially in remote areas and low-cost projects.

A solar charge controller is a necessary component for any photovoltaic system that requires power storage. This device controls the quantity of power that travels between a solar panel and a battery, preventing the battery from being overcharged or fully depleted. Charge controllers come in two main types: PWM controllers and MPPT controllers, [18]. Even though PWM controllers are cheaper and easier to manufacture than their counterparts, MPPT controllers are better in terms of efficiency. MPPT charge controllers show higher efficiency when it comes to extracting energy from the solar array; this energy is especially high when the solar panel voltage is higher than the battery voltage. Thus, the MPPT controllers help the system work at its optimum efficiency and also extend the battery life by charging the battery according to its needs as provided by the panel, [19].

In most of the MPPT charge controllers, a DC-DC converter is incorporated to either boost or buck the solar panel voltage to meet the charging circuit needs of a battery. Of these applications, the buck converter is one of the most frequently adopted DC-DC converters. The buck converter is a step-down converter that brings in a higher voltage coming from the solar array to a lower voltage appropriate for charging the battery, [20]. The buck converter works on the principle of varying a switch duty cycle (in most cases an active switch), in order to achieve a desired output voltage. When used in an MPPT charge controller, the buck converter regulates voltage in a way that will make the solar panel work at Maximum Power Point when providing the right voltage needed to the battery system. It also makes it possible not to overcharge, and charge the battery efficiently and safely, [21]. That said, following the rise of solar PV systems, several issues are still worth discussing in regard to the introduction of solar energy into the wider electric grid. One of the issues that turn into a problem is that the efficiency of solar energy depends on the weather conditions and the period of the day. This intermittency can be somewhat problematic for grid stability, as well as for energy management especially if higher penetration of solar power is involved.

2 Description of the Overall System

The Configuration of the photovoltaic system, coupled with the buck converter is presented in Figure 2. It involves integrating a PV panel as the energy source, a DC-DC converter, and the battery as the load. A detailed explanation of MPPT techniques unfolds in the following section where P&O control demonstrates its application to optimize PV system performance. The essential DC-DC buck converter switching circuit operates as an explanation to understand the energy management process for PV panel to battery connection.

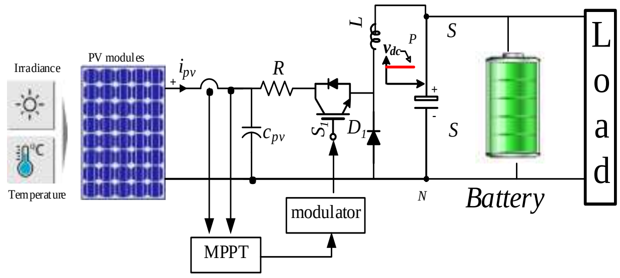

Fig. 2: Construction of the overall system

2.1 DC-DC Buck Converter

A DC-DC buck converter is generally implemented in PV systems since the supplied input voltage PV panel is frequently times higher than the needed voltage for the load, such as batteries and other storage devices. The buck converter works in the context of voltage step down; large input voltage can be converted to practical output voltage due to high efficiency with an additional converting of energy.

The Figure 1 illustration shows that buck converter functions fundamentally through control of the switching mechanism. The converter hardware includes a switch mostly made from MOSFET or IGBT along with a diode and inductor along with a capacitor. The on-off operating state of the switch produces pulsed input which the inductor and capacitor smooth into a constant DC output voltage. The switch duty cycle D represents the ratio between switching on time and the full cycle for determining the output voltage, [22]. The relationship between the input voltage V_{in}, output voltage V_{out}, and duty cycle D for an ideal buck converter is given by the following equation:

$$V_{out} = D * V_{in} \quad (1)$$

where:

V_{out} Is the output voltage, V_{in} is the input voltage from the PV panel, and D is the duty cycle, which ranges from 0 to 1.

Inductor Voltage and Current: The inductor voltage during the on and off states follows:

$$V_L = L\frac{di_L}{dt} \quad (2)$$

From this, we can find the change in inductor current (Δi_L) during the on and off states:

$$\Delta i_L = \frac{V_L}{L} \cdot t_{\text{on}} \quad \text{(for on-state)}$$
$$\Delta i_L = \frac{-V_{\text{out}}}{L} \cdot t_{\text{off}} \quad \text{(for off-state)} \quad (3)$$

where: L is the inductance, t_{on} and t_{off} are the on and off times of the switch, respectively. The inductor Ripple Current (ΔI_L) the peak-to-peak inductor ripple current is an important parameter that depends on the input voltage, output voltage, switching frequency $(f_s = 1/T)$.

2.2 P&O-based MPPT Technique

The Perturb and Observe (P&O) technique is among the most powerful techniques used in Maximum Power Point Tracking (MPPT) in photovoltaic systems, therefore its significance. It is popular due to its efficiency and ease of making certain that a PV system is operating at the vicinity of the Maximum Power Point (MPP) which is the power inputs highest level despite changes in external conditions such as solar irradiance and temperature, [23]. The P&O technique is developed on the idea that the system operating point is disturbed, usually, the voltage or current control and the consequent changes of the output power are studied. Another advantage of this feedback mechanism is to enable the system to regulate its operation parameters in tracking and sustaining the MPP, [24]. Accomplished by influencing the voltage or current by a small amount at the terminals of the PV array and noting the level of impact on the power output, the P&O MPPT algorithm works.

The current power output is compared with the previous measurement which was taken by the algorithm. It modifies the operational point as follows in light of the comparison: The mechanism keeps increasing the voltage if this leads to more power than it does so the mechanism reduces the voltage if the increase leads to reduction in the power levels. The photovoltaic (PV) cell exists in mathematical form as a voltage-controlled current source with high sensitivity to sun irradiation (W/m²) and temperature (°C) values. A PV cell equivalent circuit can be seen in Figure 3 for simulation purposes.

$$I_{pv} = I_{ph} - I_r\left[\exp\left(\frac{q(V + R_s I_{pv})}{\eta kT}\right) - 1\right] - \frac{V + R_s I_{pv}}{R_p} \quad (4)$$

$$I_{ph} = \left[I_{sc} + \alpha(T - T_{ref})\right]\frac{G}{1000} \quad (5)$$

$$I_r = I_{rr}\left(\frac{T}{T_{ref}}\right)^3 e^{\left[(qE_g/\eta k)\left((1/T_{ref}) - (1/T)\right)\right]} \quad (6)$$

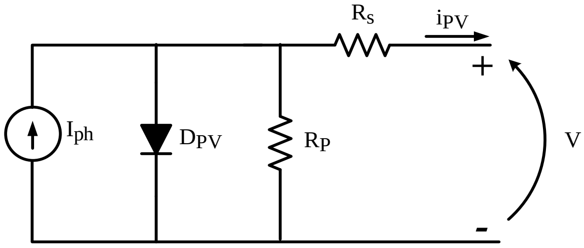

Fig. 3: Equivalent circuit of a solar cell

$$I_{rr} = \frac{I_{sc} - (V_{oc}/R_p)}{\left[\exp\left[\frac{qV_{oc}}{\eta kT_{ref}}\right]\right] - 1} \quad (7)$$

$$V_{oc}(T) = V_{oc}(T_{ref}) + \beta(T - T_{ref}) \quad (8)$$

The variables in the photovoltaic (PV) cell model include: I_{pv} , the output current of the PV cell; I_{ph} , the light-generated current; I_r , the reverse saturation current; I_{rr} , the diode reverse saturation current; V_{pv} , the voltage of the PV array; and V_{oc} , the open-circuit voltage. Additionally, and R_s and R_p portray the series and shunt resistances in turn. The model also uses Boltzmann constant K, ambient temperature T, solar insolation G (measured in W/m²), short circuit current I_{sc} , and the bandgap energy of the cell (1.1 eV). Current I under standard test conditions (STC), and the bandgap energy (1.1 eV). The photovoltaic (PV) system is a vital component in renewable energy generation, and its efficiency largely depends on the accurate tracking of its maximum power point (MPP) under varying environmental conditions. The electrical characteristics of the PV array used in this study, as detailed in Table 1, provide a solid foundation for understanding its performance. To maximize the energy output of the PV modules, the Perturb and Observe (P&O) algorithm is employed for Maximum Power Point Tracking (MPPT). This method is instrumental in continuously adjusting the operating point of the PV system to ensure that it operates at its maximum potential, regardless of fluctuations in temperature and irradiance, [25]. The P&O MPPT algorithm is widely used due to its simplicity, effectiveness, and adaptability to different environmental conditions. The basic principle of the P&O algorithm is to perturb the operating voltage of the PV array and observe the resulting change in power. If the power increases, the algorithm continues to adjust the operating voltage in the same direction; if the power decreases, it reverses the direction. This iterative process allows the PV system to track the maximum power point, ensuring optimal energy conversion. In practical applications, this dynamic adjustment is crucial, especially as the PV array's output is highly dependent on environmental factors such as solar irradiance, temperature, and shading. These factors can change rapidly throughout the day, causing the maximum power point to shift. Without an efficient MPPT algorithm, the PV system would fail to operate at its optimal point, leading to significant energy losses. The performance of the PV system is not only dependent on the MPPT algorithm but also on the interaction between various system parameters and components. These include the electrical characteristics of the PV modules, the efficiency of the power electronics used to convert DC to AC power, and the environmental conditions under which the system operates. Accurate modeling of these variables is essential for optimizing energy conversion. For instance, the current voltage (I-V) characteristics of the PV modules are non-linear and vary with temperature and irradiance. A well-designed MPPT algorithm, like P&O, must account for these changes to ensure the system consistently operates at the MPP. Moreover, the integration of energy storage systems or grid connection further complicates the system's behavior, as power flow needs to be managed efficiently to avoid losses. By accurately modeling and understanding the interaction of these variables, engineers can optimize the performance of the PV system, ensuring that it delivers reliable and efficient power under diverse operating conditions, [26]. Accurate modeling of the PV array, combined with an effective MPPT algorithm, offers several key benefits. First, it helps in maximizing energy yield, ensuring that the PV system operates at its highest efficiency throughout the day. This is particularly important in regions where sunlight availability is inconsistent or where systems need to cope with shading or other obstructions. Second, it enhances the reliability and lifespan of the PV system.

Furthermore, accurate modeling and MPPT optimization help in reducing energy losses, making the system more sustainable and cost-effective in the long run. This is crucial in large-scale renewable energy projects, where even small improvements in efficiency can translate into significant cost savings and reductions in carbon emissions.

Table 1. Electrical Characteristics of the PV Array

Parameters	Symbol	Values
Short circuit current	I_{SC}	8.75 A
Max current	I_{MPP}	8.1 A
Open circuit voltage	V_{OC}	36.6 V
Maximum power voltage	V_{MPP}	30.9 V
Maximum power	P_{MPP}	250 w
Temperature	T_m	25C
Solar irradiance		1000W/m2

One of the most widely utilized strategies for tracking the maximum power point (MPP) of photovoltaic (PV) modules is the Perturb and Observe (P&O) method. This technique is highly efficient and features a simple structure, making it a popular choice in MPPT systems, [15]. Figure 4 illustrates the typical power-voltage (P-V) curve (in green) and current-voltage (I-V) curve (in blue) for a PV panel. The P-V curve demonstrates a distinct point, highlighted in red, known as the Maximum Power Point (MPP). At this point, the system operates with optimal efficiency, allowing the maximum energy, denoted as P_{MPPT}, to be extracted from the PV panel, [27].

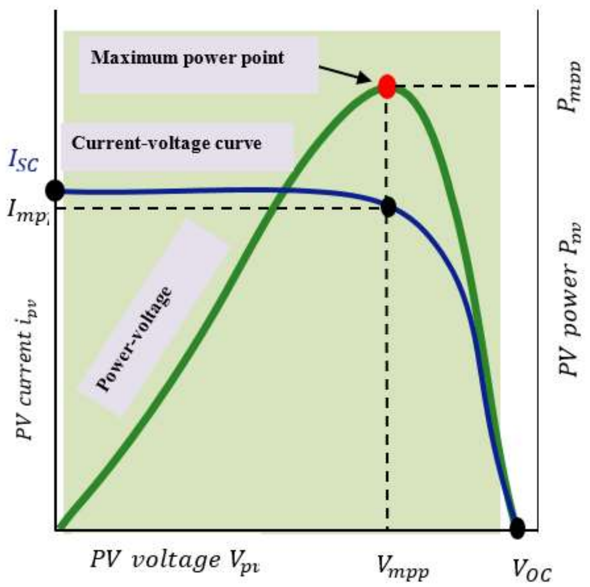

Fig. 4: Power-voltage (P-V) characteristic of PV modules

The P&O method works by periodically perturbing the operating voltage of the PV system and observing the resulting change in power. If the power increases, the system continues to adjust in the same direction; if it decreases, the perturbation direction is reversed. This iterative process ensures that the PV system operates at or near the MPP, even under varying conditions of solar irradiance and temperature. The significance of the MPP in the P-V curve is critical, as it represents the point where the product of current and voltage yields the highest possible power output. By continuously adjusting the system to operate at this point, the P&O method ensures that the energy harvested from the PV modules is maximized, [28].

In practical applications, the accuracy of the P&O algorithm and its ability to quickly adapt to environmental changes are essential for optimizing the overall performance of solar energy systems. The simplicity of its structure makes it ideal for integration into low-cost, efficient MPPT controllers, which are crucial for enhancing the reliability and sustainability of PV systems.

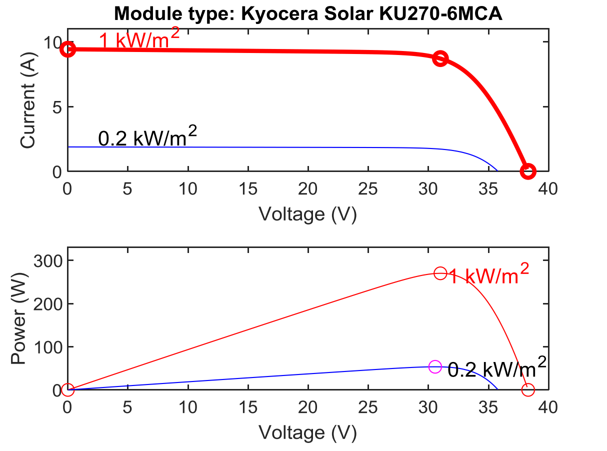

Fig. 5: The I-V characteristics curve with a constant temperature of 25°C

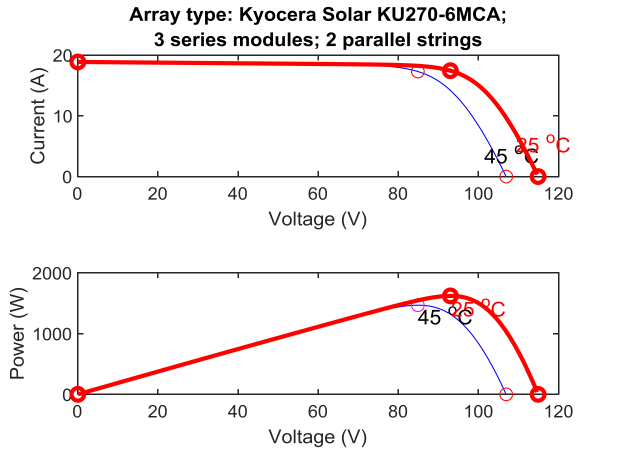

Fig. 6: The I-V characteristics curve with a variable temperature

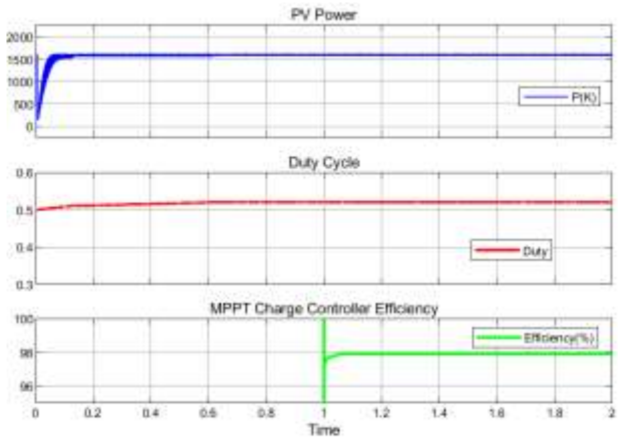

Fig. 7: The power output, duty cycle and the efficiency

3 Simulation Results

To validate the results a PV battery charging and storage system with a unidirectional DC-DC buck converter was modelled through a prototypical MATLAB/Simulink simulation. This simulation focused on understanding PV module I-V characteristics together with MPPT charge controller efficiency by testing system operation under different environmental conditions.

Figure 5 and Figure 6 demonstrate a strong correlation between the simulated I-V characteristics and the theoretical values obtained from the PV module. In Figure 5, the I-V curve is shown under varying irradiance levels with a constant temperature of 25°C, while Figure 6 presents the I-V characteristics under different temperatures with a constant irradiance of 1000 W/m². Results from the simulation validate that the PV module acts as intended while temperature and irradiance variations occur thus demonstrating the effectiveness of the MPPT algorithm to dynamically optimize power output. Figure 7 shows that the power output which reaches over 1.5 kW exceeding provides the measurements. At this operating point, the duty cycle of the DC-DC buck converter is set to 0.55, ensuring efficient power transfer from the PV array to the battery storage system. The MPPT charge controller's efficiency is calculated at 98%, highlighting its capability to maintain optimal power extraction and minimal energy loss.

These simulation results confirm the reliability of the proposed system in optimizing energy conversion under real-world conditions, showcasing its potential for practical applications in solar-powered battery charging and energy storage systems.

4 Conclusion

The growing demand for clean, renewable energy has positioned solar photovoltaic (PV) systems as a crucial solution for reducing greenhouse gas emissions and advancing global sustainability efforts. This paper has explored key components of solar energy systems, including solar panel modeling, MPPT technology, DC-DC converters, and energy storage integration. The use of Maximum Power Point Tracking (MPPT) and efficient DC-DC converters, such as buck converters, plays a pivotal role in maximizing energy generation and improving system performance under fluctuating solar irradiance and temperature conditions. Through MATLAB/Simulink simulations, the effectiveness of a two-stage solar energy system with MPPT control was demonstrated. The simulations highlighted the system's ability to dynamically track the Maximum Power Point, ensuring optimal performance even in changing environmental conditions. This dynamic adjustment is crucial for solar systems to operate efficiently and harvest the maximum available energy. Moreover, the paper discussed the challenges of integrating solar energy, particularly in terms of intermittency and energy storage limitations. Energy storage systems, such as lead-acid and lithium-ion batteries, are essential for off-grid and hybrid systems, providing a stable power supply when sunlight is unavailable. Despite these challenges, advancements in battery technology, grid management, and energy conversion systems continue to enhance the feasibility of large-scale solar deployment. Solar energy has immense potential to contribute to a sustainable energy future. While technical challenges remain, ongoing research and innovation in solar technology, energy storage, and grid integration will further improve the efficiency, reliability, and scalability of solar PV systems, making them a cornerstone of the global renewable energy transition.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work the authors used Grammarly for language editing. After using this service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

References:

[1] M.N. Geethanjali and M. H. Sidram, Performance evaluation and hardware implementation of MPPT based photovoltaic system using DC-DC converters, *International Conference on Technological Advancements in Power and Energy (TAP Energy)*, Kollam, India, 2017, pp. 1-6, doi: 10.1109/TAPENERGY.2017.8397375.

[2] Tajaldin, K. H., & Motlak, H. J., Enhancement of DC-DC Luo Converter Using Adaptive PI MPPT and P&O MPPT for Photovoltaic System. *Journal Européen des Systèmes Automatisés*, Vol. 57, Issue 3, 2024, p92, doi: 10.18280/jesa.570330.

[3] D. K. Sharma and G. Purohit, Advanced perturbation and observation (P&O) based maximum power point tracking (MPPT) of a solar photo-voltaic system, *IEEE 5th India International Conference on Power Electronics (IICPE)*, Delhi, India, 2012, pp. 1-5, doi: 10.1109/IICPE.2012.6450411.

[4] A. Srivastava, A. Nagvanshi, A. Chandra, A. Singh and A. K. Roy, Grid Integrated Solar PV System with Comparison between Fuzzy Logic Controlled MPPT and P&O MPPT, *IEEE 2nd International Conference On Electrical Power and Energy Systems (ICEPES)*, Bhopal, India, 2021, pp. 1-6, doi: 10.1109/ICEPES52894.2021.9699492.

[5] Yadav, R. S., Dhaked, D. K., & Jaiswal, A., Comparative study of MPPT techniques for solar PV-based system. *International Journal of Environment and Sustainable Development*, Vol. 20, No. 3-4 ,2021 pp366-380. https://doi.org/10.1504/IJESD.2021.116866.

[6] C. Yao, X. Ruan, X. Wang and C. K. Tse, Isolated Buck–Boost DC/DC Converters Suitable for Wide Input-Voltage Range, *IEEE Transactions on Power Electronics*, vol. 26, no. 9,2011, pp. 2599-2613, doi: 10.1109/TPEL.2011.2112672.

[7] N. P. Raj, K. P. S. Praneeth Swamy, T. V. Deepika and A. Jain, Comparative Analysis of Different MPPT Techniques, *3rd International conference on Electronics, Communication and Aerospace Technology (ICECA)*, Coimbatore, India, 2019, pp. 1091-1096, doi: 10.1109/ICECA.2019.8821904.

[8] R. Kushwaha and B. Singh, A Modified Luo Converter-Based Electric Vehicle Battery Charger With Power Quality Improvement, *IEEE Transactions on Transportation Electrification*, vol. 5, no. 4,2019, pp. 1087-

1096, doi: 10.1109/TTE.2019.2952089.

[9] Zakzouk, N.E. Continuous input current buck DC/DC converter for small-size wind energy systems featuring current sensorless MPPT control. *Scientific Reports*, Vol. 14, 380, 2024, https://doi.org/10.1038/s41598-023-50692-2.

[10] Daud, A. K., & Khader, S. H., Closed Loop Modified SEPIC Converter for Photovoltaic System. *WSEAS Transaction on Circuits and Systems*, Vol. 21, 2022, PP. 161-167. https://doi.org/10.37394/23201.2022.21.17.

[11] M. Wageh, S. M. Dabour and R. M. Mostafa, A New Four-Switch Split-Source Boosting Inverter: Analysis and Modulation, *23rd International Middle East Power Systems Conference (MEPCON)*, Cairo, Egypt, 2022, pp. 1-7, doi: 10.1109/MEPCON55441.2022.10021772 .

[12] Kamarudin, N., Abd Samat, A. A., Tajudin, M. F. N., Osman, M. K., Omar, S., & Hamzah, I. H., Design of Buck Converter Based on Maximum Power Point Tracking for Photovoltaic Applications, *Journal of Advanced Research in Applied Sciences and Engineering Technology*, Vol. 39(2),2024, pp. 242-257. https://doi.org/10.37934/araset.39.2.242257.

[13] Krim, S. A., Krim, F., Afghoul, H., & Abdelmalek, F., An improved perturb and observe MPPT for photovoltaic systems using fuzzy step size, *WSEAS Transactions on Power Systems*, Vol. 19,2024, pp. 105-114. https://doi.org/10.37394/232016.2024.19.13.

[14] T. Illuru, J. Rajender and M. Dubey, "A Review Paper on Tracking MPP Using Hybridization of P&O and FLC, *IEEE 3rd International Conference on Electrical Power and Energy Systems (ICEPES)*, Bhopal, India, 2024, pp. 1-6, doi: 10.1109/ICEPES60647.2024.10653534.

[15] M. W. Lotfy, S. M. Dabour, R. M. Mostafa, D. J. Almakhles and M. F. Elmorshedy, Modeling and Control of a Voltage-Lift Cell Split-Source Inverter With MPPT for Photovoltaic Systems, *IEEE Access*, vol. 11, 2023, pp. 54699-54712, doi: 10.1109/ACCESS.2023.3280602.

[16] Al Garni, H. Z., Sundaram, A., Awasthi, A., Chandel, R., Tajjour, S., & Singh Chandel, S. ,A comprehensive review of most competitive maximum power point tracking techniques for enhanced solar photovoltaic power generation. *Journal of Renewable Energy and Environment (JREE)*, Vol. 11(3), 2024, pp. 60-80. https://doi.org/10.30501/jree.2024.408699.1638.

[17] E. G. Shehata, J. Thomas, A. M. Brisha and M. Wageh, Design and analysis of a quasi Y-source impedance network DC-DC converter, *Nineteenth International Middle East Power Systems Conference (MEPCON)*, Cairo, Egypt, 2017, pp. 235-241, doi: 10.1109/MEPCON.2017.8301189.

[18] Behera, S., Sahu, M. K., Dash, S. K., & Swain, S. K., Optimising power of PV module using modified MPPT for standalone load, *International Journal of Power Electronics and Drive Systems (IJPEDS)*, Vol.15(2), 2024, pp. 1158-1166. DOI: 10.11591/ijpeds.v15.i2.pp1158-1166

[19] Venkatesh, A., Reddy, B. A., & Jyothsna, T. R., Impact of Discrete-Time Modeling on Dual Input Buck-SEPIC Converter. *WSEAS Transactions on Circuits and Systems*, Vol. 22, 2023, pp. 274-288. https://doi.org/10.37394/23201.2023.22.28.

[20] A. H. Bonnett, Analysis of the impact of pulse-width modulated inverter voltage waveforms on AC induction motors, *IEEE Transactions on Industry Applications*, vol. 32, no. 2, 1996, pp. 386-392. doi: 10.1109/28.491488.

[21] L. F. Lavado Villa, T. -P. Ho, J. -C. Crebier and B. Raison, A Power Electronics Equalizer Application for Partially Shaded Photovoltaic Modules, *IEEE Transactions on Industrial Electronics*, vol. 60, no. 3, 2013, pp. 1179-1190.doi: 10.1109/TIE.2012.2201431.

[22] Sai, B. S. V., Chatterjee, D., & Mekhilef, S., Inter-harmonics Mitigation for PV-based Converters Using INHARE MPPT Algorithm, *IETE Journal of Research*, Vol. 70(2), 2022, PP. 1766–1786. https://doi.org/10.1080/03772063.2022.2150693.

[23] M. A. G. de Brito, L. Galotto, L. P. Sampaio, G. d. A. e Melo and C. A. Canesin, Evaluation of the Main MPPT Techniques for Photovoltaic Applications, *IEEE Transactions on Industrial Electronics*, vol. 60, no. 3, 2013, pp. 1156-1167.doi: 10.1109/TIE.2012.2198036.

[24] Uzmus, H., Genc, N., & Celık, M. A., The Modified MPPT for PV System with Interleaved Hybrid DC-to-DC Boost Converter, *Electric Power Components and Systems*, Vol. 51(1),2023, PP. 46-58. https://doi.org/10.1080/15325008.2022.21595

88.
[25] Muzi, Francesco, and Luigi Passacantando, Improvements in power quality and efficiency with a new AC/DC high current converter, *WSEAS Transactions on Circuits and Systems*, Vol. 7, 2008, pp 338-347.
[26] Deepak Agrawal, Rajneesh Kumar Karn, Deepak Verma, Rakeshwri Agrawal, Modelling and Simulation of Integrated Topology of DC/DC converter for LED Driver Circuit, *WSEAS Transactions on Electronics*, vol. 11, pp. 18-21, 2020, https://doi.org/10.37394/232017.2020.11.3.
[27] G. Ch. Ioannidis, C. S. Psomopoulos, S. D. Kaminaris, P. Pachos, H. Villiotis, S. Tsiolis, P. Malatestas, G. A. Vokas, S. N. Manias, AC-DC & DC-DC Converters for DC Motor Drives, *WSEAS Transactions on Electronics*, vol. 12, pp. 155-162, 2021, https://doi.org/10.37394/232017.2021.12.20.
[28] Candidus U. Eya, Ayodeji Olalekan Salau, Sepiribo Lucky Braide, S. B. Goyal, Victor Adewale Owoeye, Oluwafunso Oluwole Osaloni, Assessment of Total Harmonic Distortion in Buck-Boost DC-AC Converters using Triangular Wave and Saw-Tooth based Unipolar Modulation Schemes, *WSEAS Transactions on Power Systems*, vol. 17, pp. 324-338, 2022, https://doi.org/10.37394/232016.2022.17.33.

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