Improved direct control of single stage photovoltaic powred system

Rahli Chouaib, Mehdi Ouada, Mebarek Abdesslam Ryad, Salah Saad
Laboratory of Electromechanical Systems, Department of Electromechanical Engineering, Faculty of Technology, Badji Mokhtar University, Annaba, Algeria

Article Info

Article history:

Received Apr 6, 2024
Revised Aug 17, 2024
Accepted Aug 26, 2024

Keywords:

Direct Control
MPPT
Optimization
Photovoltaic
Quasi-Zsi

ABSTRACT

This paper introduces a novel direct control quasi-Z-source inverter (qZSI) topology as a viable alternative to conventional two-stage converters in photovoltaic (PV) systems. The proposed control strategy effectively merges duty cycle and modulation index within a space vector pulse width modulation (SVPWM) framework for both DC and AC control. To assess the system's performance under diverse weather conditions, the INC and P&O maximum power point tracking maximum power point tracking (MPPT) algorithms are employed. Rigorous simulations conducted using MATLAB/Simulink demonstrate the proposed method's ability to achieve multi-objective optimization of PV systems, enhancing overall system efficiency and reliability.

Corresponding Author:

Mehdi Ouada
Laboratory of Electromechanical Systems, Department of Electromechanical
Faculty of Technology, Badji Mokhtar University
C. P. 23000. Annaba, Algeria
Email: mehdi.ouada@univ-annaba.dz

1. INTRODUCTION

The importance of sustainable energy has increased in recent times due to the depletion of the ozone layer and energy prices [1]. For these reasons and more, most developed countries have turned to renewable energy sources, which improve air quality, create jobs and reduce greenhouse gas emissions [2], [3]. Solar and wind power, two of the most popular sources of sustainable energy [4], [5] have had a significant impact on the growth of the industry by making renewable energy more affordable and competitive with traditional fuels. A complete switch to green energy is now possible thanks to the rapid growth of renewable energy sources, but there are still many hurdles to overcome [6], [7].

Photovoltaic (PV) conversion of solar energy stands out as one of the most effective and promising technologies [8]. Traditionally, PV systems have relied on a two-stage conversion process, incorporating both DC/DC and DC/AC stages. However, this approach presents challenges in terms of efficiency and system complexity.

The Z-source inverter (ZSI) has emerged as a compelling solution, offering a multi-objective optimization for PV systems [9]. This innovative technology allows for single-stage power conversion while simultaneously enabling maximum power point tracking (MPPT) control, thereby optimizing energy conversion. Furthermore, the ZSI contributes to improving the overall reliability of PV systems, addressing a critical concern in renewable energy deployment.

Current control strategies for ZSI in PV applications typically employ indirect methods, utilizing PI regulators to generate control signals [10]-[13]. While effective, there is room for improvement in terms of efficiency and responsiveness.

In a two-stage PV system, voltage source inverters (VSIs) are often used to boost the PV input voltage and DC to AC conversion. In the first stage, a DC-DC converter is used, usually incorporating a boost or boost-buck converter to transform the full DC power of the PV array into a higher or lower DC voltage. In the second stage, a VSI is used to convert the DC into AC [14], [15].

Despite their success, two-stage configurations have several drawbacks, such as lower efficiency due to higher conduction and switching losses, an increase in the number of devices required by the DC-DC converter, which in turn makes the two-stage inverter larger and more expensive, poor reliability, high costs and a large footprint. Similarly, the increase in voltage capacity of two-stage inverters is limited by the intermediate circuit voltage, making them less suitable for partial load [16].

The MPPT and conventional DC-AC distribution stages make maintenance more difficult. Combining the two energy transformation stages increases volume, weight and cost. Because of these major drawbacks, two-stage PV systems are not as efficient as the new single-stage topologies that combine MPPT and inverter functions simultaneously. New standards are accelerating the introduction of inverters by emphasizing high performance, reliability and small form factors over two-stage ideas. In recent years, researchers have increasingly focused on single-stage topologies [17]. One such topology is the ZSI, which uses a z-source impedance network to connect the inductor supply circuit to the PV source [18]. By reducing switching resources, reducing passive components, reducing costs and improving efficiency, these topologies can achieve both objectives mentioned. Extensive research has been carried out in recent years into various approaches to quasi-z source inverters (qZSI) management. Simple boost control, maximum boost control, constant maximum boost control and other approaches fall into this category. The SBC utilizes a constant shoot-through duty cycle, which allows for straightforward implementation but has restricted performance capabilities. The MBC continuously adapts the duty cycle to regulate the output voltage, whereas the MCBC tries to maximize the boost factor while keeping the input current constant [19], [20].

Space vector pulse width modulation (SVPWM) is a control technique employed for qZSI. The SVPWM approach is modified to suit the attributes of qZSIs. The SVPWM signal is produced by comparing a reference signal with a carrier signal, and the duty cycle of the SVPWM signal is modified to control the voltage and frequency of the inverter output [21]. In addition, a six-stage switching sequence is employed to smoothly transition the switching states during the active-duty periods of each phase. The SVPWM method is commonly employed in qZSI control because of its capacity to offer accurate control of output voltage and frequency, minimize harmonics for high-quality power generation, enable convenient voltage control in a computationally efficient manner suitable for digital implementation, and its overall simplicity and efficiency [22].

Direct control with duty cycle is a creative method that qZSI use to regulate output voltage and current independently, without the need for an intermediate circuit voltage control loop. Direct control is often used in applications where precise control of output voltage and frequency is required, such as renewable energy systems and motor control. Direct control can be achieved using different control strategies, such as PWM and hysteresis control. The choice of control strategy depends on the specific application and the desired performance characteristics of the inverter. Direct SVPWM control is a popular control method for the ZSI, as it allows precise control of the output voltage and frequency. The PWM signal is generated by comparing a reference signal with a carrier signal, and the duty cycle of the PWM signal is varied to control the output voltage and frequency of the inverter.

In this paper, we propose a multi-objective optimization approach for PV systems using a qZSI. Our method incorporates MPPT control with direct duty cycle control, aiming to enhance system performance and energy yield. This novel approach promises to advance the state-of-the-art in PV energy conversion, contributing to the broader goal of optimizing renewable energy sources for a sustainable future.

2. BACKGROUND

2.1. Modelling of PV generator

PV panels are technological equipment that facilitate the direct conversion of solar radiation energy into electrical energy. By absorbing photons from the sun, they can energise electrons and guide them into an electric circuit, where they produce a current and voltage. A current source, a diode, and series and parallel resistors constitute the electrical circuit that mimics the solar cell’s circuit.

The necessary current and voltage are generated by a solar generator, which consists of numerous panels linked in series and parallel. As shown in Figure 1, the current that is produced by the solar generator is given by:

$$I_{pv} = I_s - I_{sh} \quad (1)$$

$$I_s = I_{ph} - I_d \quad (2)$$

$$I_{sh} = \frac{V_{pv}+I_{pv}R_sN_{ss}}{R_pN_{ss}} \quad (3)$$

$$I_{ph} = (I_{ph,n} + K_I \Delta T)\frac{G}{G_n} \quad (4)$$

$$I_d = I_o\left(e^{\left(\frac{V_{pv}+I_{pv}R_sN_{ss}}{aV_tN_{ss}}\right)} - 1\right) \quad (5)$$

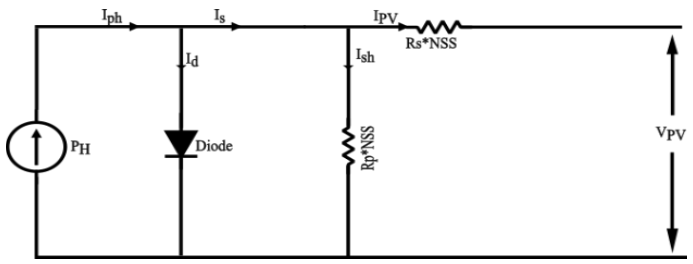
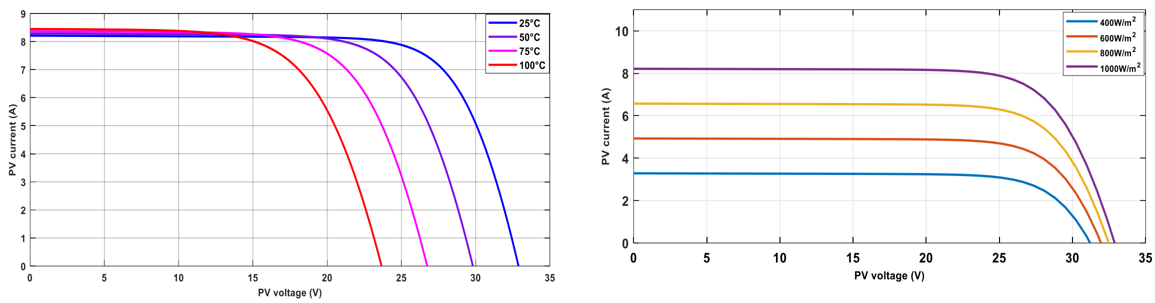


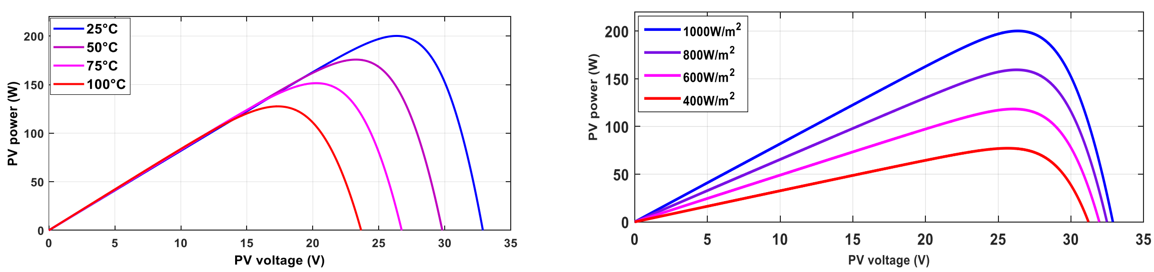
Figure 1. PV cell Simulink model

Where N_{ss} is the number of series-connected panels, R_s is the series resistance of the PV panel, and R_p is the parallel resistance. Temperature T and irradiation G determine the photocurrent I_{ph}. The nominal generated current, denoted as $I_{ph,n}$,is determined at STC with T = 25 °C and G = 1,000 W/m^2. The short-circuit current/temperature coefficient, denoted as K_I, is equal to $\Delta T = T - T_n$, where T and T_n are the current and nominal temperatures, respectively. G and G_n are the current and nominal irradiation. I_d is the current in where V_t is the PV array's thermal voltage, while I_o stands for the current that opposes saturated (Figure 2 and Figure 3).



(a) (b)

Figure 2. PVG characteristics curve with different temperature (a) curve P-V and (b) curve I-V



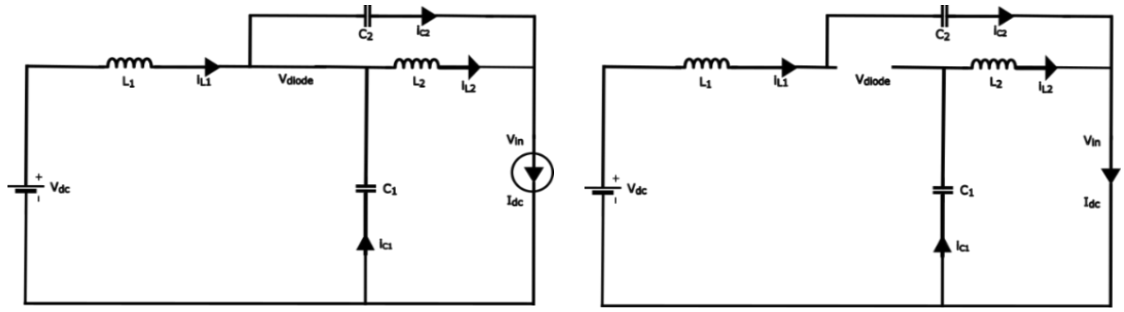
(a) (b)

Figure 3. PVG characteristics curve with different irradiation (a) curve P-V and (b) curve I-V

2.2. Operating mechanism of qZSI

A power inverter called a qZSI is a variation on the traditional Z-source that uses a capacitor-inductor network to link a solar module to the inverter. Two inductors and two capacitors linked in a quasi-Z topology constitute qZSI, which circumvent the voltage limiting issues that plague traditional VSI and CSI topologies. In a single power conversion stage, qZSIs can increase or decrease the AC output voltage relative to their DC input voltage using their Buck/Boost capabilities. The qZSI is a good choice due to its capability to purchase or increase DC voltage, as well as its high energy and short circuit immunity. Controlling the injection duty cycle allows the qZSI to follow the maximum power point.

The qZSI operates includes an additional ST state to increase the DC bus voltage, in addition to the two active states and six passive states that are typical of traditional converters' eight switching states. With six active vectors and two zero vectors (Figure 4). Figures 4(a) and 4(b) show the qZSI structure and its corresponding circuits, correspondingly [23], [24].



(a) (b)

Figure 4. The qZSI equivalent circuit in (a) ST condition and (b) non-ST condition

Here is the fundamental relationship for QZSI [25], [26]:

$$D = T_{sh}/T_s \tag{6}$$

$$T_{st} = T_s - T_{nsh} \tag{7}$$

In this case, D is the ST duty ratio and T_{nsh} denotes the time interval that is not in the ST state, T_{sh} denotes the time period that is in the ST state during a single control cycle Ts.

At constant state, the average voltage across Capacitors 1 and 2 can be described by two equations:

$$V_{c1} = \frac{T_{nsh}}{T_{nsh}-T_{sh}} V_{dc} = \frac{1-D}{1-2D} V_{dc} \tag{8}$$

$$V_{c2} = \frac{T_{sh}}{T_{nsh}-T_{sh}} V_{dc} = \frac{D}{1-2D} V_{dc} \tag{9}$$

the voltage across the inverter bridge's dc-link is,

$$V_{in} = V_{c1} + V_{c2} = \frac{1}{1-D} V_{dc} = B.V_{dc} \tag{10}$$

the peak,

$$V_{ph} = \frac{1}{2} M.V_{in} = \frac{1}{2} M.B.V_{dc} = \frac{1}{2} G.V_{dc} \tag{11}$$

where V_{ph} is the output peak phase and M is the modulation index, G is the voltage gain and B is the boost factor.

3. MPPT ALGORITHM

MPPT, or maximum power point tracking, optimizes the electrical working point of a PV module or array for optimal power production and power availability. Solar modules' optimal energy production is complexly linked to temperature and irradiation [27], [28]. MPPT algorithms optimize power production by monitoring and adapting to the most economical operating point, even when conditions change. Perturb and observe and incremental conductance are used to optimize PV energy extraction [29], [30].

3.1. Perturb and observe (P&O)

The P&O method periodically changes the PV panel/array's operating voltage and observes how it affects PV system power. This perturbation is caused by slowly adjusting the duty cycle of the power converter between the PV panel and load. Figure 5 illustrates the PV panel's MPP behaviours and operation principle. When the PV module's operating point is on the left side of the curve (ΔP/ΔV is positive), power output increases and duty cycle decrease towards MPP. When the module's operating point is on the right side of the curve (ΔP/ΔV is negative), the duty cycle rises to approach MPP [31]-[33].

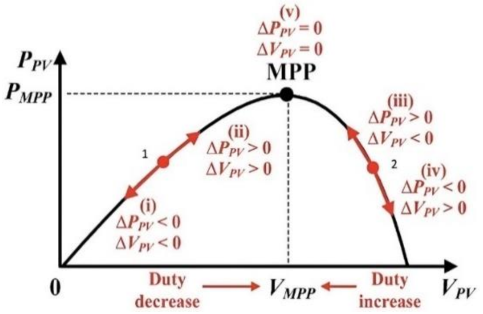


Figure 5. P&O MPPT behaviours

3.2. Incremental conductance

PV systems frequently employ the Incremental Conductance (IncCond) MPPT algorithm to maximize power extraction from solar panels. In order to find the slope of the power-voltage (P-V) curve, it continually compares the instantaneous conductance (I/V) to the incremental conductance (ΔI/ΔV). The program can find the maximum power point (MPP) by studying the relationship between these numbers and looking for the peak of the P-V curve. An economical and practical option for optimizing PV system power output, this technology is renowned for its high tracking accuracy and its capacity to respond to quickly changing environmental circumstances [34]-[37]. The expression can be represented as:

$$dI/dV = -I/V \ \textit{Condition} \text{ for achieving the MPP, } V = V_{mpp} \tag{12}$$

$$dI/dV > -I/V \text{ The operating point is to the left of the MPP, } V < V_{mpp} \tag{13}$$

$$dI/dV < -I/V \text{ The operating point is to the right of the MPP, } V > V_{mpp} \tag{14}$$

4. IMPROVED DSVPWM METHOD FOR PV SYSTEM CONTROL

The use of direct duty cycle control in power chain based on qZSI fed by PV generator (Figure 6), offering two key advantages. Firstly, it minimizes steady-state oscillations, leading to smoother power output. Secondly, it ensures faster tracking of the maximum power point (MPP) even under challenging environmental conditions (Figure 7), including partial shading and significant irradiance fluctuations, in other hand minimizing the number of static converters in the conversion chain increases the reliability and overall efficiency of this conversion chain.

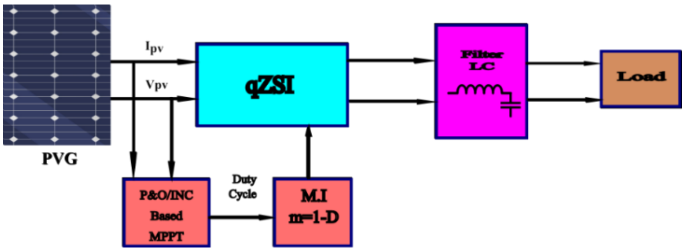


Figure 6. Diagram of the studied system

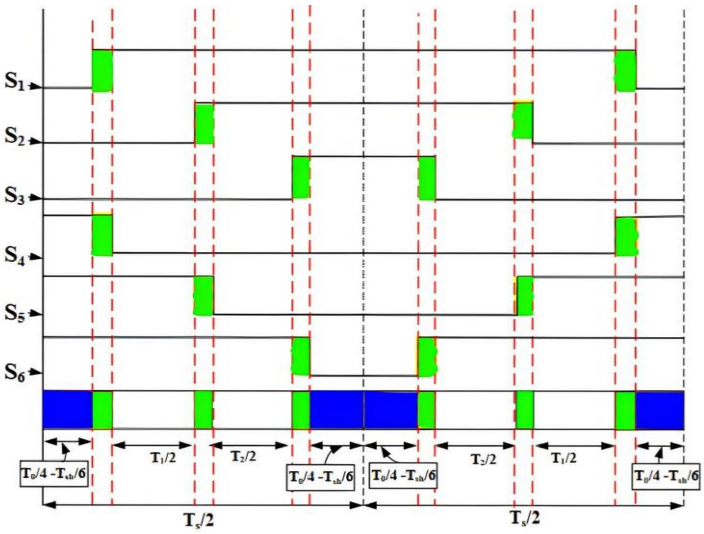


Figure 7. Switching sequence for D-ZSVPWM in sector 1

4.1. Model of the duty cycle control

Here, the using of I_{pv} and V_{pv} measurements to anticipate the MPP using the optimization procedures that have already been covered. Then, we use (15) and (16) to determine the cycle ratio, and we attack the qZSi directly using the following model [38].

The duty cycle control model is defined by:

$$\frac{d}{dt}[\Delta q_{dc}] = \underbrace{\begin{bmatrix} 0 & \frac{1}{1-D} \end{bmatrix}}_{B_{1dc}} \begin{bmatrix} \Delta i_{L2} \\ \Delta v_{C1} \end{bmatrix} + \underbrace{\begin{bmatrix} \frac{V_{dc,p}}{1-D} \end{bmatrix}}_{B_{2dc}} [\Delta d]$$
$$[\Delta d_r] = \underbrace{\begin{bmatrix} -k_p^L k_i^{dc} \end{bmatrix}}_{C_{dc}} [\Delta q_{dc}] + \underbrace{\begin{bmatrix} -k_p^L & \frac{k_p^L k_p^{dc}}{D-1} \end{bmatrix}}_{E_{1dc}} \begin{bmatrix} \Delta i_{L2} \\ \Delta v_{C1} \end{bmatrix} + \underbrace{\begin{bmatrix} \frac{k_p^L k_p^{dc}}{D-1} & V_{dc,p} \end{bmatrix}}_{E_{2dc}} [\Delta d] \quad (15)$$

where k_p^{dc} and k_i^{dc} denote the DC voltage controller's proportional and integral gains, respectively, and k_p^L denotes the inductor-L2 controller's proportional gain. The following traits define the SS LPF model:

$$\frac{d}{dt}[\Delta d] = \underbrace{[-\omega_c]}_{A_f} [\Delta d] + \underbrace{[\omega_c]}_{B_{1f}} [\Delta d_r][\Delta d] = \underbrace{[1]}_{C_f} [\Delta d] \quad (16)$$

the SSA model for duty cycle control can be expressed using (15) and (16), which are (17):

$$\frac{d}{dt}\begin{bmatrix} \Delta q_{dc} \\ \Delta d \end{bmatrix} = \underbrace{\begin{pmatrix} 0_{1x1} & B_{2dc} \\ B_{1f}C_{dc} & A_f + B_{1f}E_{2dc} \end{pmatrix}}_{B_{1d}} \begin{bmatrix} \Delta q_{dc} \\ \Delta d \end{bmatrix} + \underbrace{\begin{pmatrix} 0_{1x1} & B_{1dc} & 0_{1x1} \\ 0_{1x1} & B_{1f}E_{1dc} & 0_{1x1} \end{pmatrix}}_{B_{1d}} \begin{bmatrix} \Delta i_{L1} \\ \Delta i_{L2} \\ \Delta v_{C1} \\ \Delta v_{C2} \end{bmatrix}$$
$$[\Delta d] = \underbrace{(01)}_{C_d} \begin{bmatrix} \Delta q_{dc} \\ \Delta d \end{bmatrix} \quad (17)$$

5. RESULTS AND DISCUSSION

This work presents the development of a DSVPWM technique and evaluate its performance using INC and P&O algorithms for the qZSI single-stage system, which operates based on MPPT. The proposed system consists of a PV module with three parallel and nine series modules (Table 1), a qZSI, an LC filter, and a 10 Ω resistive load (Table 2). The solar module has a maximum power output of 200 W under standard operating conditions (STC), which involve an irradiation of 1,000 W/m^2 and a temperature of 25°C. We observe MPPT approaches across various situations, such as temperature fluctuations and varied levels of irradiance.

Table 1. PV module parameters KYOCERA KC200GT

PV parameters	Values
Maximum power (Pmax)	200.143W
Voltage at Pmax (Vmp)	26.3V
Current at Pmax (Imp)	7.61A
Open-circuit voltage (Voc)	32.9V
Short-circuit current (Isc)	8.21A

Table 2. Simulation parameters

qZSI parameters	Values
C=C1=C2	3 mF
L=L1=L2	5.37 mH
Cf	110 MF
Lf	0.5 mH
R	10

Figures 8 and 10 illustrate the scenarios of climate change irradiance and temperature, respectively. Tables 1 and 2 present the parameters of the PV module and the and qZSI simulation parameters simulation system parameters, respectively. Through MATLAB/Simulink system, the proposed DSVPWM its performance is evaluated using INC and P&O algorithms for the qZSI single-stage system for validation when temperature and irradiation varying.

Curves in Figures 9 and 11 show that the INC algorithm's maximum power reaches its steady state in 0.16 s, while the P&O algorithm's maximum power reaches its steady state in 0.21 s. This indicates that the INC system is slightly faster than the P&O, with a difference of 0.05 s. In addition, the INC algorithm demonstrated a higher level of stability and reduced volatility in comparison to the P&O algorithm, resulting in a more consistent power output over time.

Figures 9 and 11 show that the INC algorithm surpasses the P&O method in accurately tracking the MPP within the proposed system, an improvement in system stability and enhancement in time response. In contrast, it is evident that both power and coefficient of variation exhibit an upward trajectory with increasing irradiation. Conversely, with temperature, power shows an upward trend as temperature decreases.

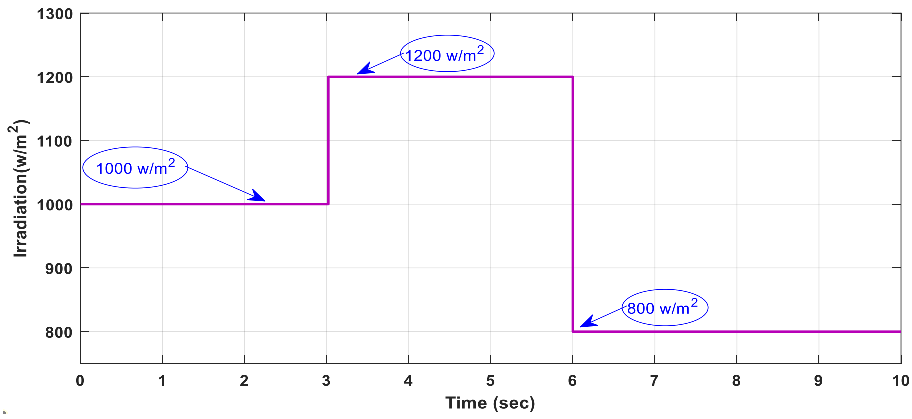


Figure 8. Diverse instances of solar irradiation

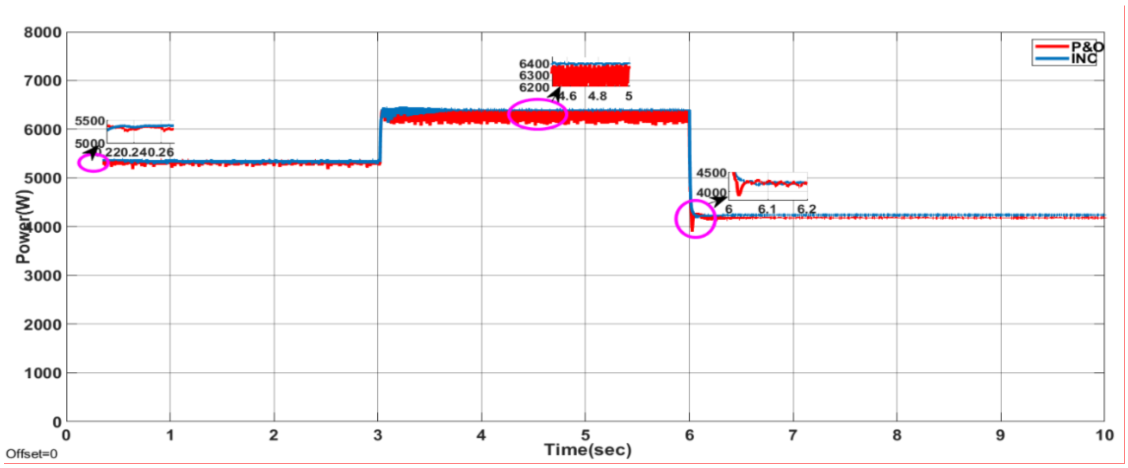


Figure 9. Evaluation of output power by comparing INC to P&O algorithms in the condition of irradiation variations

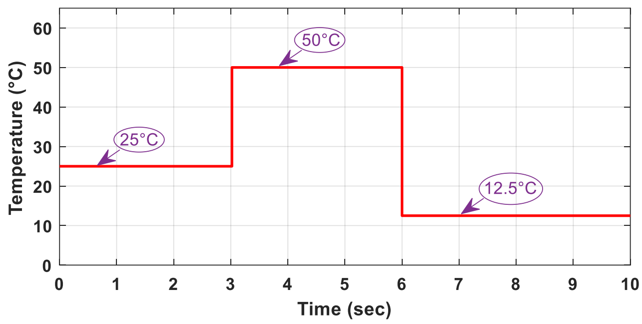


Figure 10. Diverse instances of temperature

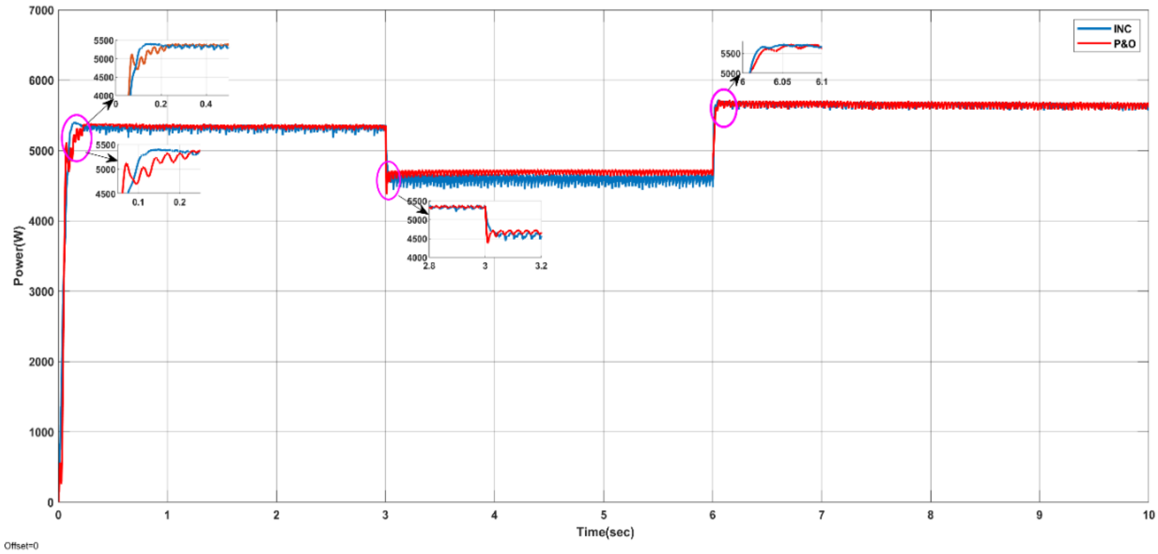


Figure 11. Evaluation of output power by comparing INC to P&O algorithms in the condition of temperature variations

The tracking performance of the proposed methodology under dynamic variations is assessed by applying rapidly changing irradiation levels (Figure 12) to the PV system using a qZSI, the simulation results show (Figurer 13) that the incremental MPPT algorithm is more stable and faster under these conditions, the incremental MPPT algorithm also demonstrates remarkable stability compared to the P&O algorithm, which exhibits significant oscillations around the maximum power point in steady-state conditions.

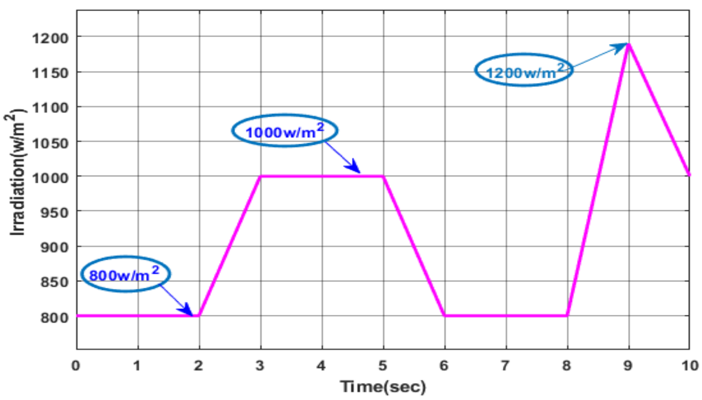


Figure 12. Second scenario of irradiation variation

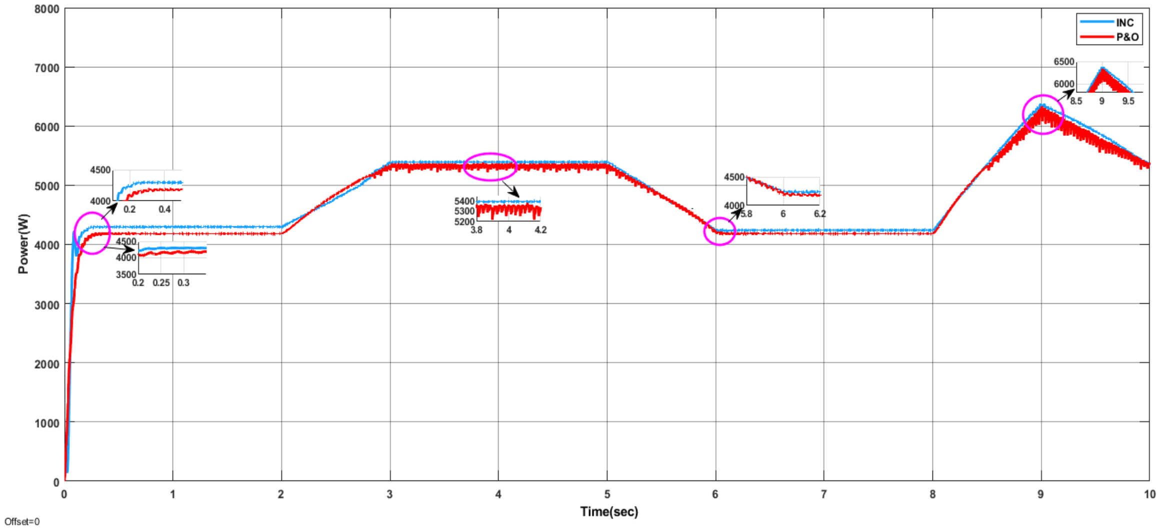


Figure 13. Response of the INC-P&O algorithm to fast irradiance change

6. CONCLUSION

This study introduces a novel control technique for qZSI using direct control of duty cycle based on space vector pulse width modulation (DSVPWM) and conducts a comparative analysis with two popular MPPT approaches INC and P&O. The DSVPWM control method, based on direct control of the duty cycle, accelerates the response time compared to traditional PI regulator-based control. The duty cycle produced by this method is derived from the combined MPPT and SVPWM techniques, ensuring efficient energy conversion and system performance. The results of this study highlight that the INC algorithm produces more consistent and faster results compared to P&O, particularly under rapidly changing climate conditions. This underscores the effectiveness of the INC algorithm in optimizing energy yield in PV systems.

By controlling the qZSI with the proposed DSVPWM control method, multi-objective optimization of PV systems was achieved, improving stability, eliminating the need for a PI controller, and ensuring operation at optimal power, this approach not only enhances the performance and reliability of PV systems but also contributes to the advancement of renewable energy technologies, promoting a more sustainable future. Future research could further explore optimization techniques and the application of this approach to other renewable energy sources.

ACKNOWLEDGEMENTS

The authors would like to thank the Algerian General Direction of Research (DGRSDT) for providing the facilities and the financial funding of this project.

REFERENCES

[1] A. M. Al-Falahat *et al.*, "Energy performance and economics assessments of a photovoltaic-heat pump system," *Results in Engineering*, vol. 13, p. 100324, Mar. 2022, doi: 10.1016/j.rineng.2021.100324.

[2] B. Talbi, F. Krim, T. Rekioua, S. Mekhilef, A. Laib, and A. Belaout, "A high-performance control scheme for photovoltaic pumping system under sudden irradiance and load changes," *Solar Energy*, vol. 159, pp. 353–368, Jan. 2018, doi: 10.1016/j.solener.2017.11.009.

[3] I. Attoui and A. Omeiri, "Fault diagnosis of an induction generator in a wind energy conversion system using signal processing techniques," *Electric Power Components and Systems*, vol. 43, no. 20, pp. 2262–2275, Dec. 2015, doi: 10.1080/15325008.2015.1082161.

[4] A. Bouraiou *et al.*, "Experimental investigation of observed defects in crystalline silicon PV modules under outdoor hot dry climatic conditions in Algeria," *Solar Energy*, vol. 159, pp. 475–487, Jan. 2018, doi: 10.1016/j.solener.2017.11.018.

[5] C. Rahli *et al.*, "PV systems operating in dynamic climatic circumstances using a PSO-based SMC and PID controller," in *2024 2nd International Conference on Electrical Engineering and Automatic Control, ICEEAC 2024*, May 2024, pp. 1–4, doi: 10.1109/ICEEAC61226.2024.10576441.

[6] N. Boutasseta, M. Ramdani, and S. Aouabdi, "Performance evaluation of photovoltaic arrays subject to a line-ground fault," in *2013 3rd International Conference on Systems and Control, ICSC 2013*, Oct. 2013, pp. 83–86, doi: 10.1109/ICoSC.2013.6750839.

[7] H. M. A. Alhussain and N. Yasin, "Modeling and simulation of solar PV module for comparison of two MPPT algorithms (P&O & INC) in MATLAB/Simulink," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 18, no. 2, pp. 666–677, May 2020, doi: 10.11591/ijeecs.v18.i2.pp666-677.

[8] M. Dada and P. Popoola, “Recent advances in solar photovoltaic materials and systems for energy storage applications: a review,” *Beni-Suef University Journal of Basic and Applied Sciences*, vol. 12, no. 1, p. 66, Jul. 2023, doi: 10.1186/s43088-023-00405-5.

[9] A. Bakeer, G. Magdy, A. Chub, and D. Vinnikov, “Predictive control based on ranking multi-objective optimization approach for quasi Z-source inverter,” *CSEE Journal of Power and Energy Systems*, vol. 7, no. 6, pp. 1152–1160, 2020, doi: 10.17775/CSEEJPES.2020.01310.

[10] J. Yuan, P. Liu, Y. P. Siwakoti, and F. Blaabjerg, “Z-source converters and their classifications,” in *Control of Power Electronic Converters and Systems: Volume 4*, vol. 4, Elsevier, 2024, pp. 3–25.

[11] R. G. Kumari, A. Ezhilarasi, and N. Pasula, “Control strategy for modified CI-based Bi-directional Γ-Z source DC-DC converter for buck-boost operation,” *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 13, no. 3, p. 1510, Sep. 2022, doi: 10.11591/ijpeds.v13.i3.pp1510-1518.

[12] B. Seif eddine and K. Djallel, “New Strategy Control of Bidirectional Quazi Z Source Inverter with Batteries and Supercapacitors Energy Storage in Grid Connected Photovoltaic System,” *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 8, no. 1, p. 335, Mar. 2017, doi: 10.11591/ijpeds.v8.i1.pp335-343.

[13] W. Anjum, S. Panda, and P. Ramasamy, “Design of semi-Z source inverter topology with reduced number switches for four quadrant control of direct current motor,” *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 13, no. 1, pp. 102–112, 2022, doi: 10.11591/ijpeds.v13.i1.pp102-112.

[14] A. Rashwan, A. Mikhaylov, M. Hemeida, G. Pinter, and D. S. Osheba, “Two-stage grid-connected inverter topology with high frequency link transformer for solar PV systems,” *Energy Reports*, vol. 10, pp. 1864–1874, Nov. 2023, doi: 10.1016/j.egyr.2023.08.037.

[15] M. Pokharel, A. Ghosh, and C. N. M. Ho, “Small-signal modelling and design validation of PV-controllers with INC-MPPT using CHIL,” *IEEE Transactions on Energy Conversion*, vol. 34, no. 1, pp. 361–371, Mar. 2019, doi: 10.1109/TEC.2018.2874563.

[16] A. Teta, A. Kouzou, M. M. Rezaoui, and A. Hafaifa, “Performance analysis of shoot through control approaches for Z-source inverters,” in *2019 4th International Conference on Power Electronics and their Applications (ICPEA)*, Sep. 2019, pp. 1–6, doi: 10.1109/ICPEA1.2019.8911152.

[17] N. Subhani, R. Kannan, A. Mahmud, and F. Blaabjerg, “Z-source inverter topologies with switched Z-impedance networks: a review,” *IET Power Electronics*, vol. 14, no. 4, pp. 727–750, Mar. 2021, doi: 10.1049/pel2.12064.

[18] Fang Zheng Peng, “Z-source inverter,” *IEEE Transactions on Industry Applications*, vol. 39, no. 2, pp. 504–510, Mar. 2003, doi: 10.1109/TIA.2003.808920.

[19] N. Saeed, A. Ibrar, and A. Saeed, “A review on industrial applications of Z-source inverter,” *Journal of Power and Energy Engineering*, vol. 05, no. 09, pp. 14–31, 2017, doi: 10.4236/jpee.2017.59002.

[20] S. Gan and W. Shi, “An improved Z-source inverter with high voltage boost ability,” *Electrical Engineering*, vol. 104, no. 2, pp. 869–881, Apr. 2022, doi: 10.1007/s00202-021-01342-1.

[21] Y. P. Siwakoti, F. Z. Peng, F. Blaabjerg, P. C. Loh, and G. E. Town, “Impedance-source networks for electric power conversion Part I: A topological review,” *IEEE Transactions on Power Electronics*, vol. 30, no. 2, pp. 699–716, Feb. 2015, doi: 10.1109/TPEL.2014.2313746.

[22] J. Zhang and R.-J. Wai, “Design of New SVPWM mechanism for three-level NPC ZSI via line-voltage coordinate system,” *IEEE Transactions on Power Electronics*, vol. 35, no. 8, pp. 8593–8606, Aug. 2020, doi: 10.1109/TPEL.2019.2961127.

[23] A. Gnanasaravanan, A. Jeyaprakash, J. J. Gnanachandran, A. P, R. A, and S. S, “Improved Series Z Source Inverter for PV System Using SVPWM Technique,” in *2021 5th International Conference on Trends in Electronics and Informatics (ICOEI)*, Jun. 2021, pp. 335–341, doi: 10.1109/ICOEI51242.2021.9453059.

[24] L. Monjo, L. Sainz, J. J. Mesas, and J. Pedra, “Quasi-z-source inverter-based photovoltaic power system modeling for grid stability studies,” *Energies*, vol. 14, no. 2, p. 508, Jan. 2021, doi: 10.3390/en14020508.

[25] Y. Liu, B. Ge, H. Abu-Rub, and F. Z. Peng, “An effective control method for quasi-Z-source cascade multilevel inverter-based grid-tie single-phase photovoltaic power system,” *IEEE Transactions on Industrial Informatics*, vol. 10, no. 1, pp. 399–407, Feb. 2014, doi: 10.1109/TII.2013.2280083.

[26] N. Sabeur, S. Mekhilef, and A. Masaoud, “A simplified time-domain modulation scheme-based maximum boost control for three-phase quasi-Z source inverters,” *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 6, no. 2, pp. 760–769, Jun. 2018, doi: 10.1109/JESTPE.2017.2763974.

[27] H. Chen, Y. Cui, Y. Zhao, and Z. Wang, “Comparison of P&O and INC methods in maximum power point tracker for PV systems,” *IOP Conference Series: Materials Science and Engineering*, vol. 322, no. 7, p. 072029, Mar. 2018, doi: 10.1088/1757-899X/322/7/072029.

[28] M. Errouha, S. Motahhir, Q. Combe, and A. Derouich, “Parameters extraction of single diode PV model and application in solar pumping,” in *Lecture Notes in Mechanical Engineering*, 2021, pp. 178–191.

[29] R. John, S. S. Mohammed, and R. Zachariah, “Variable step size Perturb and observe MPPT algorithm for standalone solar photovoltaic system,” in *2017 IEEE International Conference on Intelligent Techniques in Control, Optimization and Signal Processing (INCOS)*, Mar. 2017, vol. 2018-Febru, pp. 1–6, doi: 10.1109/ITCOSP.2017.8303163.

[30] M. T. Chuang, Y. H. Liu, and S. P. Ye, “A novel variable step size incremental conductance method with an adaptive scaling factor,” *Applied Sciences (Switzerland)*, vol. 10, no. 15, p. 5214, Jul. 2020, doi: 10.3390/app10155214.

[31] J. Mishra, S. Das, D. Kumar, and M. Pattnaik, “Performance Comparison of P&O and INC MPPT algorithm for a stand-alone PV system,” in *2019 Innovations in Power and Advanced Computing Technologies (i-PACT)*, Mar. 2019, pp. 1–5, doi: 10.1109/i-PACT44901.2019.8960005.

[32] P. T. szemes and M. Melhem, “Analyzing and modeling PV with ‘P&O’ MPPT algorithm by MATLAB/SIMULINK,” in *2020 3rd International Symposium on Small-scale Intelligent Manufacturing Systems (SIMS)*, Jun. 2020, pp. 1–6, doi: 10.1109/SIMS49386.2020.9121579.

[33] H. H. H. Mousa, A. R. Youssef, I. Hamdan, M. Ahamed, and E. E. M. Mohamed, “Performance assessment of robust PO algorithm using optimal hypothetical position of generator speed,” *IEEE Access*, vol. 9, pp. 30469–30485, 2021, doi: 10.1109/ACCESS.2021.3059884.

[34] L. Shang, H. Guo, and W. Zhu, “An improved MPPT control strategy based on incremental conductance algorithm,” *Protection and Control of Modern Power Systems*, vol. 5, no. 1, p. 14, Dec. 2020, doi: 10.1186/s41601-020-00161-z.

[35] D. A. Asoh, B. D. Noumsi, and E. N. Mbinkar, “Maximum Power point tracking using the incremental conductance algorithm for PV systems operating in rapidly changing environmental conditions,” *Smart Grid and Renewable Energy*, vol. 13, no. 05, pp. 89–108, 2022, doi: 10.4236/sgre.2022.135006.

[36] P. K. Mishra and P. Tiwari, "Incremental conductance MPPT in grid connected PV system," *International Journal of Engineering, Science and Technology*, vol. 13, no. 1, pp. 138–145, Jul. 2021, doi: 10.4314/ijest.v13i1.21s.
[37] M. Moutchou and A. Jbari, "Fast photovoltaic IncCond-MPPT and backstepping control, using DC-DC boost converter," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 10, no. 1, pp. 1101–1112, Feb. 2020, doi: 10.11591/ijece.v10i1.pp1101-1112.
[38] L. Monjo, L. Sainz, J. J. Mesas, and J. Pedra, "State-space model of quasi-z-source inverter-PV systems for transient dynamics studies and network stability assessment," *Energies*, vol. 14, no. 14, p. 4150, Jul. 2021, doi: 10.3390/en14144150.

BIOGRAPHIES OF AUTHORS

Rahli Chouaib received the B.Sc. and M.Sc. degrees from the University Badji Mokhtar-Annaba, Algeria, in 2015 and 2017, respectively, in automation and industrial computing. He is currently pursuing a Ph.D. in mechatronics at the Department of Electromechanics at the University Badji Mokhtar-Annaba. His research focuses on renewable energies. He can be contacted at email: chouaib.rahli@univ-annaba.org.

Mehdi Ouada earned his Ph.D. in Electromechanical Engineering from Badji Mokhtar Annaba University in 2017. He currently serves as a Lecturer in Electromechanical Engineering at the same university, where he is also a member of the LSELM Laboratory. His research interests lie in the areas of power system modeling and control design. He can be contacted at email: mehdi.ouada@univ-annaba.dz.

Mebarek Abdessalem Ryad received the B.Sc. and M.Sc. Degrees from the University Badji Mokhtar-Annaba, Algeria, in 2015 and 2017, respectively, in Electromechanics. He is currently pursuing a Ph.D. in Electromechanics at the Department of Electromechanics at the University Badji Mokhtar-Annaba. His research focuses on harmonic identification based on advanced methods for shunt active filters. He can be contacted at email: abdessalam-ryad.mebarek@univ-annaba.org.

Salah Saad received a Ph.D. degree from Nottingham University UK in 1988. Since 1988, he worked as a lecturer, senior lecturer then professor at Badji Mokhtar Annaba University Algeria. He has conducted many research projects in power electronics applications, electrical AC and DC drives as well as diagnosis and fault detection in AC machines and vibration sensors. His research interests are mainly in power electronics such as harmonics elimination by active filters, PWM and Space vector modulation control, multilevel inverters, and new converter topologies. He has authored and co-authored many journal and conference papers. He can be contacted at email: saadsalah2006@yahoo.fr.