Sensorless Maximum Power Point Control for Single-stage Grid Connected PV Systems

Mokhtar Abbassi
LISI Laboratory, University of Carthage Tunis, Tunisia
mok98474304@gmail.com

Abdelkarim Aouiti
LISI Laboratory University of Carthage Tunis, Tunisia
abdelkarim.aouiti.ensit@gmail.com

Faouzi Bacha
Electrical Engineering department, University of Tunis, Tunisia
faouzi.bacha@esstt.rnu.tn (corresponding author)

Received: 18 November 2023 | Revised: 3 January 2024 and 8 January 2024 | Accepted: 9 January 2024

Licensed under a CC-BY 4.0 license | Copyright (c) by the authors | DOI: https://doi.org/10.48084/etasr.6642

ABSTRACT

In this paper, a novel approach for implementing the maximum power point that could be generated from a photovoltaic (PV) panel while eliminating the need for current sensors through the application of the Hill Climbing algorithm is proposed. The active power generated by the PV panel is injected into the grid via a three-phase inverter using voltage-oriented voltage control with Spatial Vector Modulation (SVM). The developed strategy ensures minimal ripples for both active and reactive power and produces a sinusoidal alternating current waveform, even under varying lighting conditions. A comprehensive description of the adopted control strategy is provided and validated through numerical simulations conducted in MATLAB/Simulink environment. Furthermore, the performance of the proposed method is assessed by analyzing the simulation results. In an attempt to validate the effectiveness of the proposed approach, an implementation of the inverter control was conducted with the DSpace 1104 board, and the results underscored the feasibility and effectiveness of the employed approach for grid-connected PV systems.

Keywords-MPPT; photovoltaic; VOC; SVM

I. INTRODUCTION

During the recent decades, significant attention and focus have been directed towards the operation of three-phase bidirectional converters employing Pulse-Width Modulation (PWM). These converters have undergone rapid evolution, and have become attractive solutions for various industrial applications. Their key benefits include bidirectional power flow capabilities, decoupled power control, and the ability to maintain low level harmonic current distortions [1]. Numerous efforts have been undertaken and various control strategies have been employed to achieve low current distortion and stable switching frequencies [1]. Two predominant converter control strategies have emerged, namely the Direct Power Control (DPC) [2-4] and the Voltage-Oriented Control (VOC) [1]. DPC topologies often result in significant switching frequency variation with active and reactive power changes. In an effort to enhance these strategies, Model Predictive Control (MPC) [5] has been employed, effectively reducing harmonic distortions in grid-side currents. However, MPC demands a relatively high sampling frequency to achieve optimal performance, incurring substantial computational costs and, consequently, requiring expensive DSP or FPGA hardware. These drawbacks are evident in discrete control approaches such as DPC for converter control [5]. The control method relies on a predefined switching table, where selection is made to minimize errors between the output and its reference. This minimization process aims to reduce discrepancies between the control references and the actual instantaneous active and reactive power values in the case of DPC. One of the most mature and widely recognized control strategies for PWM converters is VOC [6-8], where electrical grid currents are decomposed into direct and quadrature components in the dq plane. According to [9], the VOC strategy ensures swift transient response and high static performance through internal current control loops.

Solar energy, owing to its relatively low maintenance and installation costs, has emerged as a promising resource in energy systems [10, 11], and rapidly became a significant component of the energy balance. This technology harnesses the sun as a primary energy source, meaning that the energy supplied by PVs depends on the irradiance and ambient temperature. The PV current-voltage characteristics are typically represented by nonlinear equations that lack analytical solutions. These numerous climate-related variations necessitate the use of algorithms to track the maximum power generated by the PV generators. The two most commonly used configurations in a grid-connected PV system are the single-stage and the two-stage configurations. The presence of multiple energy conversion stages impacts the overall efficiency, reliability, and cost of the system [12]. Single-stage energy conversion offers several advantages, including basic configuration, high overall efficiency, minimized cost, and compact weight. However, a control method must be developed in extent to ensure that maximum available energy can be efficiently extracted and transmitted from the PV generator to the grid.

To harness the maximum power from PV panels, robust and fast Maximum Power Point Tracking (MPPT) techniques have become of great importance in the operation of all PV systems. Many approaches and techniques have been proposed to track the Maximum Power Point (MPP). Conventional strategies, such as the Perturb and Observe (P&O) algorithm, Incremental Conductance (IC), Hill Climbing (HC) algorithm, and advanced methods like Particle Swarm Optimization (PSO), adaptive control, fuzzy logic controllers, and hybrid methods, combining classical and intelligent algorithms, have been explored. Authors in [13] introduced a P&O method for a converter connected to a PV system, whereas in [14], an IC controller for a two-stage grid-connected PV system was developed. These methods are straightforward and easy to implement. However, the obtained results showed that these approaches exhibit oscillations, which diminish the efficiency and stability of the system under steady-state conditions, in addition to requiring the use of two measuring devices, thereby increasing the costs of the proposed controllers. Methods based on fuzzy logic, sliding mode approaches, predictive techniques, adaptive strategies, and other techniques have garnered the attention of numerous researchers. In [15], the authors developed a neural network algorithm for the Single-Stage Grid-Connected PV (SSGC-PV) system. The functions are heavily depended on experimentation and subsequently exert a significant influence on control performance. Adaptive control [16] and backstepping and terminal sliding mode [10] have also been employed for MPPT control in a PV systems. While these approaches demonstrate improved performance in various weather conditions, their complexity, slow dynamics, and lower efficiency in poorly defined conditions are major challenges. In [17], a predictive method was proposed for MPPT tracking, revealing high efficiency under various disturbance conditions. However, its fundamental issue lies in the computational load, resulting in significantly higher computation requirements and longer processing times.

Optimized MPPT techniques based on metaheuristic algorithms such as PSO [18] and an Adaptive Neuro Fuzzy Inference System (ANFIS) [19] for PV system control have also been introduced. Simulations and experimental outcomes have demonstrated extremely rapid MPPT for sudden changes in irradiance, with minimized steady-state oscillations. However, these methods require highly powerful processors to perform the computations.

This paper introduces a novel sensorless MPPT control strategy based on the line current in the rotating frame. Voltage-oriented control has been achieved through a fixed switching frequency and it has been combined with a space vector modulation. The performance of the proposed VOC-SVM control has been tested under varying irradiance conditions through simulation and experimental tests.

II. PROPOSED SYSTEM CONTROL

A. Inverter Control

The VOC control strategy involves two coordinate system transformations. The first transformation is performed in the fixed (α,β) axis, and the second is carried out in the rotating (d,q) system. The goal of these transformations is to align the current vectors with the voltage vectors. This method provides the decoupling of the current vector components, ensuring a network current with no Total Harmonic Distortion (THD) and the injection of reactive power into the network through the i_q current component. The VOC control comprises two control loops, with one loop focused on the current (internal loop), while the second loop is applied to voltage (external loop). A limitation of this approach is the variable-frequency switching of IGBTs. To overcome this limitation, the application of SVM is used to establish a constant switching frequency [20]. In the subsequent sections of this paper, it is assumed that the filter's resistance is negligible. In the case of a balanced three-phase system without a neutral conductor, the equation governing the voltages and currents of the controlled converter are expressed by:

$$\begin{bmatrix} L\frac{di_a}{dt} \\ L\frac{di_b}{dt} \\ L\frac{di_c}{dt} \end{bmatrix} = \begin{bmatrix} -R_g & 0 & 0 \\ 0 & -R_g & 0 \\ 0 & 0 & -R_g \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} v_{ga} - v_a \\ v_{gb} - v_b \\ v_{gc} - v_c \end{bmatrix} \quad (1)$$

The three-phase quantities in a balanced system in abc coordinates, defined as $y_{a.b.c}$. can also be transformed into the stationary αβ coordinates using the transformation matrix provided by (2)

$$\begin{bmatrix} y_\alpha \\ y_\beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} y_a \\ y_b \\ y_c \end{bmatrix} \quad (2)$$

The transformation of (2) from αβ to dq is given by:

$$\begin{bmatrix} y_d \\ y_q \end{bmatrix} = \begin{bmatrix} \cos\omega t & \sin\omega t \\ -\sin\omega t & \cos\omega t \end{bmatrix} \begin{bmatrix} y_\alpha \\ y_\beta \end{bmatrix} \quad (3)$$

In Figure 1, the voltage-oriented control diagram based on virtual flux is depicted, illustrating the coordinate system transformations (αβ to dq) and the application of SVM to maintain a constant switching frequency.

The transformation of voltage equations into the rotating (dq) Park coordinate system leads to the following system of equations:

$$\begin{bmatrix} c_{gd} \\ c_{gq} \end{bmatrix} = \begin{cases} L\frac{di_d}{dt} + \omega L i_q + v_{cd} \\ L\frac{di_q}{dt} + \omega L i_q + v_{cq} \end{cases} \quad (4)$$

Equation (5) governs the powers in the rotating reference frame for a balanced system. The power generated by the PV converter is synchronized with the electrical grid through the use of Phase-Locked Loop (PLL) control.

$$\begin{bmatrix} p_{gd} \\ q_{gq} \end{bmatrix} = \begin{cases} \frac{3}{2}\left(v_{gd} i_{gd} - v_{gq} i_{gq}\right) \\ \frac{3}{2}\left(v_{gd} i_{gq} - v_{gq} i_{gd}\right) \end{cases} \quad (5)$$

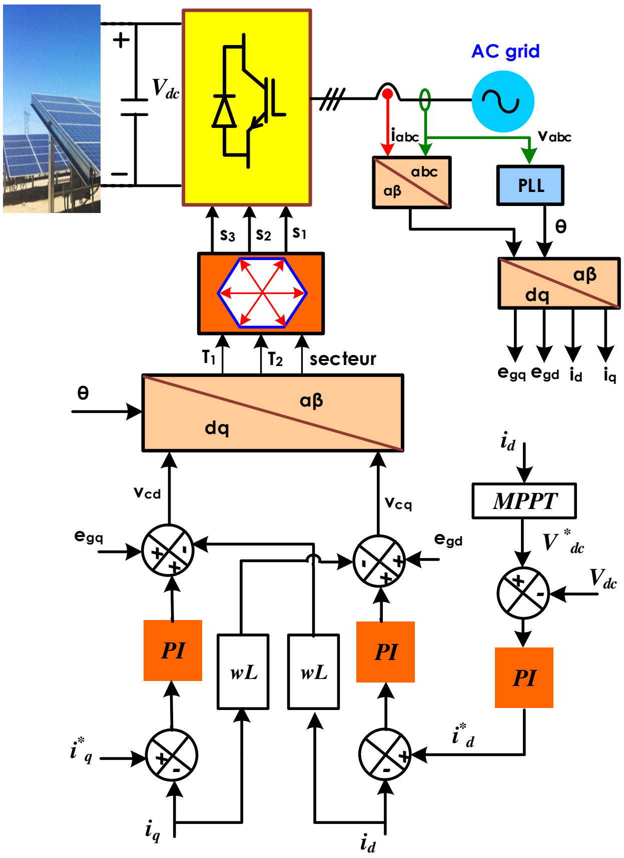


Fig. 1. Voltage-oriented control diagram based on virtual flux.

B. MPPT Control

The Hill Climbing algorithm is employed to adjust the i_d current, shifting the operating point along the PV generator's characteristic curve, within a predefined maximum limit. The search process persists until the maximum current point is reached or closely approached. This approach has gained popularity among manufacturers for its simplicity and avoidance of complex calculations. Additionally, it enables the switch of the measurement sensor from the DC current to the line current in the rotating frame (i_d), resulting in benefits such as simplicity, speed, reliability, and cost reduction. Figure 2 displays the proposed MPPT algorithm control.

III. DISCUSSION OF EXPERIMENTAL AND SIMULATION RESULTS

Experimental validation of the novel approach and the performance of the proposed control were tested utilizing the DSpace 1104 board. Simulation analysis was conducted in MATLAB/Simulink for the single-stage grid-connected PV generator under various irradiance variations. The simulation block diagram of the control block is portrayed in Figure 3. It is mainly composed of the MPPT algorithm block that guarantees maximum power tracking and generates the corresponding reference voltage from the measured current i_d, from the external control to provide the reference current in the d-axis, and from two internal current control blocks to have the inverter control voltages V_d and V_q. Fixed frequency control is carried out by the SVM block. The currents and voltages in the dq-axis and the locking loop are obtained by transformation blocks from the voltages and currents measured at the electrical grid. Tables I and II provide the simulation and practical validation parameters.

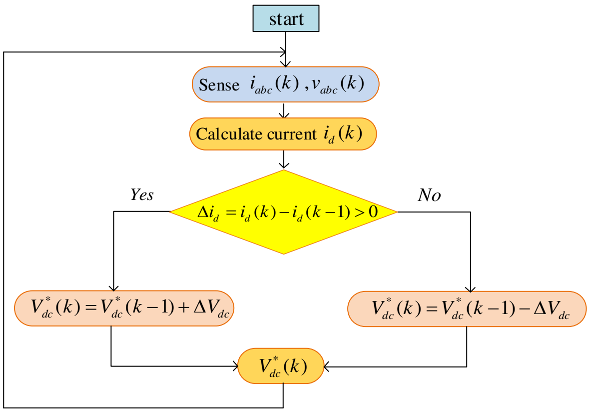


Fig. 2. The proposed MPPT algorithm.

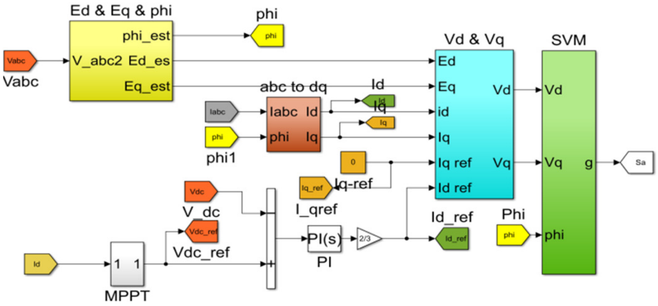


Fig. 3. Simulink model of the proposed control approach.

TABLE I. SIMULATION AND PRACTICAL VALIDATION PARAMETERS

Designation	Simulation	Experimentation
RMS Line to Line voltage	220 V - 50 Hz	220 V - 50 Hz
Line inductors *L*	12 mH	12 mH
DC bus Capacitor: *C*	1100 μF	1100 μF
K_p (outer loop)	0.2	0.2
K_i (outer loop)	10 s^{-1}	10 s^{-1}
K_{pd} (inner loop)	0.2	0.2
K_{id} (inner loop)	10 s^{-1}	10 s^{-1}
K_{pq} (inner loop)	0.2	0.2
K_{iq} (inner loop)	10 s^{-1}	10 s^{-1}
Sampling time T_s / Ode	10 μs (Fixed step)	70 μs (Fixed step)
DC bus voltage	325 V	325 V
Switching frequency	5 KHz	5 KHz

TABLE II. PV PANEL PARAMETERS

Designations	**Values**
Module type	ENN solar Energiy EST-110
Maximum power generated by PV	109.2 W
PV voltage *Voc*	138 V

The initial scenario aims to evaluate the performance of the MPPT algorithm control strategy within a single-stage grid-connected PV system. This section encompasses a comprehensive array of practical and numerical simulation results for the monitoring and tracking of the MPP of the PV generator and the power injected into the grid. Figure 4 shows the irradiance scenario, while Figure 5 depicts the results.

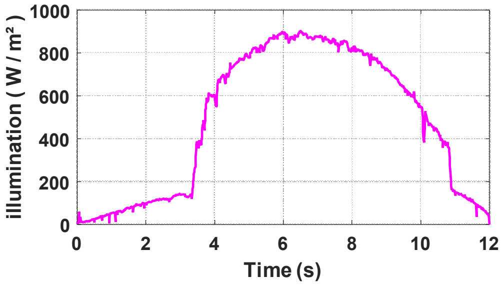
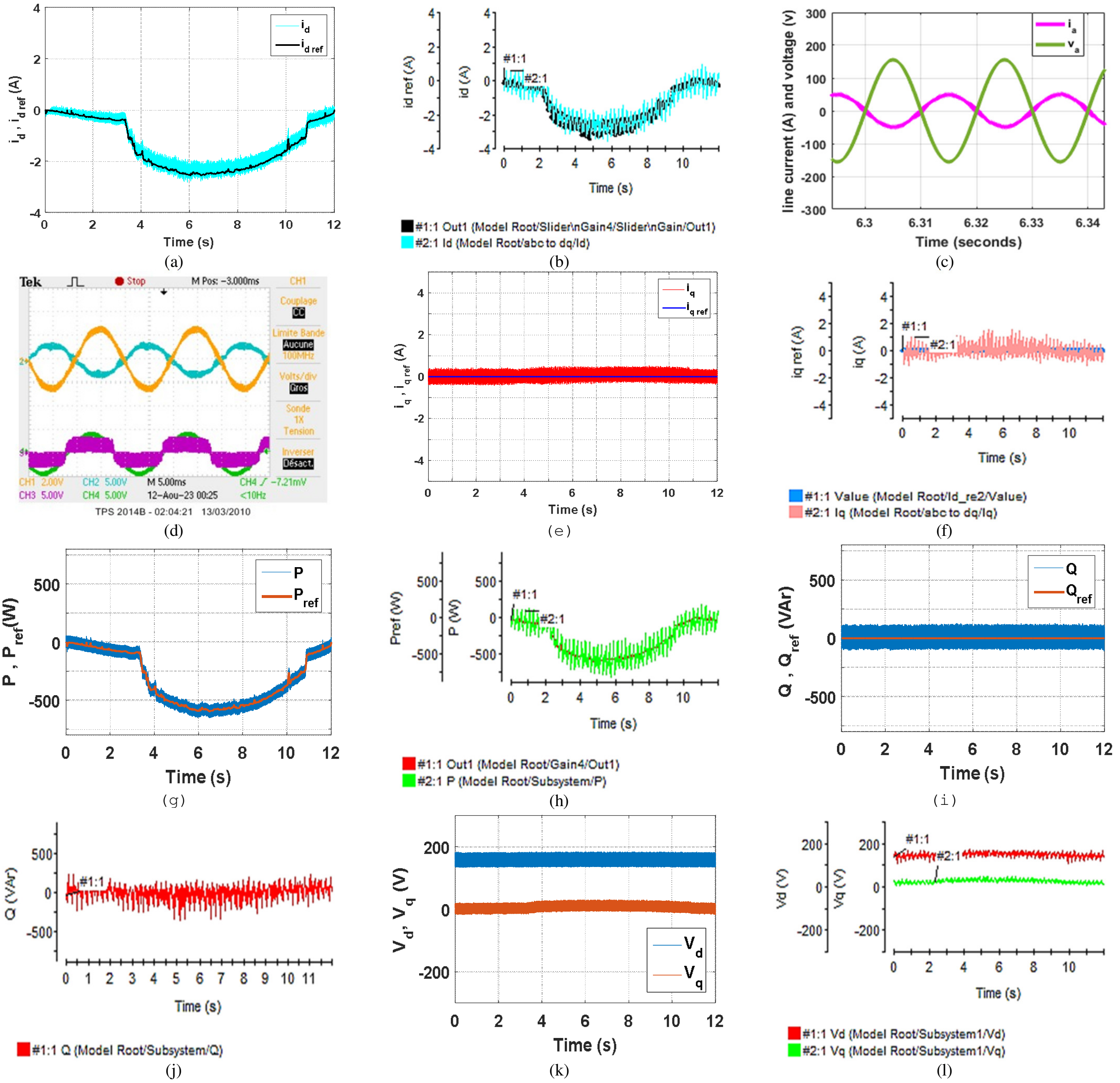


Fig. 4. Irradiance scenario.



(a) (b) (c)

(d) (e) (f)

(g) (h) (i)

(j) (k) (l)

Fig. 5. Simulation and experimental results.

Figures 5 (a) and (b) showcase the inner current loop performance for the d-axis current. The i_d current accurately follows its reference, which is generated by the PV panels, whether in the simulation results or in the practical validation. In Figures 5 (c) and (d), it can be observed that the current injected into the electrical grid exhibits a sinusoidal form with minimal distortion. The internal controller is responsible for maintaining the q-axis current at an average value of zero during variations in the irradiance, as depicted in the simulation and experimental result illustrated in Figures 5 (e) and (f). Figures 5 (g) and (h) depict the variations in the active power injected into the grid for simulation and experimental tests, respectively. It can be seen that the injected power closely tracks its reference value with negligible error across the entire range of irradiance variations. This strongly implies that the Hill Climbing algorithm is very effective and underlines the sensorless MPPT control system's rapid response. The reactive power response can be evaluated through Figures 5 (i) and (j), where the defined values of reactive power remain close to their reference. This implies that the PV system generates an electrical energy with an important power factor. Figures 5 (k) and (l) evidently showcase that the SVM control parameters are pristine. In fact, V_q maintains a null value and exhibits no harmonics, resulting in a notably efficient control of the system. Table III offers a comparison between the method proposed in [10] and the approach employed in this paper.

TABLE III. COMPARISON TABLE

Evaluated parameters	**Proposed method**	**[10]**
Convergence ability to the MPP	Medium	High
Efficiency of MPPT (%)	95 to 99.50	99.33
Control variable	Voltage	Duty cycle
Required sensors	Estimated	1 current sensor 1 Voltage sensor
Control strategy	Sampling method	Intelligent control based on FLC
Algorithm complexity	Low	High
Overall system performance (%)	96	93

IV. CONCLUSION

This paper describes a voltage-oriented control of a three-phase grid-connected photovoltaic inverter, based on a sensorless maximum power point tracking strategy. The main objective of the control system is to obtain the maximum power from the photovoltaic panel and to regulate the bus voltage to the desired reference value, employing a MPPT algorithm, while guaranteeing sinusoidal current injection into the network for active and reactive power injection scenarios. The newly introduced strategies were synthesized and evaluated via the Matlab environment and the DSpace 1104 platform. Moreover, the implemented control system exhibits excellent performance in stable and transient scenarios at low cost. In conclusion, the proposed control method aims to decrease the number of sensors, improve system efficiency, reduce cost, and lighten the weight of the system while minimizing CPU-level computation.

REFERENCES

[1] J. Y. Lee, R. Verayiah, K. H. Ong, A. Ramasamy, and M. B. Marsadek, "Voltage Oriented Control and Direct Power Control Strategies in solving under and overvoltage conditions for heavy load application on Malaysian Distribution Representative Network," *Electrical Engineering*, vol. 103, no. 3, pp. 1597–1612, Jun. 2021, https://doi.org/10.1007/s00202-020-01143-y.

[2] B. Bouaziz and F. Bacha, "Direct power control of grid-connected converters using sliding mode controller," in *2013 International Conference on Electrical Engineering and Software Applications*, Hammamet, Tunisia, Mar. 2013, pp. 1–6, https://doi.org/10.1109/ICEESA.2013.6578497.

[3] K. Sayahi, A. Kadri, F. Bacha, and H. Marzougui, "Implementation of a D-STATCOM control strategy based on direct power control method for grid connected wind turbine," *International Journal of Electrical Power & Energy Systems*, vol. 121, Oct. 2020, Art. no. 106105, https://doi.org/10.1016/j.ijepes.2020.106105.

[4] F. Tlili, A. Kadri, and F. Bacha, "Advanced control strategy for bidirectional three phase AC/DC converter," *Electric Power Systems Research*, vol. 179, Feb. 2020, Art. no. 106078, https://doi.org/10.1016/j.epsr.2019.106078.

[5] M. Easley, M. B. Shadmand, and H. Abu-Rub, "Hierarchical Model Predictive Control of Grid-Connected Cascaded Multilevel Inverter," *Journal of Emerging and Selected Topics in Power Electronics*, vol. 9, no. 3, pp. 3137-3149, Jun. 2021, https://doi.org/10.1109/JESTPE.2020.3015128.

[6] A. Soyed, A. Kadri, O. Hasnaoui, and F. Bacha, "Direct Power and Voltage Oriented Control Strategies of Grid-Connected Wind Energy Conversion System Based on Permanent Magnet Synchronous Generator," *Cybernetics and Systems*, vol. 53, no. 1, pp. 103–125, Jan. 2022, https://doi.org/10.1080/01969722.2021.2008684.

[7] M. Baazouzi, K. Sayahi, and F. Bacha, "Control strategy used for AC fault ride-through in VSC–HVDC transmission systems," *IEEE Transactions of the Institute of Measurement and Control*, Jun. 2023, Art. no. 01423312231180546, https://doi.org/10.1177/01423312231180546.

[8] M. N. Tasnim *et al.*, "Voltage-Oriented Control-Based Three-Phase, Three-Leg Bidirectional AC–DC Converter with Improved Power Quality for Microgrids," *Energies*, vol. 16, no. 17, Jan. 2023, Art. no. 6188, https://doi.org/10.3390/en16176188.

[9] R. Kadri, J. -P. Gaubert, and G. Champenois, "An Improved Maximum Power Point Tracking for Photovoltaic Grid-Connected Inverter Based on Voltage-Oriented Control," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 1, pp. 66-75, Jan. 2011, https://doi.org/10.1109/TIE.2010.2044733.

[10] F. Z. Kebbab, L. Sabah, and H. Nouri, "A Comparative Analysis of MPPT Techniques for Grid Connected PVs," *Engineering, Technology & Applied Science Research*, vol. 12, no. 2, pp. 8228–8235, Apr. 2022, https://doi.org/10.48084/etasr.4704.

[11] K. Behih and H. Attoui, "Backstepping Terminal Sliding Mode MPPT Controller for Photovoltaic Systems," *Engineering, Technology & Applied Science Research*, vol. 11, no. 2, pp. 7060–7067, Apr. 2021, https://doi.org/10.48084/etasr.4101.

[12] W. Libo, Z. Zhengming, and L. Jianzheng, "A Single-Stage Three-Phase Grid-Connected Photovoltaic System With Modified MPPT Method and Reactive Power Compensation," *IEEE Transactions on Energy Conversion*, vol. 22, no. 4, pp. 881–886, Sep. 2007, https://doi.org/10.1109/TEC.2007.895461.

[13] A. A. H. AlZubaidi, L. A. Khaliq, H. S. Hamad, W. K. Al-Azzawi, M. S. Jabbar, and T. A. Shihab, "MPPT implementation and simulation using developed P&O algorithm for photovoltaic system concerning efficiency," *Bulletin of Electrical Engineering and Informatics*, vol. 11, no. 5, pp. 2460–2470, Oct. 2022, https://doi.org/10.11591/eei.v11i5.3949.

[14] R. I. Putri, S. Wibowo, and M. Rifa'i, "Maximum Power Point Tracking for Photovoltaic Using Incremental Conductance Method," *Energy Procedia*, vol. 68, pp. 22–30, Apr. 2015, https://doi.org/10.1016/j.egypro.2015.03.228.

[15] L. Bouselham, M. Hajji, B. Hajji, and H. Bouali, "A New MPPT-based ANN for Photovoltaic System under Partial Shading Conditions," *Energy Procedia*, vol. 111, pp. 924–933, Mar. 2017, https://doi.org/10.1016/j.egypro.2017.03.255.

[16] S. K. Kollimalla and M. K. Mishra, "A Novel Adaptive P&O MPPT Algorithm Considering Sudden Changes in the Irradiance," *IEEE Transactions on Energy Conversion*, vol. 29, no. 3, pp. 602-610, Sep. 2014, https://doi.org/10.1109/TEC.2014.2320930.

[17] A. Lashab, D. Sera, J. M. Guerrero, L. Mathe and A. Bouzid, "Discrete Model-Predictive-Control-Based Maximum Power Point Tracking for PV Systems: Overview and Evaluation," *IEEE Transactions on Power Electronics*, vol. 33, no. 8, pp. 7273-7287, Aug. 2018, https://doi.org/10.1109/TPEL.2017.2764321.

[18] V. V. Prabhakaran and A. Singh, "Enhancing Power Quality in PV-SOFC Microgrids Using Improved Particle Swarm Optimization," *Engineering, Technology & Applied Science Research*, vol. 9, no. 5, pp. 4616–4622, Oct. 2019, https://doi.org/10.48084/etasr.2963.

[19] A. Baraean, M. Kassas, M. S. Alam, and M. A. Abido, "Hybrid Neural Network and Adaptive Terminal Sliding Mode MPPT Controller for Partially Shaded Standalone PV Systems," *Arabian Journal for Science and Engineering*, vol. 48, no. 11, pp. 15527–15539, Nov. 2023, https://doi.org/10.1007/s13369-023-08179-9.

[20] S. Ouchen, M. Benbouzid, F. Blaabjerg, A. Betka, and H. Steinhart, "Direct Power Control of Shunt Active Power Filter Using Space Vector Modulation Based on Supertwisting Sliding Mode Control," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 9, no. 3, pp. 3243–3253, Jun. 2021, https://doi.org/10.1109/JESTPE.2020.3007900.