Smart Power Conditioning Unit Utilizing Enhanced Inc-Con MPPT for Photovoltaic Power Plants

Abdelhakim BELKAID[a], KorhanKAYISLI[b], IlhamiCOLAK[c], Slimane HADJI[a], OuahibGUENOUNOU[a]

belkaid08@yahoo.fr; korhankayisli@gmail.com; ilhcol@gmail.com; mail.hadji@gmail.com; ouahib.guenounou@univ-bejaia.dz

[a]*Laboratoire de Tech. Industrielle et de l'Infor., Faculté de Tech., Université de Bejaia, Bejaia 06000, Algeria*
[b]*Department of Electrical Electronics Eng., Eng. Faculty, Gazi University, Ankara, Turkey*
[c]*Depart. of Electrical and Electronics Eng., Faculty of Eng. and Natural Science, Istanbul/Turkey*

Received: 01.03.2024 Accepted:30.03.2024

Abstract—To optimize the performance of a solar energy system, integrating a smart power converter featuring an appropriate Maximum Power Point Tracking (MPPT) control between the PV source and the load is essential. This intelligent converter, also known as a power conditioning unit (PCU), serves to maximize power extraction from the solar panel through real-time impedance matching. The proposed PCU incorporates a boost DC-DC converter controlled by an advanced smart energy recovery technique utilizing an improved Incremental Conductance (Inc-Con) algorithm. Validation of the proposed PCU model, interfacing a sixty watts module with a DC load, was conducted using Matlab tools. The designed system demonstrates exceptional efficacy, delivering optimal performance across transient and stable states, notwithstanding fluctuations in environmental conditions. Even amidst fluctuations, it achieves heightened energy efficiency, exhibiting an impressive increase of over 3%.

Keywords: Photovoltaic Power Plants; BoostDC-DC converter; power conditioning unit; Inc-Con MPPT; maximum power point tracking.

NOMENCLATURE

I_{pv}	PV current (A)
V_{pv}	PV voltage (V)
N_s	number of PV modules connected in series
N_p	number of PV modules connected in parallel
n_s	number of PV cells connected in series in one string
R_s	PV module series resistance (Ω)
R_p	PV module parallel resistance (Ω)
a	the *p-n* junction ideality factor
P_{max}	Maximum power
V_{oc}	Open-circuit voltage
I_{sc}	Short-circuit current
V_{opt}	Voltage at MPP
I_{opt}	Current at MPP
k_v	Temperature coefficient of V_{oc}
k_i	Temperature coefficient of I_{sc}
f	Switching frequency
L	Inductor
$C_1\&C_2$	Capacitors
R	Resistance
I_{ph}	The photo-current
I_s	The reverse saturation current
v_t	the thermal voltage
k_b	the Boltzmann's constant
q	the charge of an electron
d	Duty cycle
u	switch position
V_o	Output voltage
MPPT	maximum power point tracking
PCU	power conditioning unit
Inc-Con	incremental conductance

1. Introduction

Photovoltaic systems have experienced remarkable growth, with an average annual growth of 60% over the last decade. This rapid expansion has consolidated their status as an essential element of the energy landscape of certain regions. Along with this growth, photovoltaic power converters have evolved to become exceptionally efficient, compact and reliable. These advancements make it possible to harness maximum solar energy in various areas, including residential, commercial and industrial applications [1].

In most photovoltaic applications, it is very important to operate the photovoltaic array in its optimal mode. To achieve this goal, a power conditioning unit (PCU) is required. The PCU is just a power electronic converter with adequate MPPT method [2-3]. Numerous MPPT algorithms have been documented in various references [4–9], highlighting their widespread exploration and validation in the literature. Amongst these algorithms, Perturbing and Observing and Inc-Con algorithms stand out as the most employed algorithms in the literature [10]. Their widespread adoption is attributed to their straightforward implementation and ability to operate independently of PV array parameters [11-12]. The Basic Inc-Con method adjusts the duty ratio incrementally until peak power is achieved using a fixed step size. However, it is hampered by slow tracking speeds and may lose track of the optimal direction when light intensities change rapidly. To address these shortcomings, researchers have proposed variable step size strategies in Inc-Con MPPT [13-14]. Nonetheless, both the basic and variable step size Inc-Con techniques struggle to respond accurately to rapid fluctuations in solar radiance.

This paper is structured as follows: Following the introduction, Section 2 presents the PV panel model, while Section 3 discusses the boost chopper model. Subsequently, the fundamentals of both classical and modified Inc-Con techniques are outlined. Moving forward, Section 5 presents the simulation results. Finally, the paper concludes with a summary of findings and implications.

2. PV Panel Model

The equivalent circuit based on a single diode model of the PV module is illustrated in Fig. 1. Mathematically, the PV panel can be characterized by some equations, as described in [2].

$$I_{pv} = N_p\, I_{ph} - N_p I_s \left[exp\left(\frac{V_{pv} + \left(\frac{N_s}{N_p}\right) R_s I_{pv}}{n_s a\, v_t} \right) - 1 \right] - \frac{V_{pv} + \left(\frac{N_s}{N_p}\right) R_s I_{pv}}{\left(\frac{N_s}{N_p}\right) R_p} \quad (1)$$

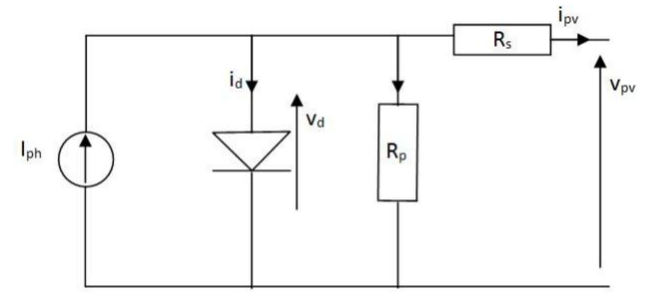


Fig. 1 *Single diode model of a photovoltaic module*

Table 1.
Photovoltaic module specifications[2].

P_{max}	60 W
V_{oc}	21.1 V
I_{sc}	3.8 A
V_{opt}	17.1 V
I_{opt}	3.5 A
k_v	-0.08 V/°C
k_i	0.003 %/°C

$$I_{ph} = [I_{sc}^* + k_i(T - T^*)]\,\frac{G}{G^*} \quad (2)$$

$$I_s = \frac{I_{sc}^* + k_i(T - T^*)}{exp\left(\frac{V_{oc}^* + k_v(T - T^*)}{n_s v_t}\right) - 1} \quad (3)$$

where X^* is the parameter$X$at STC conditions, $v_t = k_b\, T/q$is the thermal voltage, $k_b = 1.38065 \cdot 10^{-23}\, J/K$ and $q = 1.60218 \cdot 10^{-19}\, C$.

The equations outlined above were translated into code and implemented using Matlab software, adhering closely to the established reference specifications for a 60W solar module as detailed in Table 1.

3. Modelling of the Boost Circuit

Drawing upon Kirchhoff's rules, one can derive the dynamic model of the boost converter as outlined in reference [1]:

$$\begin{cases} \frac{di_L}{dt} = \frac{V_{pv} - V_o}{L} + \frac{V_o}{L} \cdot u \\ \frac{dV_o}{dt} = \left(-\frac{V_o}{RC_2} + \frac{i_L}{C_2}\right) - \frac{i_L}{C_2} \cdot u \end{cases} \quad (4)$$

The transfer function of theconverter is given by:

$$\frac{V_o}{V_{pv}} = \frac{1}{1-d} \quad (5)$$

The inductor has current ripple of:

$$\Delta i_L = \frac{d \cdot V_{pv}}{L \cdot f} \quad (6)$$

The ripple of the output voltage is:

$$\Delta V_o = \frac{d \cdot V_{pv}}{(1-d) RC \cdot f} \quad (7)$$

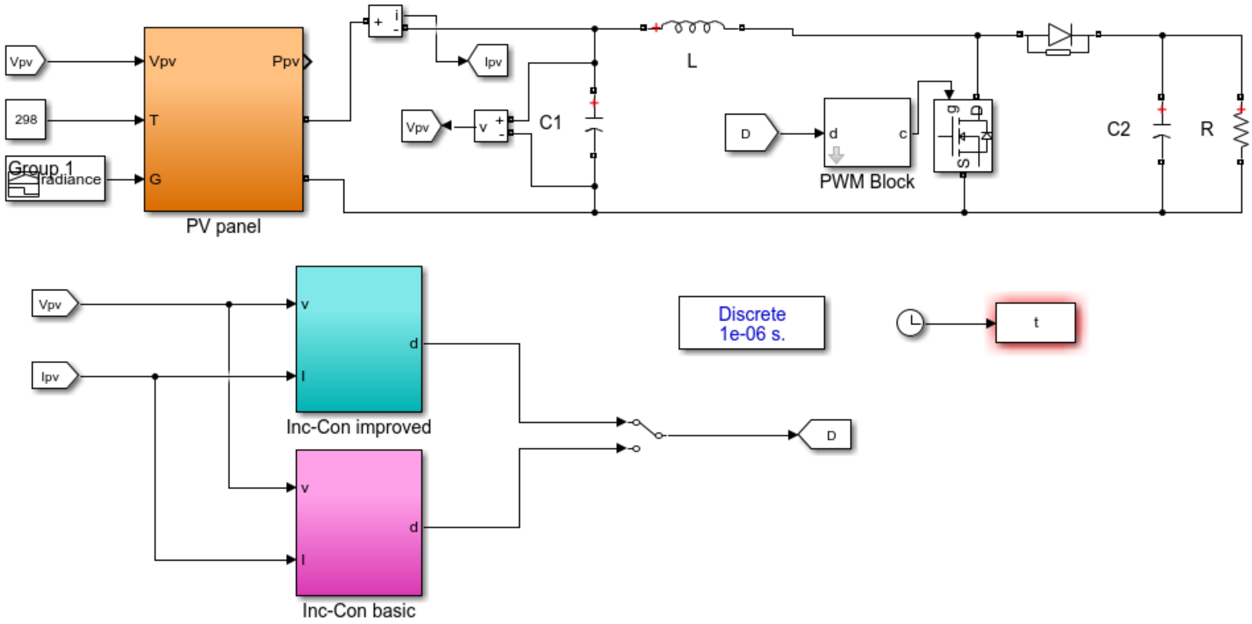
Using equations (5) to (7), the design parameters of the converter are shown in Table 2.

Table 2. Optimized Values for Boost Converter Components

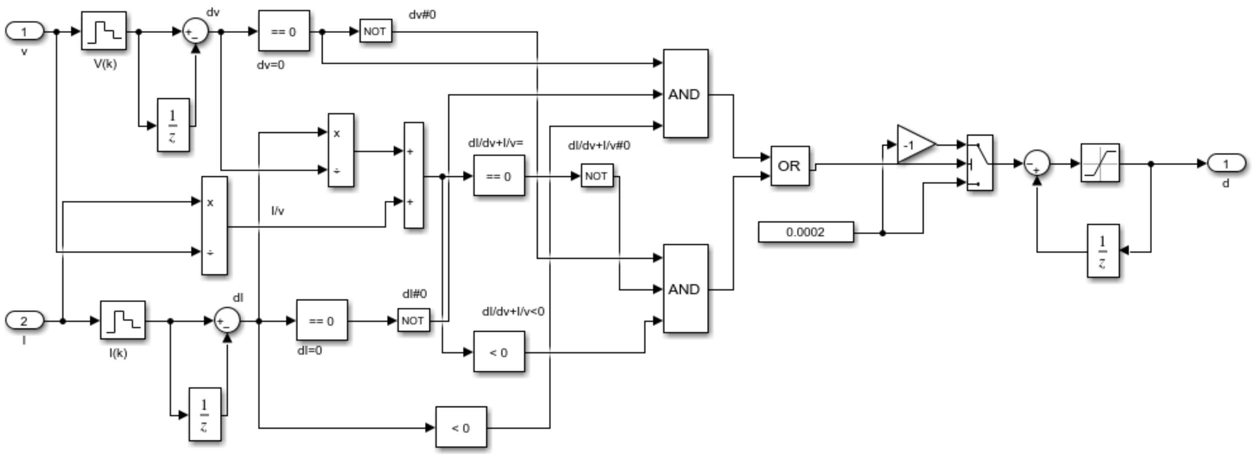
f	10 kHz
L	5 mH
C_1	1000 µF
C_2	470 µF
R	30 Ω

4. The Proposed Inc-Con MPPT

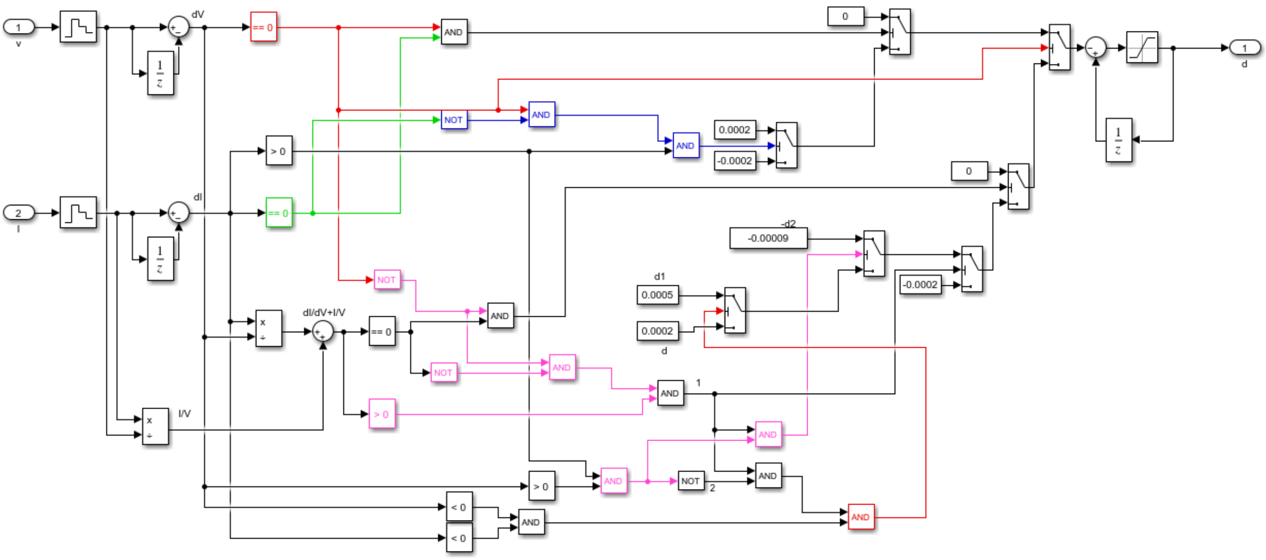
Fig. 2 depicts the simulink scheme of the PV system. The Inc-Con algorithm operates on the principle that the slope of the power-versus-voltage curve ($\frac{dP}{dV} = I + \frac{\Delta I}{\Delta V} \cdot V$) of the PV panel is zero at the MPP, positive to the left, and negative to the right. When the slope is superior than zero, indicating that the current operating point is to the left of the MPP, the algorithm adjusts the module voltage upwards. Conversely, when the slope is inferior than zero, signifying that the operating point is to the right of the MPP, the algorithm lowers the module voltage. Upon reaching a slope of zero, indicating alignment with the MPP, the algorithm halts voltage adjustments. Part b of Fig.2 shows the simulink diagram that explains the operational principle of this control. This method presents two significant limitations: Firstly, in stable conditions, the operating point tends to oscillate around the MPP without ever precisely reaching it. Secondly, in dynamic scenarios where illumination fluctuates rapidly, the algorithm may struggle to accurately track the MPP, potentially losing its path altogether (as discussed in references [10]).



a)



b)



c)

Fig. 2 Simulink model of: a) the proposed system, b) Basic Inc-Con, c) Improved Inc-Con.

In stable conditions characterized by a fixed irradiance level, the current versus voltage characteristic clearly demonstrates that changes in voltage precede changes in current with differing signs. If a perturbation in voltage induces a corresponding change in current with the same sign, it suggests sudden variations in irradiance affecting the PV array.

In contrast to traditional methods, the modified Inc-Con algorithm can discern between these two operational conditions, thereby avoiding divergence in the latter circumstance by adjusting the direction of the perturbation. Essentially, the new algorithm must counteract the behavior of the old algorithm when the system operates under fast-varying conditions. This principle is elucidated in part c of Fig. 2, depicted in the Simulink scheme of the enhanced Inc-Con algorithm.

The new algorithm is obtained by adding to the old one, two tests demonstrating changes in current and voltage with the same signs, indicating rapid fluctuations in the intensity of sunlight.

5. Simulation Results and Discussion

This section presents a MATLAB/Simulink simulations. In fact, the paper aims to demonstrate the performance of the enhanced MPPT controller (IInc-Con) in comparison with the basic algorithm (BInc-Con). Thus, to achieve this objective, a strict profile was chosen to modify the solar radiation, maintaining both the temperature and the resistive load at fixed values.

The tests were carried out under the irradiance change shown in Figure 3. The duty cycle increments used for both algorithms have been shown in Figure 2.

Fig. 4 illustrates a comparative analysis of peak power tracking between BInc-Con and IInc-Con techniques. The improved algorithm demonstrates superior performance over the basic approach, particularly in dynamic response. Notably, the standard method exhibits diminished performance compared to the new method, particularly under decreasing solar radiation, and its performance further deteriorates during increasing solar radiation. This observation highlights the divergence of the standard method from the MPP under varying irradiance levels. The proposed MPPT technique effectively addresses this issue. Hence, it can be inferred that the improved IInc-Con enhances the performance of the conventional approach.

Fig. 5 displays the evolution of the simulation curves of the PV voltage, PV current, PV power, and the output voltage during a change in sunshine using the improved algorithm. It is evident that the optimal current closely mirrors the sunlight profile, achieving power very proximate to the true Maximum Power Point (MPP) throughout the entire variation profile, albeit with a slight deviation during start-up. The behavior of the optimal voltage is minimally affected, with a gentle adjustment, resulting in a boosted output voltage. The corresponding waveform of the duty cycle during a change in sunshine using the improved algorithm is described in Fig. 6.

Figure 7 illustrates the progression of the tracking efficiency amidst irradiance fluctuations for both algorithms. The tracking efficiency or the power efficacy, denoted as P_{eff}, represents the average MPPT efficiency and is evaluated as per equation [9]:

$$P_{eff} = \frac{\int_0^t P_{MPP}}{\int_0^t P_{PV}} \cdot 100\ [\%] \qquad (8)$$

Where P_{MPP} represents the power attained by a specific MPPT technique, and P_{PV} signifies the theoretical power available.

Analysis of Figure 7 reveals that the average of the power efficacy of the basic Inc-Con stands at approximately $P_{eff} =$ 93.33%, whereas for the newInc-Con, it reaches $P_{eff} =$ 96.74%. Notably, the proposed MPPT technique exhibits a notable increase in tracking efficiency above three percent.

Based on the results obtained above, it can be concluded that the suggested method ensures superior dynamic response, particularly under fast-varying solar irradiance scenarios, whether the changes follow an ascending or descending slope.

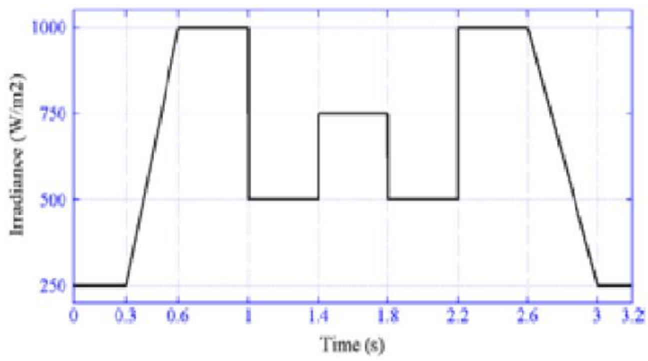


Fig. 3 The change in irradiance

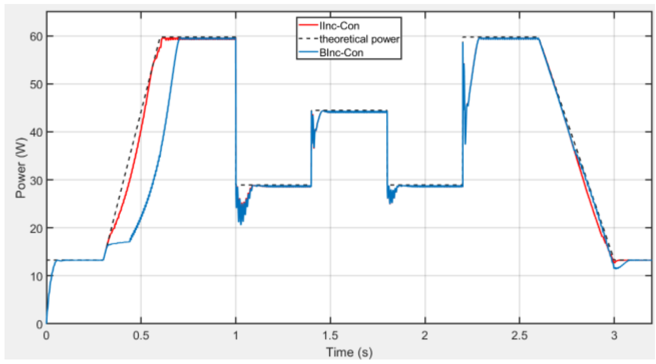


Fig. 4 The maximum power obtained by the two algorithms under the change in sunshine.

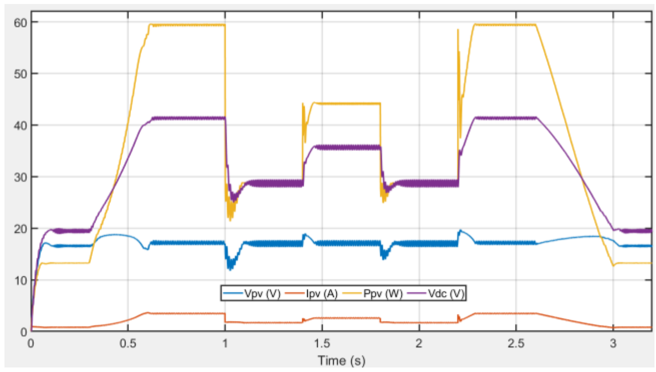


Fig. 5 PV voltage, PV current, PV power, and the output voltage during a change in sunshine using the improved algorithm.

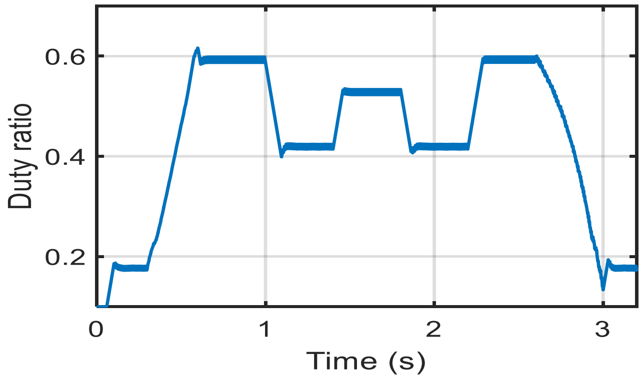


Fig. 6 The corresponding waveform of the duty cycle during a change in sunshine using the improved algorithm.

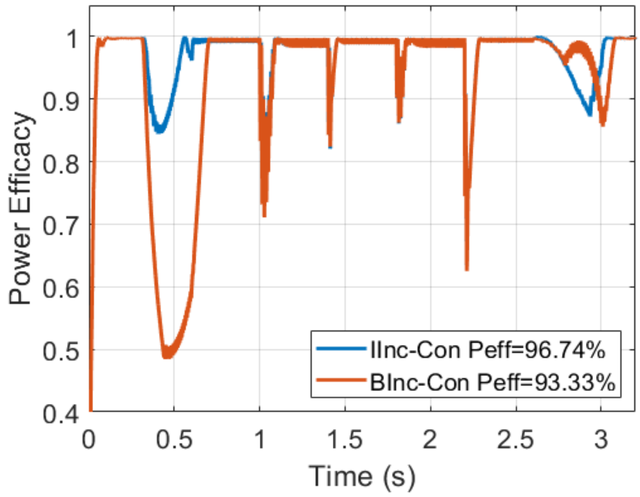


Fig. 7 The corresponding waveforms of the power efficacy during a change in sunshine using the two algorithms.

6. Conclusion

In this article, mathematical modelling, numerical simulation under the MATLAB-SIMULINK software and intelligent control of an autonomous photovoltaic system have been proposed. A boost converter with an improved incremental conductance MPPT control is incorporated between the load and the panel to allow the latter to be used at its maximum power. In comparison to the basic Inc-Con technique, employing the proposed MPPT control significantly enhances the performance of the PV system, particularly during dynamic states. This improvement leads to a reduction in power loss and a notable increase in power tracking efficiency of over three percent.

ACKNOWLEDGMENTS

This study, conducted at the Department of Automatic, Telecommunications and Electronics, Faculty of Technology, Bejaia University, Algeria, received support from the PRFU research project No. A01L07UN060120220001**;** and by the Faculty of Engineering and Architecture of Istinye University, Istanbul, Turkey. We greatly appreciate this support.

References

[1] J. Linares-Flores, A. Hernández-Mendez, J. A. Juárez-Abad, M. A. Contreras-Ordaz, C. García-Rodriguez and J. F. Guerrero-Castellanos, "MPPT Novel Controller Based on Passivity for the PV Solar Panel-Boost Power Converter Combination," in *IEEE Transactions on Industry Applications*, vol. 59, no. 5, pp. 6436-6444, Sept.-Oct. 2023, doi: 10.1109/TIA.2023.3274618.

[2] W. A. Abri, R. A. Abri, H. Yousef and A. Al-Hinai, "A Global MPPT Based on Bald Eagle Search Technique for PV System Operating under Partial Shading Conditions," *2022 10th International Conference on Smart Grid (icSmartGrid)*, Istanbul, Turkey, 2022, pp. 325-332, doi: 10.1109/icSmartGrid55722.2022.9848561.

[3] A.Belkaid, I.Colak, O.Isik, "Photovoltaic maximum power point tracking under fast varying of solar radiation", Applied Energy 179 (2016) 523–530, http://dx.doi.org/10.1016/j.apenergy.2016.07.034.

[4] I. Shams, S. Mekhilef, and K. S. Tey, (2021),"Maximum power point tracking using modified butterfly optimization algorithm for partial shading, uniform shading, and fast varying load conditions", IEEE Trans. Power Elect. 36 (5), 5569–5581. doi:10.1109/tpel.2020.3029607.

[5] A. F. Mirza, Q. Ling, M. Y. Javed, and M. Mansoor, (2019),"Novel MPPT techniques for photovoltaic systems under uniform irradiance and partial shading", Sol. Energy 184, 628–648. doi:10.1016/j.solener.2019.04.034.

[6] J. E. Hernandez-Diez, C. F. Mendez-Barrios, S. Niculescu, and E. Barcenas-Barcenas, "A Current Sensorless Delay–Based Control Scheme for MPPT–Boost Converters in Photovoltaic Systems", IEEE Access, vol. 8, no. 1, pp. 174449–174462, 2020.

[7] R. Z. Caglayan, K. Kayisli, N. Zhakiyev, A. Harrouz, I. Colak. A Review of Hybrid Renewable Energy Systems and MPPT Methods. Int. J. Smart Grid-ijSmartGrid, vol. 6, no. 3, pp. 72-82, 2022.

[8] Celia Aoughlis, Abdelhakim Belkaid, Mohand Akli Kacimi, Ilhami Colak, Ouahib Guenounou, Toufik Bakir & Lamine Brikh (29 Dec 2023),"A Novel Dynamic and Self-Adaptive InCre Technique Based on PI Control and EO Optimization for Hybrid PV-TEG Conversion Systems", Electric Power Components and Systems, DOI: 10.1080/15325008.2023.2296964.

[9] A.Belkaid, I.Colak, K. Kayisli, "A comprehensive study of different photovoltaic peak power tracking methods", 6th International Conference on Renewable Energy Research and Applications (ICRERA), San Diego, CA, 5-8 Nov 2017, pp. 1073 - 1079.

[10] S. Fadhil Jaber, A. Mahmoud Shakir. Design and Simulation of a Boost-Microinverter for Optimized Photovoltaic System Performance. Int. J. Smart Grid-ijSmartGrid, vol. 5, no. 2, pp. 94-102, 2021.

[11] V. Balaji and A. Peer Fathima, "Enhancing the Maximum Power Extraction in Partially Shaded PV Arrays Using Hybrid Salp Swarm Perturb and Observe Algorithm," Int. J. Renew. Energy Res., vol. 10, no. 2, pp. 898–911, 2020.

[12] A. Belkaid, I. Colak, K. Kayisli, and R. Bayindir, "Design and Implementation of a Cuk Converter Controlled by a Direct Duty Cycle INC-MPPT in PV Battery System" Int. J. Smart Grid, vol. 3, no. 1, pp. 19–25, Mar. 2019.

[13] Rizzo Santi Agatino and Scelba Giacomo,"ANN based MPPT method for rapidly variable shading conditions", Appl Energy 2015;145:124–32.

[14] I. Owusu-Nyarko, M. A. Elgenedy, I. Abdelsalam, K. H. Ahmed, "Modified Variable Step-Size Incremental Conductance MPPT Technique for Photovoltaic Systems", Electronics 2021, 10, 2331. https://doi.org/10.3390/electronics10192331