# Power control-based fuzzy and modulated hysteresis methods for micro-grid using a photovoltaic system

Djamila Rekioua
Laboratoire LTII, Faculté de Technologie
Université de Bejaia
Bejaia, Algeria
djamila.ziani@univ-bejaia.dz

Khodir Kakouche
Laboratoire LTII, Faculté de Technologie,
Université de Bejaia
Algeria
khodir.kakouche@univ-bejaia.dz

Pierre-Olivier Logerais
Univ Paris Est Créteil
CERTES, IUT de Sénart-Fontainebleau,
Paris, France
pierre-olivier.logerais@iutsf.org

Toufik rekioua
Laboratoire LTII, Faculté de Technologie,
Université de Bejaia
Bejaia, Algeria
toufik.rekioua@univ-bejaia.dz

*Abstract*— **This paper discusses the smart grid integration of a photovoltaic system. Several methods can be applied for controlling the power injected into the grid by a photovoltaic system. These techniques ensure that the system operates safely and efficiently, and that the power levels are maintained within the required limits. Maximum power point tracking based on fuzzy logic control (FLC) is incorporated into the inverter control in our work. The inverter keeps the power factor by managing the reactive power while controlling the voltage and frequency of the photovoltaic system. Although the hysteresis current control is a useful technique, it has its limitations, particularly when it comes to the frequency control. In the present study, a modulated hysteresis control (MHC) was applied, to ensure that the inverter operates at a constant switching frequency, enhancing the efficiency of the system. The study was done using the Matlab software, and the findings demonstrate that the MHC-studied system supplied low-harmonic energy to a utility grid.**

***Keywords*— Grid, Photovoltaic, FLC MPPT, Power control.**

## I. INTRODUCTION

Smart grid integration of photovoltaic systems is an important step towards a more sustainable and efficient electrical grid. Due to its many benefits, including its durability and availability in many parts of the world, photovoltaic energy has become increasingly important in electrical applications. However, the power output of photovoltaic panels can be unpredictable as it can fluctuate throughout the day according to varying climate conditions. To address this problem, maximum power point tracking (MPPT) methods are being employed[1-2], including digital MPPT techniques [3-16]. One of the most popular digital MPPT techniques is the fuzzy logic control (FLC) [17-23].It has several advantages over other MPPT techniques, namely its ability to handle non-linear and uncertain systems, its flexibility to adapt to changing operating conditions, and its capability to provide better performance in complex systems. FLC-based MPPT systems have been utilized for various applications.

In this study, a modulated hysteresis control (MHC) is used to overcome the drawbacks of the hysteresis control current, such as a variable switching frequency. This control strategy reduces the switching losses and boosts the total efficiency of the system by adjusting the switching frequency based on the output voltage of the inverter. This control technique results in a more sinusoidal output waveform, which reduces the harmonic distortion. Also, MHC is relatively easy to implement and requires less complex control algorithms compared to other control techniques, which makes it a cost-effective solution for many applications.

The simulation findings reveal how effectively the modulated hysteresis control method operates to control the output power of the photovoltaic system. Also, the results show that the technique ensures that the inverter operates at a constant switching frequency, leading to improved efficiency and performance..

## II. MODELING OF THE STUDIED SYSTEM

The studied system is represented in Fig.1. The photovoltaic generator is made up of 10 strings, each string comprising 12 panels of 80 Wp (Table 1) connected in series. The inverter includes an MPPT control. Through the incorporation of MPPT in the inverter management, the DC/AC conversion process is effective and optimized. The inverter control also includes an MHC technique to ensure that the inverter operates at a constant switching frequency.

TABLE I. . PARAMETERS OF THE PV PANEL.

| Parameters | Values |
|---|---|
| Photovoltaic power | 80 Wp |
| Maximum current at MPP | 4.65 A |
| Maximum voltage at MPP | 17.5V |
| Short-circuit current | 4.95A |
| Open-circuit voltage | 21.9V |
| Temperature coefficient of the short-circuit current | 3 mA/°C |
| Temperature coefficient of the open-circuit voltage | -150mV/°C |

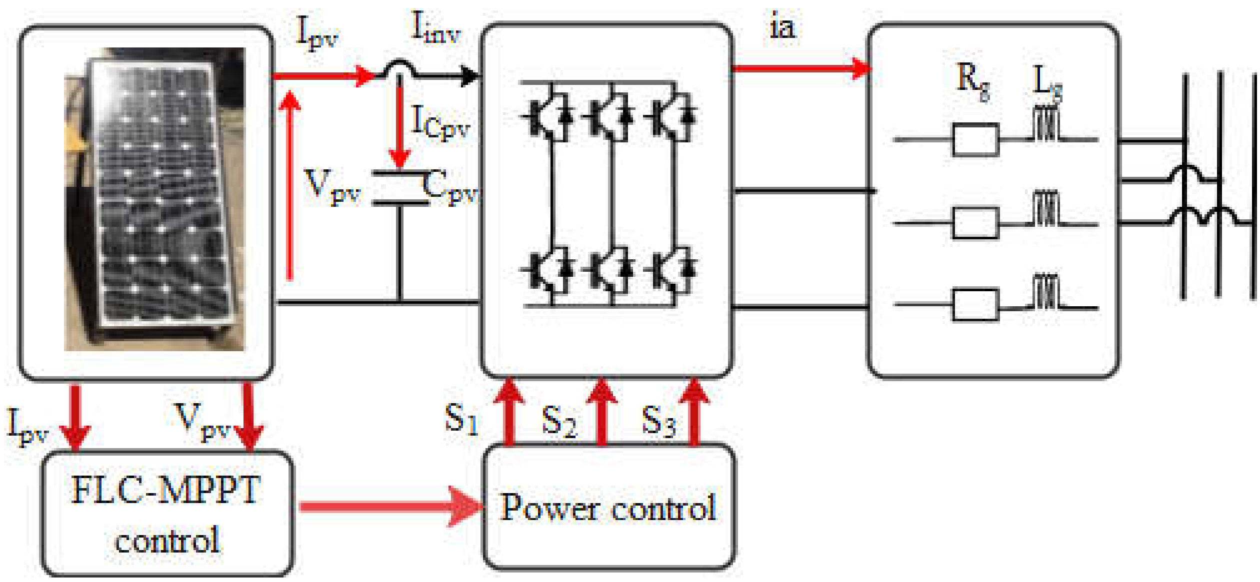



Fig. 1. Studied system.

### A. Photovoltaic generator

Different mathematical models can be used to calculate the electrical characteristics of a PV panel. They vary in complexity and accuracy. In our work, we used the single-diode model [1]. This model is a simple but useful tool for describing the electrical characteristics of a photovoltaic generator. The electrical current of the single-diode model is [3, 16]:

$$I_{pv} = I_{ph} - I_0 \times \left[ \exp\left( \frac{q \times (V_{pv} + R_s \times I_{pv})}{A \times N_s \times K \times T_j} \right) - 1 \right] - \frac{V_{pv} + R_s \times I_{pv}}{R_{sh}} \tag{1}$$

where $I_{ph}$ is the photo-current, $I_d$ the diode-current and $R_{sh}$ shunt resistance, $I_0$ the reverse saturation current of the diode, q the electron charge, *k* Botzman's constant, A diode ideality factor and $N_s$ the serial number of cells.

Photovoltaic electrical characteristics were established using the test bench displayed in Fig. 2.

Fig. 2. Test bench to determinate the electrical caracteristics.

The electrical characteristics are shown in Fig.3.

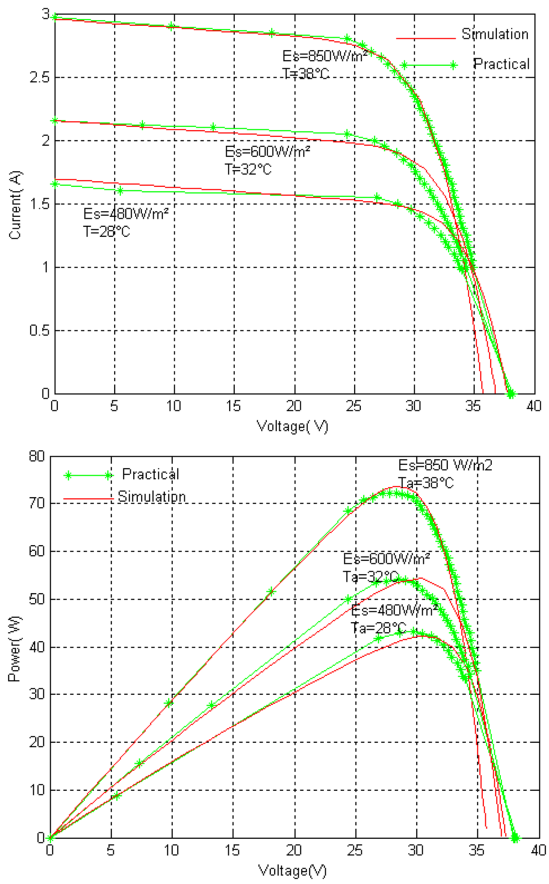



Fig. 3. Electrical characteristics of the PV panel.

### B. MPPT control

The P&O algorithm is simple and effective, but it can sometimes oscillate around the maximum power point (MPP), especially if the perturbations are too large. The use of a FLC in a photovoltaic system can help to improve its performance and efficiency, making it a more reliable and cost-effective source for clean energy. The FLC generates an output reference voltage variation $V_{pv,ref}$ used to converge to the optimal point by taking two inputs: the power variation $\Delta P_{pv}$ and the voltage variation $\Delta V_{pv}$. The fuzzy rules are based on power variations ($\Delta P_{pv}$) and voltage variations ($\Delta V_{pv}$) as given in Table 2. [25].

TABLE II. FUZZY RULES

| $\Delta P_{pv}$ \ $\Delta V_{pv}$ | BN | MN | SN | Z | SP | MP | BP |
|---|---|---|---|---|---|---|---|
| BN | BP | BP | MP | Z | MN | BN | BN |
| MN | BP | MP | SP | Z | SN | MN | BN |
| SN | MP | SP | SP | Z | SN | SN | MN |
| Z | BN | MN | SN | Z | SP | MP | BP |
| SP | MN | SN | SN | Z | SP | SP | MP |
| MP | BN | MN | SN | Z | SP | MP | BP |
| BP | BN | BN | MN | Z | MP | BP | BP |

The MPPT algorithm is provided by using these linguistic rules [26].

$$\begin{cases} \Delta P_{pv} = P_{pv}(t) - P_{pv}(t-1) \\ \Delta V_{pv} = V_{pv}(t) - V_{pv}(t-1) \\ V_{pv-ref}(t) = V_{pv}(t-1) + \Delta V_{pv-ref}(t) \end{cases} \quad (2)$$

$P_{pv}(t)$, $V_{pv}(t)$, and $V_{pv,ref}(t)$, respectively, refer to the power, voltage and reference voltage of a PV generator at a particular time t. Fig. 4 depicts the structural scheme of the fuzzy logic controller.

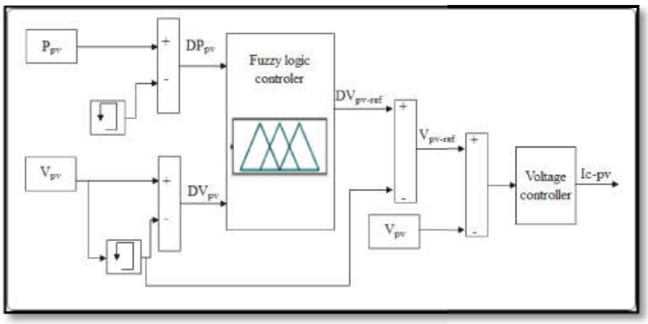



Fig. 4. Structural scheme of the fuzzy logic controller.

## C. Proposed Power control

### 1) Modulated hysteresis control

By using the MHC control technique, the switching frequency of the inverter can be kept constant to reduce the switching losses. The MHC involves adding a triangular signal to the reference current, and their comparison is used to control the output of the inverter. The triangular carrier signal frequency matches the semiconductor switching frequency in the inverter. The amplitude of the triangular carrier signal is typically chosen to be small compared to the reference current signal to avoid excessive switching of the inverter. The resulting signal is compared to a hysteresis band, having a fixed range of values centered on the reference current. If the resulting signal falls outside the hysteresis band $B_H$, the output of the inverter is adjusted to bring the signal back within the hysteresis band.

$$i_{\mathrm{mod}-ref} = i_{ref} + i_{tr} \quad (3)$$

The triangle signal is represented by $i_{tr}$, while $i_{mod-ref}$ and $i_{ref}$ are respectively the modulated reference current and the reference current.

The requirements of the system and the characteristics of the load are usually taken into consideration when choosing the bandwidth. A larger bandwidth allows a more rapid response to changes in the input signal, but may result in more switching of the converter and also in increased losses. A narrower bandwidth may reduce the switching losses but may result in a slower response to changes in the input signal. The value of the band width $B_H$ is typically chosen as a compromise between these factors to optimize the performance of the system. The switching frequency is equal to the frequency of the triangular carrier signal, is typically chosen to be a multiple of the desired output frequency. In order to maintain a constant switching frequency and minimize the switching losses [4], the measured current variation during half a period of the triangular signal should not exceed the difference between the upper and lower limits. These limits define the switching times of the voltage inverter when the measured current intersects only the hysteresis band limits (Fig. 5) for each twice half-period $T_{tr}/2$ of the triangular signal.

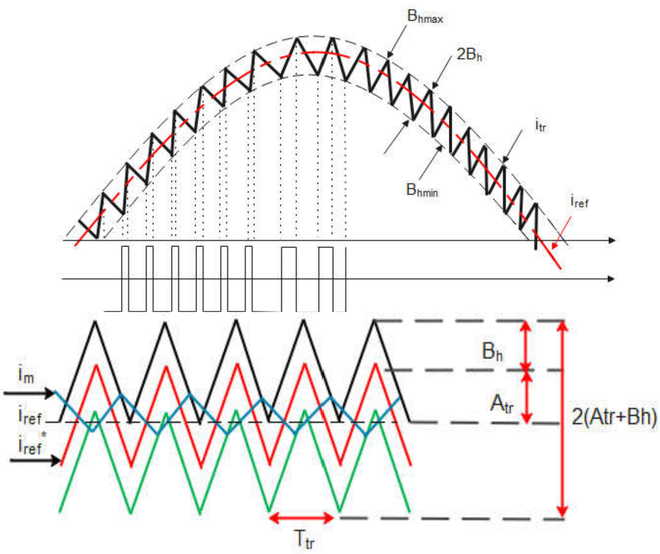



Fig. 5. States of the switches in MHC.

### 2) Power control

It is based on controlling the power factor by maintaining it to the unit factor, and controlling active power flow to eliminate reactive power. A PI controller, used to control the direct bus voltage, generates a reference value for the active power, is then used to adjust the output power of the power converter. The reference current is produced by dividing the active power reference by the grid capacitance. Thus a reference current is generated corresponding to the amount of current required to supply the grid with the intended active power:

$$i_{inv} = S_1 i_a + S_2 i_b + S_3 i_c \quad (4)$$

where ($i_a$, $i_b$, $i_c$) are the grid currents and $S_i$ ($i=1, 2, 3$) are the logic functions.

Also, the voltages inverter ($v_1, v_2, v_3$) are defined by:

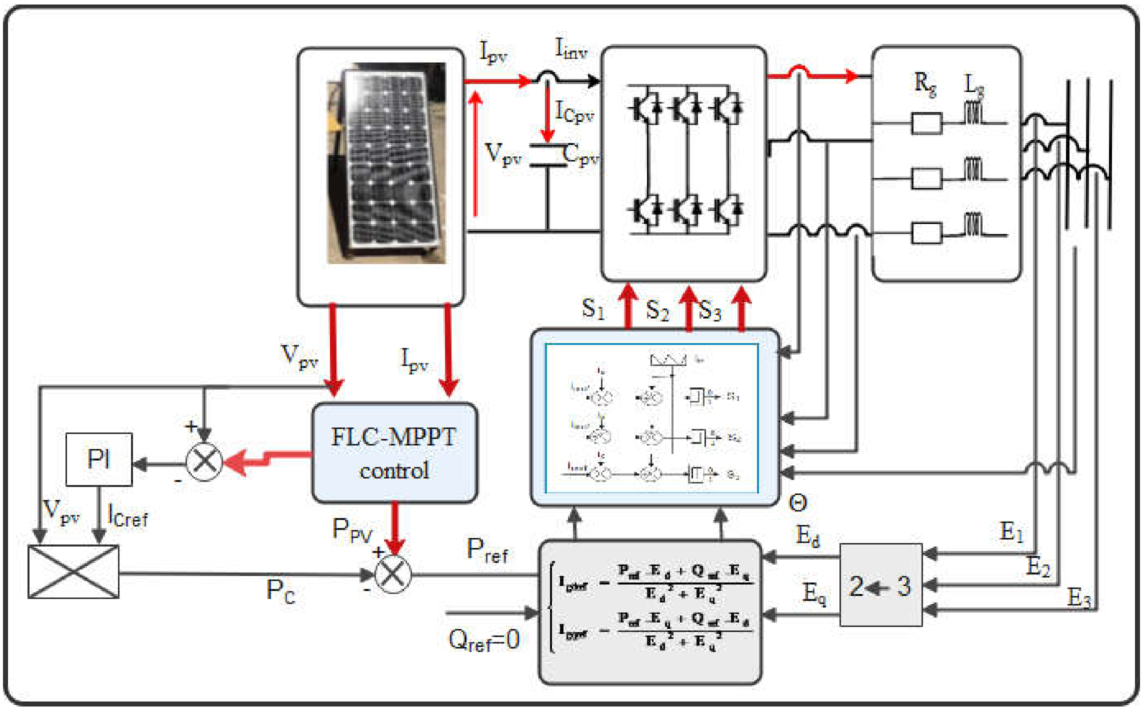



Fig. 6. Studied system configuration

$$\begin{pmatrix} v_1 \\ v_2 \\ v_3 \end{pmatrix} = \frac{V_{pv}}{3} \begin{pmatrix} -2 & 1 & 1 \\ 1 & -2 & 1 \\ 1 & 1 & -2 \end{pmatrix} \begin{pmatrix} S_1 \\ S_2 \\ S_3 \end{pmatrix} \tag{5}$$

Using the filter, which is constituted of a resistance $R_g$ and an inductance $L_g$, the phase voltages of the grid are generated:

$$\begin{pmatrix} v_1 \\ v_2 \\ v_3 \end{pmatrix} = R_g \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} + L_g \frac{d}{dt} \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} + \begin{pmatrix} E_1 \\ E_2 \\ E_3 \end{pmatrix} \tag{6}$$

Fig. 6 shows the control system for the inverter and the grid connection. The unit power factor can be set to zero reactive power and the supplied active power to its reference to adjust the direct bus voltage and generate the current reference based on the capacitance.

The different equations of the powers are expressed as follows:

$$\begin{cases} P_{ref} = P_{pv} - P_c \\ P_c = I_{cref} . V_{pv} \\ I_{cref} = PI(V_{dcref} - V_{dc}) \end{cases} \tag{7}$$

$$\begin{cases} P_{ref} = E_d . I_{adref} + E_q . I_{aqref} \\ Q_{ref} = E_q . I_{adref} - E_d . I_{adref} \end{cases} \tag{8}$$

The current references are then obtained:

$$\begin{cases} I_{adref} = \dfrac{P_{ref} . E_d + Q_{ref} . E_q}{E_d^2 + E_q^2} \\ I_{aqref} = \dfrac{P_{ref} . E_q + Q_{ref} . E_d}{E_d^2 + E_q^2} \end{cases} \tag{9}$$

To achieve the reference power, the inverter must control the PV generator power output. $P_C$ represents the capacitance power, which filters the output voltage of the inverter and reduces the harmonics in the system, while $Q_{ref}$ refers to the reactive power injected or absorbed from the grid.

## III. SIMULATION STUDY

The studied system was simulated under three different solar irradiance profiles (Fig.7). The FLC algorithm is used for the photovoltaic power maximization and the inverter current is controlled by using the MHC approach ($A_{tr}+B_H>0.3$, f=10 kHz, $B_H<0.27$).The proposed system consists of a photovoltaic generator with a total peak power of approximately 9.6 kW and a photovoltaic voltage of 600 V in standard test conditions ($E_s$=1000 W/m², cell temperature of 25°C). The photovoltaic power tracks its reference (Fig.8) across three different solar irradiance profiles.

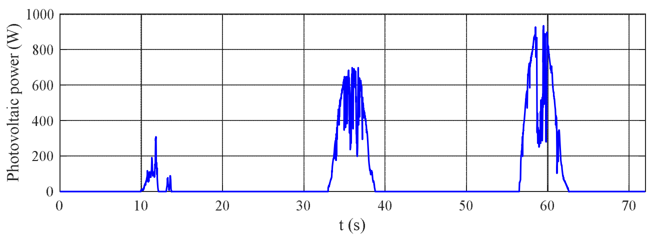



Fig. 7. Measured solar irradiance profiles.

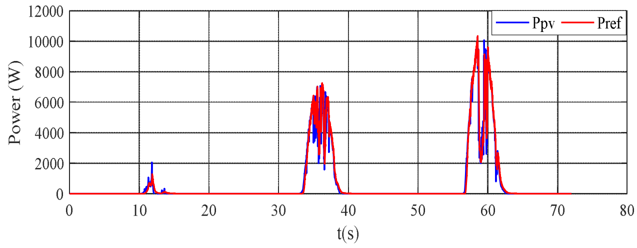
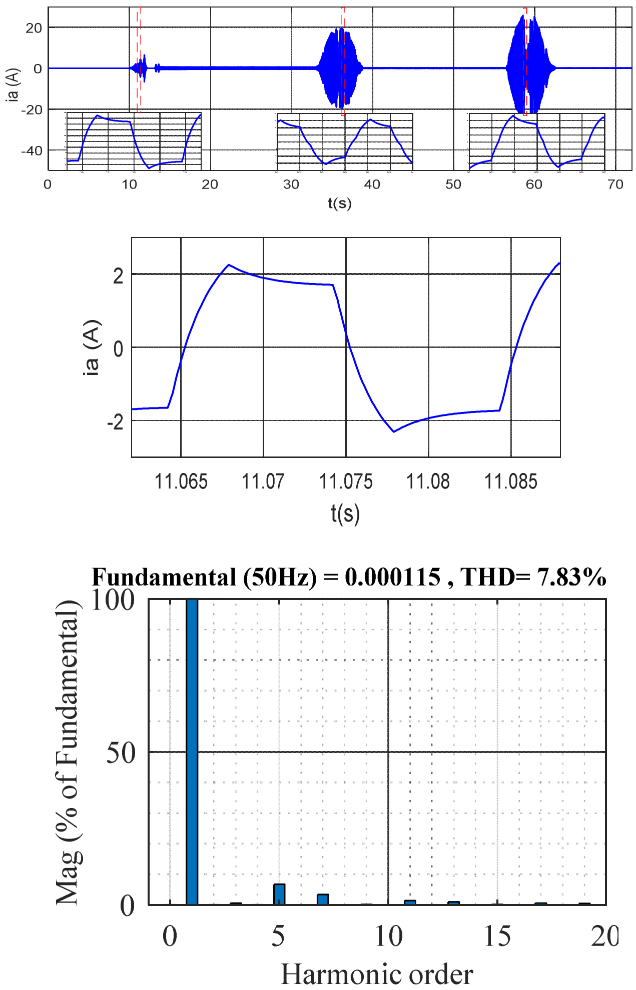
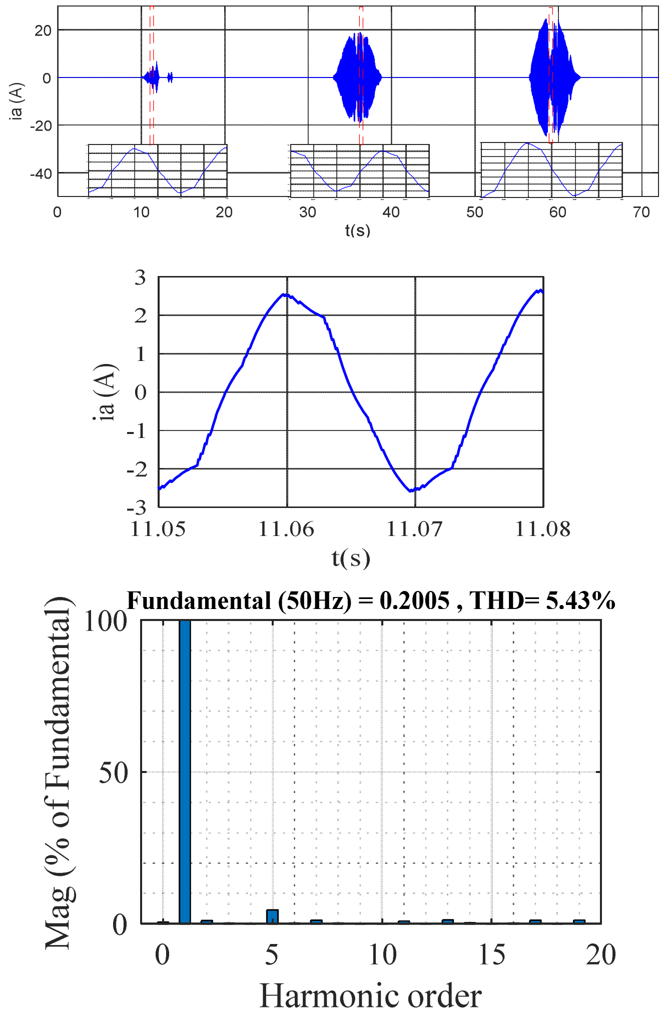



Fig. 8. Photovoltaic and reference powers.

Fig.9(a, b) shows the current and voltage on the grid side under the three days using the classical hysteresis control and the modulated hysteresis control. The currents in the case of the classical hysteresis present irregularities in the shape (Fig. 9-a). The total harmonic distortion (THD) is around 7.83 %. Nevertheless, for the MHC, the grid current has a smooth shape and a THD of 5.43% (Fig.9-b), and the frequency is almost steady at 50 Hz. Additionally, as can be seen in Fig. 10, the voltage and current are in phase. This implies that the maximum power extracted from the photovoltaic (PV) array is transmitted to the grid, and the system operates at a unit power factor (Fig.11) with no exchange of reactive power.




(a) Classical hysteresis control




(b) MHC approach

Fig. 9. Grid current waveforms with their THD

Based on this finding, it can be concluded that when utilizing Maximum Harmonic Control (MHC), the system has the capability of supplying energy to a utility grid with reduced harmonics in comparison to the traditional control approach.

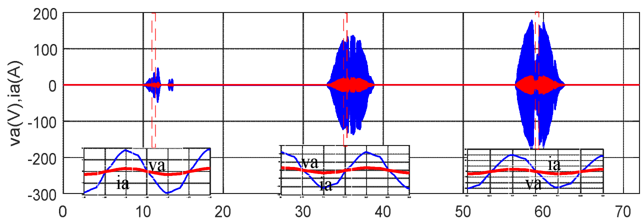



Fig. 10. Grid voltage and currentusing the MHC current.

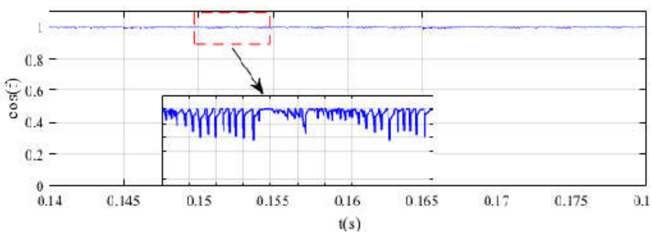



Fig. 11. Power factor.

From these findings, it shows that the grid-connected photovoltaic system at the MPP is capable of operating continuously while supplying low harmonic and unit power factor energy to the utility grid.

## IV. CONCLUSION

This paper presents a study on a grid-connected photovoltaic (PV) system controlled by fuzzy logic control (FLC). A fast and stable FLC maximum power point tracking (MPPT) controller is employed in the control system to integrate the MPPT algorithm into the inverter control, resulting in faster MPP tracking compared to traditional methods. The current control is implemented using the modulated hysteresis control (MHC) to ensure a steady switching frequency. This innovative approach utilizing fuzzy logic theory and MHC control has great potential in enhancing the performance and efficiency of PV systems, ultimately making them a more sustainable source of energy for the future. The results of the study demonstrate that the MHC controller generates lower total harmonic distortion (THD) in the grid current compared to a classical controller, indicating the potential of using fuzzy logic theory and MHC control in improving the quality of power injected into the grid. Furthermore, the research shows that the grid-connected PV system can operate continuously at the MPP while supplying low harmonic and unit power factor energy to the utility grid, highlighting the promise of this approach in improving power quality.

## REFERENCES


[1] D. Rekioua, E. Matagne, "Optimization of photovoltaic power systems: Modelization, Simulation and Control, 2012 Series: Green Energy and Technology. Ed Springer.

[2] M.M.Kamal, I.Ashraf, E.Fernandez, "Planning and optimization of microgrid for rural electrification with integration of renewable energy resources," Journal of Energy Storage, vol. 52 , art. no. 104782, pp. 86562 - 86579, 2022.

[3] A. Yazdani, "A Control Methodology and Characterization of Dynamics for a Photovoltaic (PV) System Interfaced With a Distribution Network," IEEE Trans On Power Delivery, vol.. 24, No. 3, pp.1538-1555, 2009.

[4] D. Rekioua, S. Bensmail, N. Bettar, "Development of hybrid photovoltaic-fuel cell system for stand-alone application, " International, Journal of Hydrogen Energy, vol. 39, No. 3, pp.1604-1611, 2014.

[5] Elmouatamid, A., Ouladsine, R., Bakhouya, M., El Kamoun, N., Khaidar, M., Zine-Dine, K., " Review of Control and Energy Management Approaches in Micro-Grid Systems," Energies, vol. 14, No. 168, pp. 1-30, 2021.

[6] L. J.L. Santos, F. Antunes, A. Chehab and C. Cruz "A Maximum Power Point Tracker for PV Systems Using a High Performance Boost Converter " Solar Energy, vol. 80, No. 7, pp.772-778, 2006.

[7] J. Alonso-Martínez, J. Eloy-García and S.Arnaltes, "Control of a Three-Phase Grid-Connected Inverter for Photovoltaic Applications with a Fuzzy MPPT Under Unbalanced Conditions" 13th European Conference on Power Electronics and Applications, 2009, pp.1–7.

[8] D Rekioua, S Bensmail, T Rekioua, "Application of adaptive fuzzy logic controller to improve photovoltaic pumping system performances, "Turkish Journal of Electromechanics and Energy, vol. 7, No. 3, pp. 92-99, 2022.

[9] M. B. Smida, A. Sakly, "Fuzzy logic control of a hybrid renewable energy system: A comparative study," Wind Engineering, vol. 45, No. 4, pp.793-806, 2021.

[10] J-A. Jiang, T-L Huang, Y-T Hsiao and C-H. Chen, "Maximum power tracking for photovoltaic power systems" In J. of Science and Engineering, vol. 8, No. 2, pp.147-153, 2005.

[11] M. I. S. Guerra, F. M. U. de Araujo, M. Dhimish, R. G. Vieira, "Assessing maximum power point tracking intelligent techniques on a PV system with a buck–boost converter, " Energies, vol. 14, No. 22, art. no. 7453, pp.1-21, 2021.

[12] R. Gules, J. Pellegrin Pacheco, HL. Hey, J. Imhoff, "A Maximum Power Point Tracking System with Parallel Connection for PV Stand-Alone Applications, " IEEE Transactions on Industrial Electronics, vol. 55, No. 7, pp.2674–2683, 2008.

[13] M. Taherbaneh, H. Ghaforifard, A.H Rezaie, S. Karbasian " Combination of fuzz maximum power point tracker and sun tracker for deployable solar panels in photovoltaic systems" Proc. FUZZ-IEEE 2007, pp.23-36.

[14] I.H. Altas and A.M. Sharaf "Novel maximum power fuzzy logic controller for photovoltaic solar energy systems", Renewable Energy, Vol. 33, No. 3, pp.388-399, 2008.

[15] I. Hamzaoui, F. Bouchafaa, A .Hadjammar. "Investigation of the behavior of a three phase grid connected photovoltaic system to control active and reactive power with DPC" Energy Procedia, vol. 6, pp.493–502, 2011.

[16] M.G. Simoes, N.N. Franceschetti "Fuzzy optimization based control of a solar array. IEE Proc. Electr. Power Appl.1999, vol. 146, No. 5, pp.552-558.

[17] N.Patcharaprakiti, S.Premrudeepreechacharn, Y.Sriuthaisiriwong "Maximum power point trackingusing adaptive fuzzylogic control for gridconnectedphotovoltaic system. " Renewable Energy, vol. 30, No. 11, pp.1771-1788, 2005.

[18] D. Rekioua, T. Rekioua, Y. Soufi, "Control of a grid connected photovoltaic system, In:2015 International Conference on Renewable Energy Research and Applications, "ICRERA 2015, art. no. 7418634, pp.1382-1387.

[19] K. Punitha, D. Devaraj, S.Sakthive, "Adaptive Hysteresis Current Control of Inverter for Solar Photovoltaic Applications. "International Journal of Innovative Technology & Creative Engineering, vol. 1, No. 3, pp.25-33, 2011.

[20] D. Rekioua, " Power Electronics in Hybrid Renewable Energies Systems, " Green Energy and Technology, 39-77, Edition Springer, 2020.

[21] A. Mohammedi, D. Rekioua, T. Rekioua, S.Bacha, " Valve Regulated Lead Acid battery behavior in a renewable energy system under an ideal Mediterranean climate," International Journal of Hydrogen Energy, vol. 41, No.45, pp.20928-20938, 2016.

[22] B.Borowy and Z. Salameh, "Methodology for the Optimally Sizing the Combination of a Battery Bank and PV Array in a Wind/PV Hybrid System. "IEEE Trans. on Energy Conversion, vol. 11, No. 2, pp.367-375, 1996.

[23] M. Nikraz, H. Dehbonei, C.V. Nayar, "A DSP-Controlled PV System with MPPT."Australian Power Engineering Conference, Christchurch 2003, pp. 1–6.

[24] K. Kakouche, A Oubelaid, S. Mezani, D. Rekioua, T. Rekioua, "Different Control Techniques of Permanent Magnet Synchronous Motor with Fuzzy Logic for Electric Vehicles: Analysis, Modelling, and Comparison, " Energies 16 (7), 3116, 2023.

[25] O. Ibrahim, M.S. Bakare, T.I.Amosa, A.O. Otuoze, W.O. Owonikoko, E.M. Ali, Adesina L.M., Ogunbiyi O., "Development of fuzzy logic-based demand-side energy management system for hybrid energy sources," Energy Conversion and Management: X, 18, art. no. 100354, 2023.

[26] V.Boglou, C.-S., Karavas, K. Arvanitis, A. Karlis, "A fuzzy energy management strategy for the coordination of electric vehicle charging in low voltage distribution grids", *Energies*, 13 (14), art. no. 3709, pp.1-34, 2020.