ADVANCED CONTROL OF A CHARGE REGULATOR FOR AUTONOMOUS PHOTOVOLTAIC SOLAR SYSTEM

[1]IBRAHIMA GUEYE, [2]ABDOULAYE KEBE, [3]MOUSTAPHA DIOP, [4]PAPA MAKHTAR NDIAYE

[1,2,3,4] Ibrahima GUEYE, Université Cheikh Anta Diop Dakar, Laboratoire L3EPI, Ecole Supérieure Polytechnique, Ecole Normale Supérieure d'Enseignement Technique et Professionnel,
E-mail: [1]ibrahima64.gueye@ucad.edu.sn, [2]abdoulaye.kebe@ucad.edu.sn,[3]moustapha17.diop@ucad.edu.sn
[4]ndiayematar327@gmail.com

Abstract - In the context of the solar era and the challenges of energy autonomy, this study focuses on the design and optimization of an advanced control system for a charge regulator in standalone photovoltaic systems. By combining creativity and precision, we aim to efficiently harness solar energy while ensuring battery longevity and optimal energy management. Our approach employs advanced control algorithms, including fuzzy logic and PI regulation, to enhance the control of standalone photovoltaic systems. We implemented simulations using MATLAB/Simulink to compare the performance of these algorithms. The results show that the fuzzy logic-based controller improves response speed and energy efficiency compared to the PI regulator. Specifically, the simulations were conducted using a buck DC/DC converter and a battery as the load. Performance was measured in terms of dynamic response speed and energy efficiency. The fuzzy logic controller demonstrated a 25% reduction in response time and a 15% improvement in energy efficiency compared to the PI regulator, thus proving its superiority for this application. These results highlight the potential of fuzzy logic to optimize standalone photovoltaic systems by offering more efficient solar energy management and better battery protection. This research paves the way for more efficient and sustainable energy solutions for a brighter energy future.

Keywords - autonomous photovoltaic system, controller, PI regulation, Buck converter, fuzzy logic

I. INTRODUCTION

The past few years have seen a significant increase in electricity production from renewable energy sources, driven by environmental challenges and concerns over the limitation of traditional energy sources in the near future. The solar photovoltaic system plays a crucial role among these sources, offering advantages such as non-polluting energy production, reduced maintenance, and inexhaustible availability [1].

However, the conversion rate of the photovoltaic system remains relatively low. Factors influencing the power produced by the photovoltaic module include light intensity, temperature, and electrical loads. The charge regulation device plays a critical role in charging the batteries that store the energy generated by solar panels. It is crucial to have advanced control over this regulator to maximize the conversion of solar energy into usable electricity while preserving battery life and ensuring efficient electrical energy management.

The main goal of this article is to design an advanced control method that achieves an optimal balance between battery charging, energy management, and overall system efficiency using fuzzy logic. This becomes extremely beneficial when dealing with systems that are difficult to represent. Indeed, the use of fuzzy logic allows for the representation of knowledge in a primitive language.

For example, in her doctoral thesis approved at the University of Burgundy, Aouchiche Nedjma argues that fuzzy logic (FL) represents an improvement over traditional artificial intelligence algorithms for designing an optimized MPPT control for a photovoltaic system in terms of robustness, stability, and ease of use [2]. Her research examines various methods aimed at optimizing photovoltaic power, concluding that the Particle Swarm Optimization (PSO) method is the most effective with a success rate of 99.84%. The aim of this study is to enhance fuzzy control to surpass previous performances and compare this approach with traditional strategies such as PI control.

II. PHOTOVOTAIC (PV) SYSTEM

The studied system contains a photovoltaic panel, a Buck-type DC-DC converter, and a battery. The converter is controlled by a PWM signal derived from fuzzy logic control.

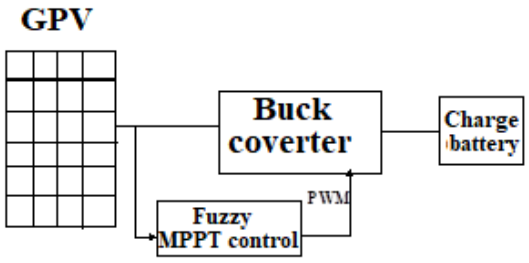


Figure 1.Descriptive diagram of the complete photovoltaic system

Photovoltaic generator

Among the various solar panel options available on MATLAB/Simulink, we have chosen the panel below.

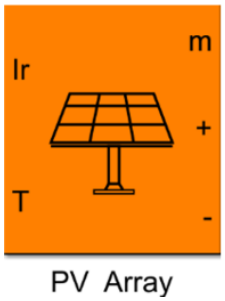


Figure 2. Solar Enertech (Shanghai) SE175-72M

Number of panels in series Ns : 4
Number of panels in parallel Np : 1

Characteristics of the PV generator	
Monocrystalline cell type	
Nominal power at STC Pmp (W)	175
Open-circuit voltage Voc (V)	44.8
Short-circuit current Isc (A)	5.17
Voltage at maximum power Vmp (V)	36.0
Current at maximum power Imp (A)	4.86
Weight (kg)	16.0

Table 1. Characteristics of the PV System

Influence of Temperature and Sunlight

The two main parameters influencing the operation of a photovoltaic generator are temperature and sunlight. Figures 3 and 4 depict the response of a photovoltaic cell based on these two parameters.

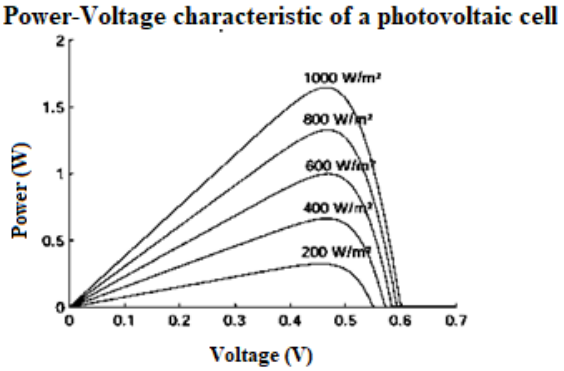


Figure 3.Effect of sunlight on the P-V characteristic of a PV cell

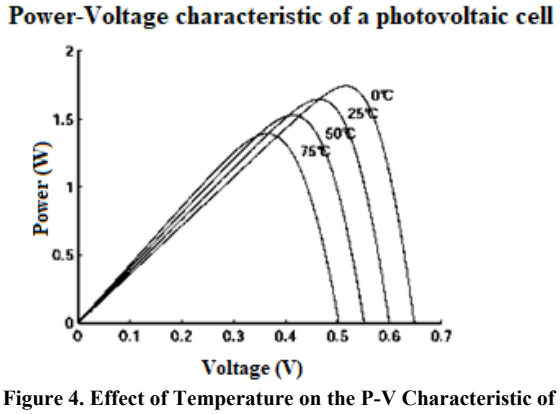


Figure 4. Effect of Temperature on the P-V Characteristic of a PV Cell

A. Modeling of the Buck-type DC-DC converter:

The buck converter consists of capacitors, inductors, and a switch. In the ideal case, none of these devices consume power, which is why buck converters have high efficiencies. The search for the maximum power point is achieved by varying the duty cycle of the converter [3]. The use of the buck converter is justified by the fact that the voltage supplied by the panel is higher than the battery voltage. DC-DC converters (buck converters) convert one DC voltage to another DC voltage. The principle of the buck converter involves periodically establishing and interrupting the source-load connection using an electronic switch. This switch must be able to be closed or opened to achieve an adjustable continuous output voltage.

It is used as a source-load adapter to extract the maximum power from the photovoltaic generator.

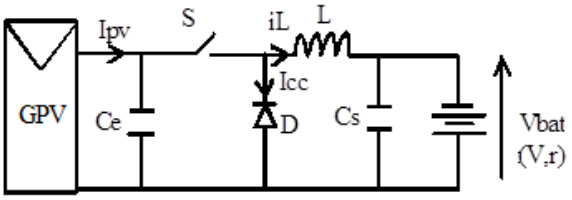


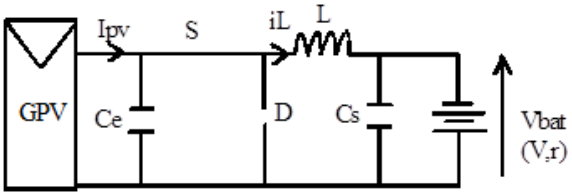
Figure 5 :Photovoltaic generator supplying a battery via Buck DC-DC Converter

With :

S: controlled triggering and blocking switch (bipolar transistor, MOS transistor, or IGBT) and a spontaneous blocking and triggering switch.
The load element is represented by the battery.

Operation of the buck converter

From the interval 0 to αT, we have switch S closed and diode D blocked.



✓ Applying Kirchhoff's voltage law, we have

$$V_{pv} = V_{bat} + L\frac{diL}{dt}$$

$$\frac{diL}{dt} = \frac{V_{pv} - V_{bat}}{L}$$

✓ By applying Kirchhoff's current law, we have

$I_{pv} = I_{ce} + iL$

However

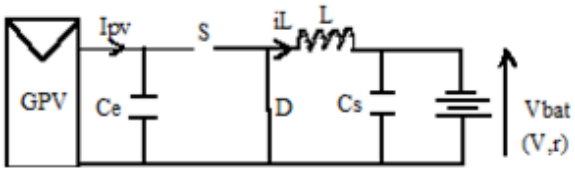
$I_{ce} = Ce\frac{dV_{pn}}{dt}$ and $I_{pv} = \frac{V_{pv}}{R_{pv}}$

We have :

$$\frac{V_{pv}}{R_{pv}} = Ce\frac{dV_{pn}}{dt} + i_L : \frac{dV_{pn}}{dt} = \frac{V_{pv}}{R_{pv} * Ce} - \frac{i_L}{Ce}$$

$$\begin{cases} \frac{di_L}{dt} = \frac{V_{pv} - V_{bat}}{L} \\ \frac{dV_{pn}}{dt} = \frac{V_{pv}}{R_{pv} * Ce} - \frac{i_L}{Ce} \end{cases}$$

- During the interval αT to T, we have switch S open and diode D conducting.



✓ Applying Kirchhoff's voltage law, we have

$$L\frac{di_L}{dt} + V_{bat} = 0 donc$$

$$\frac{di_L}{dt} = -\frac{Vbat}{L}$$

✓ By applying Kirchhoff's current law, we have :

$I_{pv} = I_{ce}$ or $I_{pv} = \frac{V_{pv}}{R_{pv}}$ and

$I_{ce} = Ce\ \frac{dVpn}{dt}$ this implies $\frac{dV_{pn}}{dt} = \frac{V_{pv}}{R_{pv}*Ce}$

$$\begin{cases} \frac{di_L}{dt} = -\frac{V_{bat}}{L} \\ \frac{dV_{pn}}{dt} = \frac{V_{pv}}{R_{pv} * Ce} \end{cases}$$

The average model of the converter is obtained by considering the two operating sequences: 0 < t < T [3].

$$\begin{cases} \frac{di_L}{dt} = \frac{\alpha V - Vbat}{L} \\ \frac{dVpn}{dt} = \frac{Vpv}{Rpv * Ce} - \frac{\alpha i_L}{Ce} \end{cases}$$

In the small-signal model framework, we assume that during dynamic phases, every variable x is expressed through .

x = X +x̆
X : average value ; x̆ : small variation
We have:

$$\begin{cases} v_{pv} = V_{pv} + \breve{V}pv \\ Il = I_l + \breve{i}_L \\ \alpha = \alpha_0 + \breve{\alpha} \end{cases}$$

With this change of variables, we obtain the following equations:

$$\begin{cases} \frac{diL}{dt} = \frac{\alpha 0 \breve{V}_{pv} + \breve{\alpha} V_{pv} - V_{bat}}{L} \\ \frac{dV_{pn}}{dt} = \frac{\breve{V}_{pv}}{R_{pv} * Ce} - \frac{\alpha 0\ IL + \breve{\alpha} i_L}{Ce} \end{cases}$$

By applying the Laplace transform, we can derive the transfer function of the buck converter, which is essential for implementing the control loop.

$$G(s) = \frac{\breve{V}_{pv}}{\breve{\alpha}} = \frac{Vbat + Li_L S}{-LCeS^2 + \frac{L}{R_{pv}} S - \alpha_0^2}$$

To optimize the voltage delivered by the solar panel during the maximum power point tracking, correction is essential. The parameters of the controller are calculated based on the information from the control loop [4].

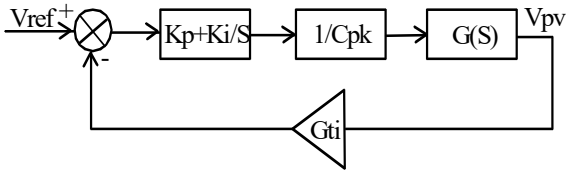


Figure 6:Transfer function of the control loop

$$H(s) = \left(Kp + \frac{Ki}{S}\right)\left(\frac{Gti}{Cpk}\right)(G(s)) =$$

$$(K_p + \frac{K_i}{S})(\frac{G_{ti}}{C_{pk}})\ (\frac{V_{bat} + Li_L S}{-LCeS^2 + \frac{L}{R_{pv}} S - \alpha_0^2})$$

The following expressions are obtained for the controller parameters:

$$K_p = \frac{Cpk}{Gti}\sqrt{\frac{(LCeW_c^2 - \alpha_0^2)^2 + (\frac{LWc}{Rpv})2}{P1 + P2}}$$

$$P_1 = (\frac{L^2 I_L \omega_c^2}{Rpv} + V_{bat}(LCe\omega_c^2) - \alpha_0^2)^2 P_2 =$$

$$L^2 I_L C_e \omega_c^3 - LI_L \alpha_0^2 \omega_c^2 - \left(\frac{LVbat\omega_c^2}{R_{pv}}\right)^2$$

$$K_i = \frac{K_p * \omega_c}{\tan(phm + \frac{\pi}{2} + \arctan K_1 - \arctan K_2)}$$

$$K_1 = \frac{L\omega_c}{R_{pv}(LC_e\omega_c^2 - \alpha_0^2)} K_2 = \frac{LI_L\ \omega_c}{V_{bat}}$$

Phm represents the phase margin; its value should be between 45 degrees and 65 degrees.
ω_c is the cutoff frequency.

❖ Design of the filtering process for the series converter

In order to ensure a constant current, it is necessary to determine the values of the inductance (L) and capacitor (C),which play a crucial role in filtering the output current [5].
For a series buck converter

- The formula for calculating the ripple current ratio is: $\Delta i_{Lmax} = \frac{V_{pv}}{4LF}$
- The formula for calculating the minimum capacitance of the capacitor is: $C = \frac{\Delta_i L_{max}}{8f\Delta_{vc}}$

B. Implementation of the fuzzy controller

The proposed fuzzy control has been designed based on four fundamental steps:

Definition of variables:

The inputs (E and CE) and the output (S) each have the following fuzzy variables: NPN (smallest negative), SN (small negative), GN (large negative), Z (zero), SP (small positive), GP (large positive), and LPGP (largest positive).

❖ **Fuzzification**

Fuzzification refers to the transformation of real variables into fuzzy variables using approved membership functions for the defined linguistic sets. The inputs to the fuzzy logic controller, E(k) and CE(k), undergo this conversion process.

$$E(k) = \frac{I(k) - I(k-1)}{V(k) - V(k-1)} + \frac{I(k)}{V(k)};$$
$$CE(k) = E(k) - E(k-1) \text{ [6,7].}$$

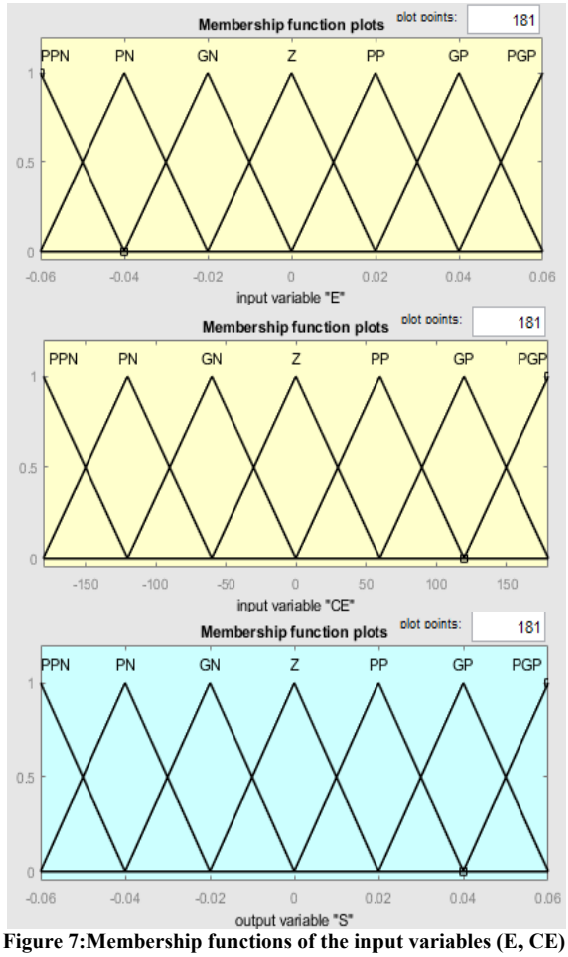


Figure 7:Membership functions of the input variables (E, CE) and output variable (S)

❖ **Inference rules**

Inference rules are conditional expressions that specify how the inputs (E and CE) are combined to produce the output S.

In our case, this operation is carried out using the Mamdani method.

CE / E	PPN	PN	GN	Z	PP	GP	PGP
PPN	Z	Z	Z	GP	GP	GP	GP
PN	Z	Z	Z	GP	GP	PP	PP
GN	Z	Z	Z	PP	PP	GP	GP
Z	PP	PP	Z	Z	Z	PN	PN
PP	PN	PN	PN	Z	Z	Z	Z
GP	PN	PN	PN	PN	Z	Z	Z
PGP	GN	GN	GN	GN	Z	Z	Z

Table 1.Inference matrix

❖ **Defuzzification**

Defuzzification is the inverse process of fuzzification in fuzzy logic. It converts a fuzzy conclusion (expressed in terms of linguistic sets) into a precise numerical value..

There are many defuzzification strategies; however, we have chosen the center of gravity method given by the following equation:

$$S = \frac{\sum_{j=1}^{n}(Dj) - Dj}{\sum_{j=1}^{n}\mu(Dj)} \text{[6].}$$

III. RESULTS AND DISCUSSIONS

A. Résults :

Classical PI Controller :

The internal parameters of the PI controller, such as the proportional coefficient (Kp) and the integral coefficient (Ki), play a crucial role in regulating the system's performance according to the specifications established in our requirements document. We will observe the variations in power and efficiency curves using the PI controller.

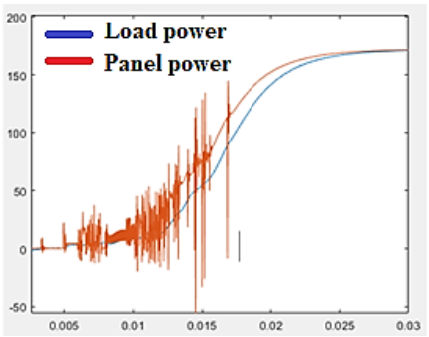


Figure 8 :Load power and photovoltaic panel power

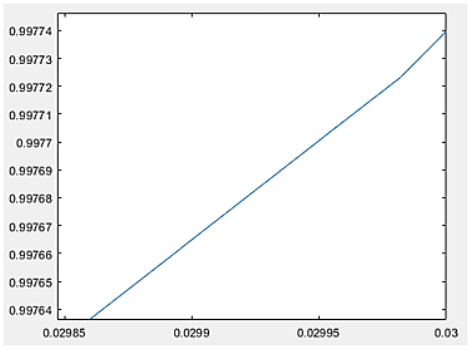


Figure 9: Efficiency under standard conditions

Fuzzy Controller:

The modeling of the photovoltaic system (PV system) is developed and implemented within the MATLAB/Simulink environment. This simulation was conducted in two phases using the fuzzy controller:

In the first phase, the shapes of the power curves, battery voltage, duty cycle, and efficiency were visualized under standard conditions (temperature = 25°C and irradiance = 1000W/m²).

Note: The load power is in blue, and the panel power is in orange (See below).

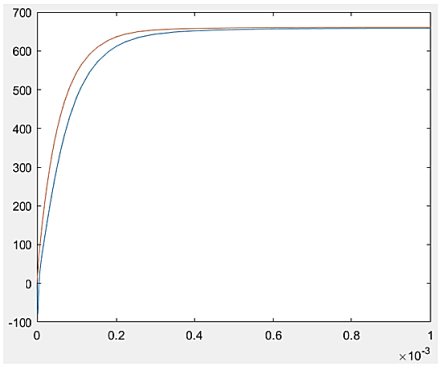


Figure 10:Load power and photovoltaic panel power

The figure 10 clearly shows that both powers were almost equal at 0.001s, demonstrating a significant preservation of the power provided by the panels.

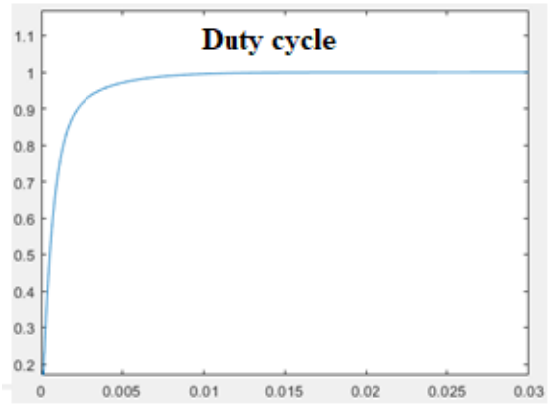


Figure 11: Duty cycle

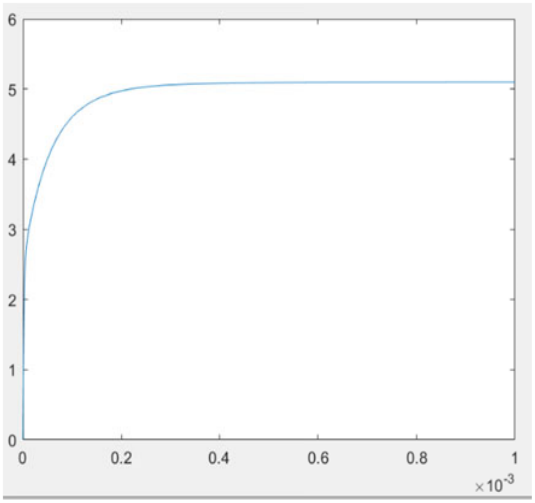


Figure 12: Battery voltage

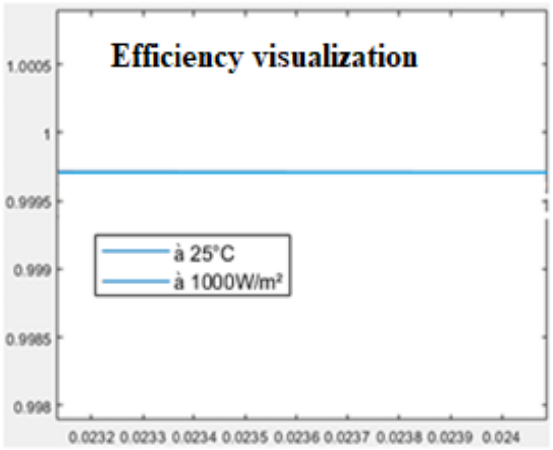


Figure 13: Efficiency under standard conditions

- Secondly, we visualize the efficiency by first varying
- Secondly, we visualize the efficiency by first varying

The temperature

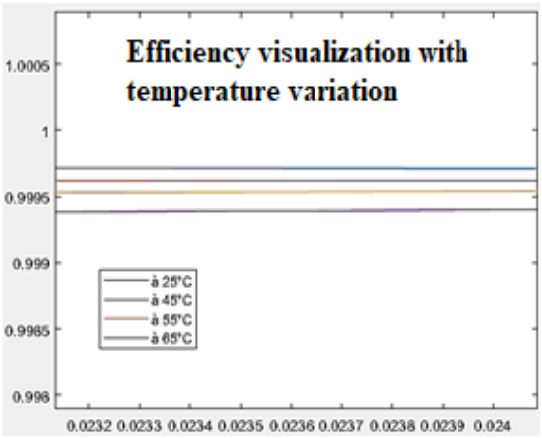


Figure 14:Efficiency as a function of temperature changes

Irradiance

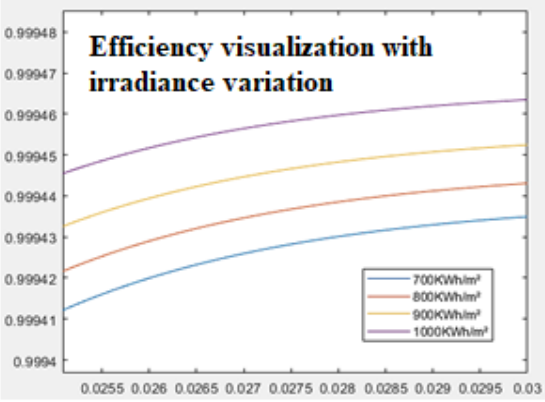


Figure 15:Efficiency as a function of irradiance changes

B. Discussions:

- For the PI controller, it is observed that the efficiency (99.74%) is satisfactory but does not meet a requirement from our specifications (efficiency ≥ 99.84%) under similar conditions. Additionally, we notice a longer response time with a lot of damping.
- Examining figures 10, 11, 12, 13, 14, and 15 highlights that the fuzzy controller exhibits exceptional performance, with remarkable efficiency (exceeding 99.95%) along with sufficient charging voltage for the battery and an almost equal duty cycle of 1. Furthermore, in addition to maintaining its efficiency under standard conditions, the controller exhibits consistently the same efficiency regardless of variations in temperature or irradiance.
- Compared to the PI controller, we can say that the fuzzy control is more precise, faster, and has no overshoots. It improves system performance and allows for achieving very good results.

IV. CONCLUSION

This article highlights the design steps, optimization methods, and results obtained from implementing an advanced control system for a standalone photovoltaic system charge regulator. The research specifically emphasized the benefits of fuzzy control for this application, demonstrating its significant contribution to improving the overall performance and reliability of these systems. Fuzzy control, with its ability to handle uncertainties and adjust parameters in real-time, offers a robust and flexible solution to the variations in weather conditions and electrical loads. This results in better energy management, increased photovoltaic conversion efficiency, and extended lifespan of system components. Additionally, improving system reliability is crucial for remote areas where access to electricity is limited and regular maintenance can be difficult and costly.

The results obtained show that integrating fuzzy control into photovoltaic charge regulators can reduce energy losses and ensure a more stable and continuous power supply. Moreover, the flexibility of this approach allows adaptation to future technological innovations and evolving energy needs. In conclusion, the study not only encourages the adoption of fuzzy control but also the modeling and simulation of various algorithms under different conditions. It also proposes exploring additional advanced control approaches to further optimize standalone photovoltaic systems. This could include machine learning and artificial intelligence techniques to predict optimal operating conditions and adjust system parameters accordingly, further enhancing the efficiency and resilience of these vital energy systems.

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