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ORIGINAL

Harmonic control in a photovoltaic microgrid and prediction using Monte Carlo simulation

Control de armónicos en una microrred de energía fotovoltaica y predicción mediante simulación de Monte Carlo

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ABSTRACT

Introduction: photovoltaic systems are a key alternative for electricity generation, although they present harmonic distortion due to inverters. However, this study presents alternatives to avoid continuity problems in the grid.
Objective: for this reason, this study analyzes harmonic mitigation in a microgrid modeled in real time at Redes y Telecomunicaciones Cotopaxi to ensure the stability, efficiency, and longevity of the equipment connected to the grid.
Method: evaluating three control strategies: conventional MPPT, MPPT with passive filter, and a fuzzy controller, using data measured in real time over a period of seven days.
This study was based on seven scientific articles, three websites, and regulations related to the topic.
Results: the results show that the fuzzy controller is the best option, reducing THDv to 4,09 % and THDi to 4,41 % with a stability time of 0,028 s, remaining within the limits established by the IEEE 519 standard and being a more economical alternative. while passive filters reduced THDv from 13,19 % to 0,69 % and THDi from 22,81 % to 0,03 %. However, this option involves a higher economic cost.
Conclusions: finally, the Monte Carlo method allowed the THD to be predicted with results similar to the FLC, validating its effectiveness under variable conditions and confirming its stability and efficiency.

Keywords: Fuzzy Logic; Harmonic; Prediction; Photovoltaic System.

RESUMEN

Introducción: los sistemas fotovoltaicos son una alternativa clave para la generación de electricidad, aunque presentan distorsión armónica debido a los inversores, sin embargo, este estudio presenta alternativas para evitar problemas de continuidad en la red.
Objetivo: por esta razón, este estudio analiza la mitigación de armónicos en una microrred modelada en tiempo real en Redes y Telecomunicaciones Cotopaxi para asegurar estabilidad, la eficiencia y la longevidad de los equipos conectados a la red.
Método: evaluando tres estrategias de control: MPPT convencional, MPPT con filtro pasivo y un controlador difuso, empleando datos medidos en tiempo real durante un periodo de siete días. Este estudio se basó en 7 artículos científicos, 3 sitios web y normativas acorde al tema.
Resultados: los resultados demuestran que el controlador difuso es la mejor opción logando reducir el THDv al 4,09 % y el THDi al 4,41 % con un tiempo de estabilidad de 0,028 s, manteniéndose dentro de los límites establecidos por la norma IEEE 519, siendo una alternativa más económica, mientras que los filtros pasivos redujeron el THDv de 13,19 % a 0,69 % y el THDi de 22,81 % a 0,03 %, sin embargo, esta opción implica un mayor costo económico.

Conclusiones: finalmente, el método de Montecarlo permitió predecir el THD con resultados similares al FLC, validando su efectividad bajo condiciones variable confirmando su estabilidad y eficiencia.

Palabras clave: Lógica Difusa; Harmónicos; Predicción; Sistema Fotovoltaico.

INTRODUCTION

In 2024, Ecuador faced an energy crisis due to low rainfall, which reduced hydroelectric generation and caused frequent power outages. This situation highlighted the National Interconnected System's (SNI) high dependence on water sources. In response, solar energy has emerged as a viable alternative not only to address energy crises, but also as a long-term solution that improves the reliability and continuity of electricity service.[1] In this context, solar generation has grown significantly over the last decade in both the commercial and residential sectors, offering benefits such as self-sufficiency, reduced dependence on the grid, and surplus compensation, thereby strengthening the reliability of the system.[2] However, according to the Electricity Master Plan[3], photovoltaic energy represents only 0,18 % of total generation (38,07 GWh), which demonstrates its limited use within the national energy matrix. According to the Solar Atlas of Ecuador[4] The country's equatorial location gives it a geographical advantage, receiving direct solar radiation throughout the year, which ensures a constant and reliable energy resource.

Despite this, solar modules do not always operate at their maximum power point due to climatic factors. MPPT techniques are used to optimize their performance, although these face challenges in terms of response speed, which has led to the use of fuzzy logic-based strategies, which are adaptable and accurate under varying conditions.[5] According to Zehan[6], fuzzy logic in MPPT employs linguistic rules, which allow it to adapt to nonlinear variations without requiring an exact mathematical model. For his part, Abbas[7] describes that these techniques employ membership functions (triangular, trapezoidal) to transform the power error and its derivative into control actions. However, Oussoul.[8] He points out that the performance of these systems depends on the appropriate design of the rules and membership functions (MFs), which are adjusted using simulations or experimental data.

Lastly, Adam J.[9] It is mentioned that photovoltaic systems (PFS) can cause harmonic distortion and increase the short-circuit current, because the inverters act as nonlinear loads, generating harmonics that distort the waveform. This distortion is measured by the percentage of total harmonic distortion (THD). In this regard, IEEE standards 519.[10] and ARCONEL-009/24.[11] They establish maximum limits of harmonic distortion (THD) in order to protect both the electrical network and the connected equipment, setting a maximum THD of ≤5 % in both voltage and current.

Given this problem, this study designs a fuzzy logic controller (FLC) for maximum power point tracking (MPPT) in a photovoltaic system connected to a microgrid developed in MATLAB-Simulink software. Its main objective is to improve the dynamic response of the system, reduce harmonics, and maintain operational stability, complying with the limits established by IEEE 519 and ARCONELL-009/24 standards.

Nomenclature

The following abbreviations are used in this manuscript:

- MPPT: Maximum Power Point Tracking.
- FLC: Fuzzy Logic Controller.
- P&O: Disturber and Observer.
- SFV: Photovoltaic System.
- THD: Total Harmonic Distortion.
- FPS: Passive filter.

METHOD

The study is a simulated experiment that seeks to reduce THD in a photovoltaic system connected to a microgrid using a fuzzy logic controller (FLC), complying with IEEE 519 and ARCONEL-009/24 standards. The methodology includes the design of the microgrid, the implementation of the FLC, P&O and P&O with filter, and the simulation of the system to compare its performance between the different controllers. The unit of analysis is the photovoltaic microgrid model, and the sample consists of the three types of controllers evaluated.

Microgrid Design

Irradiance and temperature values were measured in real time using an Apogee MP-200 pyranometer and compared with NASA data, demonstrating minimal error, validating their use in system analysis.

A 7-day sampling interval corresponding to the month of February was used in the parish of San Felipe, Latacunga. The improved database was integrated into the microgrid model, and simulations were performed in MATLAB-Simulink considering three dynamic scenarios in order to analyze the robustness and effectiveness of each controller. The FFT analysis tool available in the software was used to compare the optimal controller.

Simulation of the photovoltaic system

The microgrid was then simulated by entering the solar panel parameters obtained in the study area, (Short-circuit current 13,95(A), Open-circuit voltage 41,014 (V), Rated power (350W), Type (Monocrystalline)), along with the final irradiance and temperature data for greater accuracy.[12] The photovoltaic array was then connected to the grid via a buck-boost converter, which regulates the DC voltage sent to the inverter. This converts the signal into AC voltage, facilitating grid synchronization and improving power quality through appropriate controls.

The converter model includes its work and transformation relationships, obtained from equations (1), whose values are represented by: Inductor (110 uH), Input capacitor (10 mF), Output capacitor (6,2 mF), Duty cycle (0,3832).

$$C_{in} = \frac{I_E(1-\delta)}{f \Delta V_{C_{in}}}, L = \frac{(1-\delta)^2 R}{2f}, \delta = \frac{V_O}{V_{in}\sqrt{\frac{R}{2fL}}} \quad (1)$$

Rules

Fuzzy Logic Controllers (FLCs) are notable for operating without a mathematical model, allowing them to adapt to nonlinear systems and improve power extraction in photovoltaic systems. Furthermore, they respond appropriately to changes in temperature and irradiance. FLCs are composed of three operating units, Fuzzification, Defuzzification, Rule evaluation.

Fuzzification

The membership functions for the power and voltage inputs are divided into five fuzzy linguistic categories: large negative (LNG), medium negative (MN), zero (Z), medium positive (MP), and large positive (LP). The output is also organized into these five groups, distributed within a defined range.

Defuzzification

Defuzzification transforms the fuzzy value into a precise signal that serves as a reference. The Fuzzy Logic Controller (FLC), in conjunction with the MPPT algorithm, generates an output based on the membership functions of the inputs. This signal is converted into a PWM pulse, which is applied to the gate of the IGBT. Buck-Boost converter.

Rule evaluation

The inputs, power and voltage, have triangular membership functions from -1 to 1, divided into five categories: NG (-1 to -0,58), NM (-0,58 to 0), Z (-0,5 to 0,5), PM (0 to 0,58), and PG (0,58 to 1). The “duty” output ranges from -0,01 to 0,01 and follows the same classification with tight ranges, as shown in figure 1.

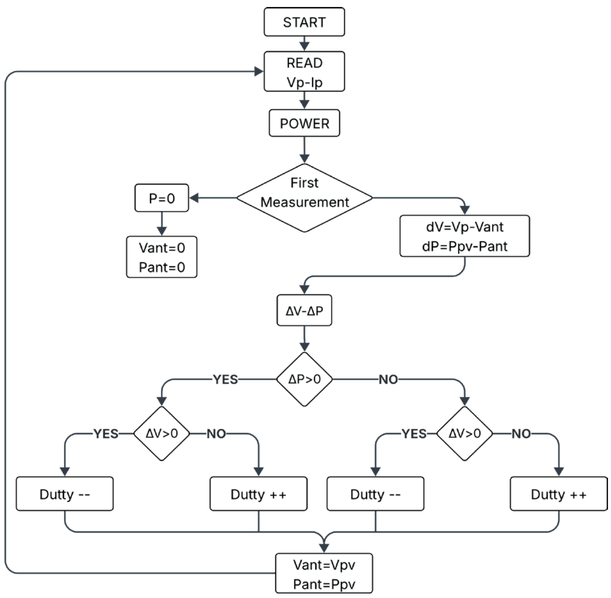

Figure 1. Fuzzy rule flowchart

RESULTS

Simulation results

Figure 2 shows a MATLAB-Simulink simulation of a fuzzy controller for a grid-connected PV system. The model includes a PV module connected to a buck-boost converter, controlled by an MPPT algorithm that calculates the power and voltage derivatives. The controller generates a reference current to produce PWM signals that regulate the converter and the DC-AC inverter. The latter supplies a grid-synchronized load, achieving optimal integration.

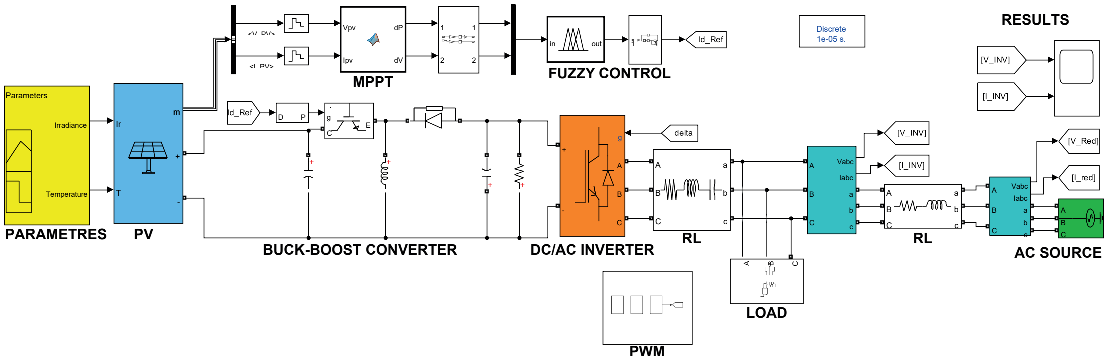

Figure 2. Study model using Matlab-Simulink

This section shows the simulation results for three scenarios: conventional MPPT control, MPPT with a Passive Filter, and a grid-connected Fuzzy Controller. The simulated system is a 120 V photovoltaic generator connected to the grid to power an electronic load.

MPPT Control

Figure 3 shows the voltage and current signals of an MPPT control without harmonic filter, where the maximum current per phase reaches 31 A and the voltage is maintained at 120 V. During the first 0,044 s, significant distortion is observed in both signals, indicating an initial instability that affects the quality of the power supply. The analysis using the Fast Fourier Transform (FFT), applied to the first six operating cycles of one of the three phases, reveals total harmonic distortion (THD) levels higher than the limits established by the IEEE 519-2014 standard, with a voltage THD of 13,19 % and current of 22,81 %, which demonstrates the need to implement corrective measures to ensure compliance with quality standards.

MPPT Control with Filter

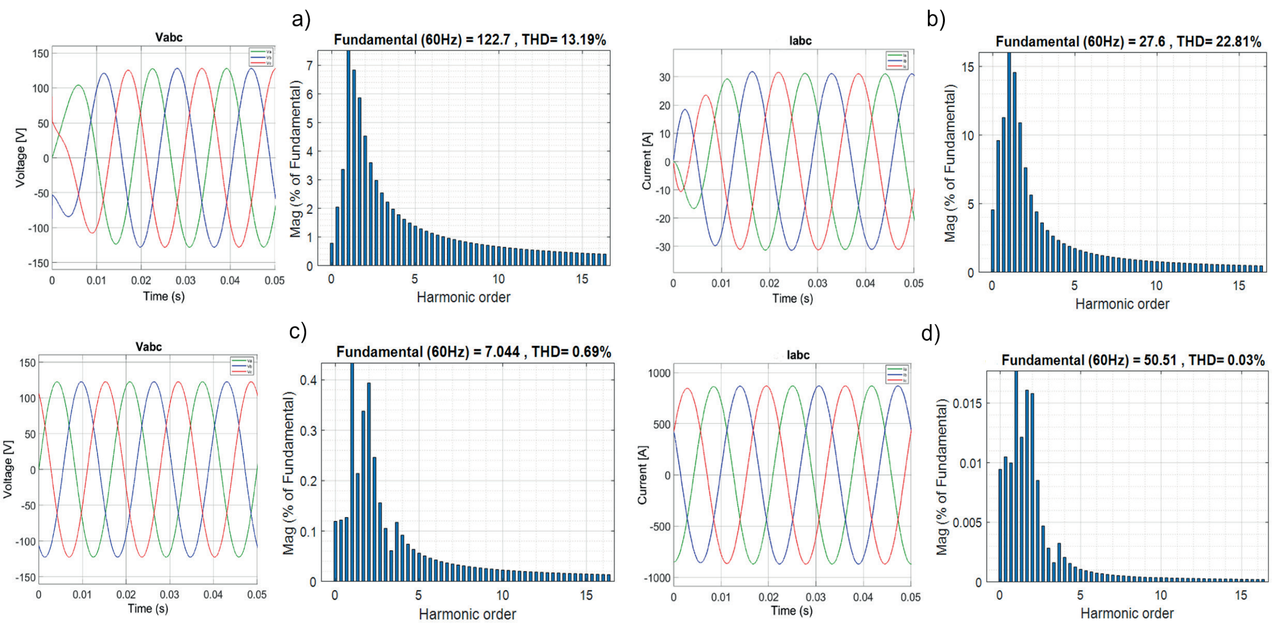

Figure 3. (MPPT Control) a) Voltage signal and THD level of the voltage under MPPT control, b) Current signal and THD level of the current under MPPT control. (MPPT Control with Filter) c) Voltage signal and THD level of voltage with FPS, d) Current signal and THD level of current with FPS.

By incorporating a passive filter into the MPPT control, the results show a significant reduction in the voltage and current THD in one of the three phases, as observed in figure 3. This improvement reflects a notable optimization in power quality, remaining within the limits established by the IEEE 519-2014 standard, with a voltage THD of 0,69 % and a current THD of 0,03 %. In addition, a slight transient distortion is observed during the first 0,01 s. The use of passive filters is proven to be one of the most effective solutions for mitigating harmonics and improving the energy performance of the system.

Fuzzy Controller

Lastly, the fuzzy logic (FLC)-based MPPT control system showed a voltage THD of 4,09 % and a current THD of 4,41 %, with distortion present during the first 0,028 s. According to IEEE standard 519-2014, these values are within permissible limits, since for systems below 69 kV, a voltage and current THD of up to 5 % is permitted. The waveforms observed in Figure 4 exhibit sinusoidal behavior, reaching values of up to 120 V for voltage and 59 A for current, respectively. Although the distortion levels are higher than those obtained with the use of passive filters, the fuzzy controller guarantees a fast dynamic response and acceptable power quality, making it a viable alternative for environments with nonlinear conditions.

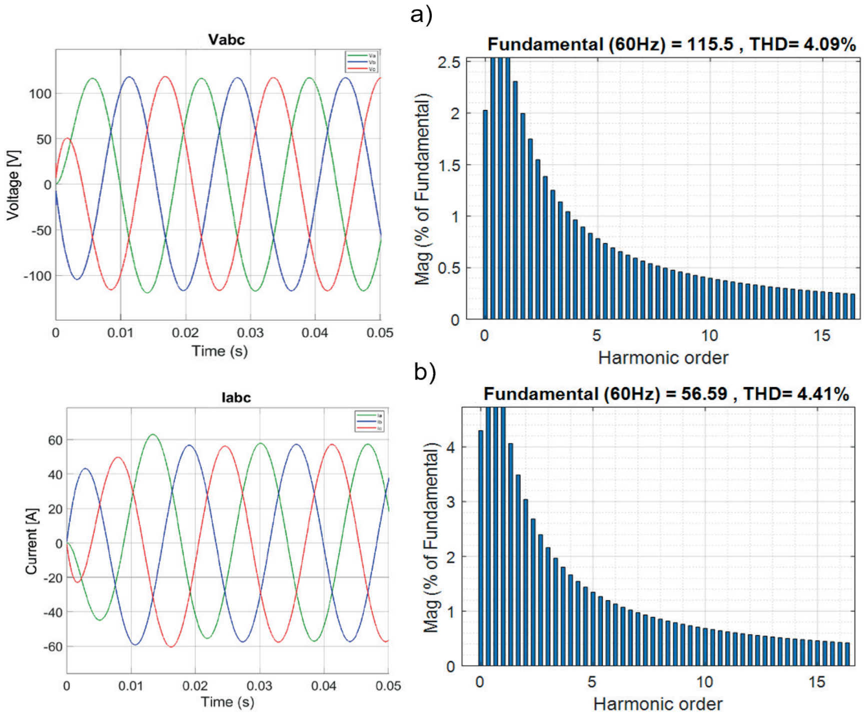

Figure 4. a) Voltage signal and THD level of the voltage under FLC control, b) Current signal and THD level of the current under FLC control

Table 1 summarizes the THD and stability time values for the different types of control implemented, allowing comparison of system performance in terms of power quality and dynamic response.

Table 1. Comparison between THD and voltage and current stability

Control	THDv (%)	THDi (%)	Stability Time (s)
MPPT	13,19	22,81	0,04
MPPT with Filter	0,69	0,03	0,01
FLC	4,09	4,41	0,028

Harmonic Prediction

The Monte Carlo method was applied to predict the THD, with the purpose of estimating the uncertainty and reliability of the results obtained, from the original series, multiple simulations were performed, which allowed analyzing the variability. The statistical accuracy of the method was determined by means of the expression (2).

$$\sigma_\mu = \frac{\sigma}{\sqrt{N}} \quad (2)$$

Where σ represents the standard deviation and N the number of simulations performed, thus ensuring that the values obtained are within an acceptable range for THD analysis in compliance with the IEEE 519 standard.

To estimate the total harmonic distortion in the photovoltaic inverter, input parameters based on irradiance and temperature were used. The Monte Carlo method was employed for the prediction over a 7-day period. Harmonic measurements were taken using a Fluke device, obtaining a total of 672 data points, which are crucial for predicting the THD % in the inverter. The resulting values from this method showed a high similarity with those obtained in our simulation, recording a THD of 4 % with a relative error of 5 %. Figure 5 shows the Monte Carlo method for the prediction.

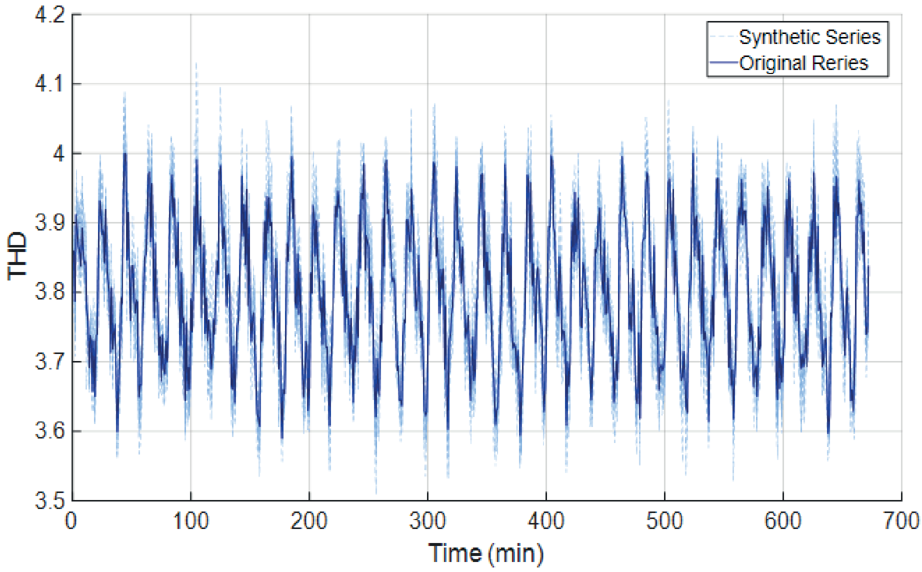

Figure 5. Monte Carlo method used to predict THD

DISCUSSION

The results indicate differences among the three methods evaluated for harmonic control in a microgrid. The traditional MPPT showed low accuracy in the face of rapid variations in irradiance and temperature, demonstrating limited robustness that can lead to transient errors and a decrease in the system's energy efficiency. Similar results were reported by Logan and Jothi(5) who pointed out that classical methods for tracking the maximum power point perform less well under dynamic conditions.

On the other hand, the fuzzy logic controller (FLC) showed more stable behavior in the face of disturbances and a better response to changing conditions without the need for a specific model, making it an ideal choice for microgrids where disturbances exist. The THD values obtained (4,09 % in voltage and 4,41 % in current) are within the limits established by the IEEE 519 standard, confirming their effectiveness in reducing harmonic distortion. This result coincides with that proposed by Zehan et al.(6), who demonstrated that fuzzy controllers improve power quality and offer a faster response to environmental variations. This control not only represents a cost-effective alternative, but also requires a more detailed initial design, including the creation of fuzzy rules, without the need for complex mathematical models.

As for the prediction of THD using the Monte Carlo method, it proved to be an effective tool for evaluating the system's harmonic distortion, incorporating variables such as temperature and irradiance. The results obtained indicate that THD levels remained around 4 %, within the limits established by the IEEE 519 standard, thus validating the performance and effectiveness of the fuzzy controller. This approach provides a more complete view of system behavior under different energy scenarios, ensuring its long-term reliability and efficiency.

CONCLUSIONS

This study evaluated the mitigation of harmonics generated by the inverter of a photovoltaic system (PVS) in a microgrid located in the San Felipe area, Latacunga canton, through the implementation of three control strategies. It was found that irradiance and temperature variables directly affect total harmonic distortion (THD) levels, being higher when irradiance is low.

The results show that the fuzzy logic controller (FLC) proved to be an effective alternative for improving the dynamic response of the photovoltaic system and reducing total harmonic distortion (THD) in the microgrid analyzed. This approach allowed for more efficient use of available solar energy, ensuring greater operational stability and complying with the limits established by the IEEE 519 standard.

On the other hand, the application of the Monte Carlo method allowed for highly accurate predictions of THD behavior under variations in irradiance and temperature, providing a probabilistic assessment of the system's performance. This approach not only validates the effectiveness of FLC in changing conditions, but also demonstrates its potential as a diagnostic and optimization tool in the design of smart controllers for photovoltaic microgrids.

Finally, it is recommended that future work integrate machine learning algorithms to improve the prediction and mitigation of harmonics.

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FINANCING

None.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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