

Photovoltaic System Regulation Based on a PID Fuzzy Controller to Ensure a Fixed Settling Time

Regulación de un Sistema Fotovoltaico Basada en un Controlador PID Fuzzy para Asegurar un Tiempo de Establecimiento Constante

Paula A. Ortiz-Valencia¹
Adriana Trejos-Grisales²
Carlos A. Ramos-Paja³

1 Facultad de Ingenierías, Instituto Tecnológico
Metropolitano, Medellín-Colombia
paulaortiz@itm.edu.co

2 Facultad de Minas, Universidad Nacional de Colombia
Sede Medellín, Medellín-Colombia
latrejosg@unal.edu.co

3 Facultad de Minas, Universidad Nacional de Colombia
Sede Medellín, Medellín-Colombia
caramosp@unal.edu.co

Abstract

The main objective of the controllers in photovoltaic systems (PV) is to ensure the maximum extraction of the available power. Those controllers usually combine the action of a maximum power point tracking algorithm (MPPT) with a voltage regulator, which has the function of rejecting disturbances at the panel terminals. Such controllers are commonly based on PI and PID structures, it requiring linearized models at an operating point. But, due to disturbances generated by the environment and the load, the operating point of the system changes drastically, which hinder to obtain the desired system performance. This paper proposes to regulate the PV system using a Fuzzy PID controller, which adapts to changes in solar irradiance and load oscillations. This characteristic guarantees a constant settling time, which is required to precisely define the period of the MPPT algorithm. In the case of classical linear controllers, the period of the MPPT algorithm is set to the worst case (longest period) which generates additional power losses by slowing down the tracking of the optimal operating point. Therefore, the solution proposed in this paper improves the overall system efficiency. Finally, such a solution is validated through simulations in Matlab®.

Keywords

Photovoltaic system; maximum power point; PID controller; ANFIS; Fuzzy.

Resumen

El objetivo principal de controlar los sistemas fotovoltaicos (PV) es asegurar la máxima extracción de potencia disponible. Estos controladores usualmente combinan la acción de un algoritmo de seguimiento del punto de máxima potencia (MPPT) con un regulador de tensión, el cual tiene la función de rechazar las perturbaciones en los terminales del panel. Estos controladores se basan comúnmente en estructuras PI-PID que requieren modelos linealizados alrededor del punto de operación. Pero, debido a perturbaciones generadas por el ambiente y la carga, el punto de operación cambia drásticamente, lo que dificulta obtener el desempeño deseado. Este artículo propone regular el sistema PV utilizando un controlador Fuzzy-PID, el cual se adapta a los cambios de irradiancia solar y oscilaciones en la carga. Esta característica garantiza un tiempo de establecimiento constante, el cual se requiere para definir de forma precisa el periodo del algoritmo MPPT. En el caso de controladores lineales, el periodo del MPPT se fija en el peor caso (periodo más largo), lo cual genera pérdidas de potencia adicionales al disminuir la velocidad del seguimiento del punto de operación óptimo. La solución propuesta en este artículo mejora la eficiencia general del sistema. Finalmente, la solución se valida con simulaciones en Matlab®.

Palabras clave

Sistema fotovoltaico; punto de máxima potencia; controlador PID; ANFIS; Fuzzy.

1. INTRODUCTION

Renewable energies are based in resources which are considered inexhaustible like the sun, the wind, water bodies, or earth inner heat. The extraction of energy through those kinds of sources is becoming an important research area, particularly photovoltaic (PV) systems. Facts like the high cost of conventional energy generation, environment issues, and high risk of nuclear energy, encourage the recent interest in this area. Moreover, the current breakthroughs in power electronics and processor technologies provide suitable tools for the development of new advances in renewable energy applications (Choi et al., 2012). Due to its geographical location, Colombia provides optimal conditions for photovoltaic generation (CVN, 2012). In the last years, the Colombian Government has invested in the development and application of alternative technologies for energy production through strategies as PROURE (Programa de uso racional y eficiente de la energía y demás formas de energía no convencional) (Ministerio de Minas y Energía, 2010), strengthening the researching in this area.

In PV systems, the main objective of the control strategies is to ensure the extraction of the maximum power available in the source. This process is commonly made by implementing a maximum power point tracking algorithm (MPPT) in cascade with a voltage regulator, which is oriented to reject load and environment disturbances. The interface between the PV panel (source) and the load is usually implemented through power electronics based equipment, where the double stage (DS) structure is widely adopted. Fig. 1 shows such a structure, which is considered effective in terms of controllability, since the first stage is intended to perform the MPPT while the second stage is oriented to the current modulation and factor power correction (Trejos et al., 2012).

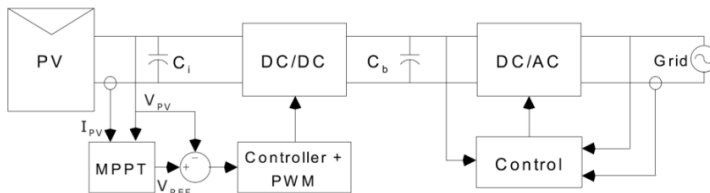


Fig. 1. Double stage architecture. Source: (Trejos et al., 2012)

Several MPPT techniques have been reported in literature, but due to its ease and low cost implementation, the Perturb and Observe (P&O) algorithm is the most widely used (Ishaque & Salamb, 2013). This algorithm tracks the maximum power point (MPP) by perturbing the voltage of the PV array and observing the power drawn from the PV array. Although the P&O algorithm is very attractive for PV applications, some of its drawbacks are: in steady state, the operating point oscillates around the MPP causing power losses, slow response speed, and even tracking in wrong way under rapidly changing atmospheric conditions (Sera et al., 2013). Some improvements to the P&O algorithm have been proposed: in (Femia et al., 2009) the issue of low frequencies disturbances coming from the grid is addressed by proposing a compensation network, while in (Petrone et al., 2011) a multivariable P&O algorithm is proposed. The performance of the algorithm depends on the perturbation amplitude and sampling interval, where the latter must be according with the dynamic behavior of the DC/DC converter.

This paper focuses on the problem of defining the sampling interval, presenting the design and simulation of a PV system using a Fuzzy PID controller, which adapts the system to compensate different perturbations as: irradiance changes and load oscillations. This kind of controller allows to guarantee a constant settling time. Such a characteristics allows to accurately define, the time perturbation required by the MPPT algorithm, which is not possible by using classical controllers like PI or PID, where the perturbation time must be overestimated causing additional power losses. The paper is organized as follows: section 2 presents the modeling of the PV system, the concepts related to P&O algorithm and the Fuzzy PID controller. Section 3 presents the simulation results and its discussion. Finally, section 4 gives some conclusions.

2. MODELING AND CONTROLLING THE PV SYSTEM

Fig. 2 shows the typical DC/DC conversion scheme based on a boost converter, which is commonly used for control purposes. In

the case of this work a loss-free PV system was modeled, moreover this system considers the voltage load model, which represents the bulk capacitor, the DC/AC inverter that regulates the bulk voltage, and the connection to the grid (Trejos et al., 2012).

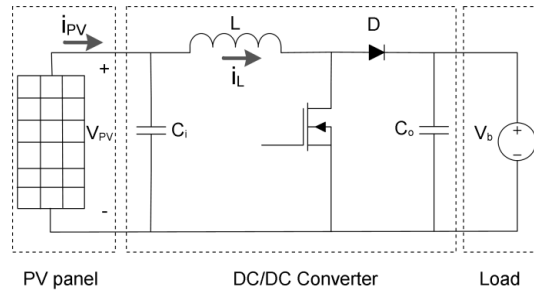


Fig. 2. PV system based on a boost converter. Source: (Trejos et al., 2012)

The dynamic equations (1) and (2) represent the PV system in state space, where the inductor current i_L and the input capacitor voltage v_{Ci} are the state variables, while the control variable is the DC/DC converter duty cycle d . The bulk voltage v_b and PV panel current i_{PV} are the perturbation variables of the system.

$$\frac{di_L}{dt} = \frac{v_{Ci}}{L} - \frac{v_b(1-d)}{L} \tag{1}$$

$$\frac{dv_{Ci}}{dt} = \frac{i_{PV}}{C_i} - \frac{i_L}{C_i} \tag{2}$$

2.1 Model of the PV Panel

Several models to represent the PV panel from cells to arrays have been reported in literature (Trejos et al., 2012). Those models are nonlinear, in consequence they are too complex for controller design and therefore for control purposes linear models have been introduced to modeling PV systems, among which the Norton model has been widely used (Petrone et al., 2011). In this work, a nonlinear model was used since the simulation in Simulink® allows to implement function blocks, therefore for modeling the PV

panel it was used a simplified model based on the classical single-diode model (Petrone & Ramos-Paja, 2011), (3) represents the relation between the current and voltage of the PV panel.

$$i_{pV} = I_{ph} - A \left[\exp\left(\frac{V_{pV}}{B}\right) - 1 \right] \quad (3)$$

Coefficients A and B are related to inherent PV panel and environment characteristics; they can be obtained from the datasheet of the PV panel and temperature measurements. In this paper the values used for A and B are 1.5415e-8 A and 1.1088 V, respectively, which belongs to a BP-585 PV panel (Bastidas et al., 2013).

2.2 P&O Algorithm

Among the MPPT techniques, the P&O algorithm has been widely used due to its simple implementation. This MPP tracking technique operates periodically perturbing the voltage (increasing it or decreasing it), measuring the power variation after perturbation and depending on that variation, the sign for the next perturbation must be chosen. In other words, the algorithm tracks the MPP following the P-V characteristic of the PV panel, searching the operating condition in which the derivate of the power in function of the voltage is zero (Sera et al., 2013). Despite its simplicity and relatively good performance, one of the drawbacks of the P&O algorithm is that, at steady state, the operating point oscillates around the MPP causing waste of available energy. It also has a poor dynamic performance when a change in irradiance occurs (Femia et al., 2005).

The algorithm is based in two parameters: the perturbation amplitude and sampling interval, whose can be optimized to provide a higher efficient algorithm. The problem of choosing the sampling time is related to the changes in the atmospheric conditions since they cannot be predicted. In general, the sampling interval should be chosen to avoid instability of the MPPT algorithm and to reduce the number of oscillations around the MPP in steady state (Femia et al., 2005). If the algorithm samples the power in the PV array too quickly, it may incur in mistakes caused

by the transient behavior of the complete system composed by the PV array and the converter such a situation implies a confusion in the operating point causing wrong operation and decrement of the produced energy. Classical controllers like PI and PID are commonly used in PV application (Gonzalez et al., 2011); those controllers require linearized models at an operating point but due to disturbances generated by the environment and the load, the operating point of the system may change drastically. Therefore, such classical controllers require to set the sampling interval to the worst case: the longest period. Hence, an adaptive controller is required.

2.3 ANFIS System

An ANFIS network is a neuro-fuzzy inference system, which combines the expert knowledge through fuzzy rules providing an intuitive but high level mechanism of representing the system behavior (Naderloo et al., 2012), with the learning capability of artificial neural networks. The equivalent ANFIS architecture for the first order Takagi-Sugeno inference system is shown in Fig. 3. In a formal way, this neural network can be defined by (4):

$$yr_m = C_{jm}S_{jn} = C_{jm}e^{-\frac{1}{2}\left(\frac{\|XC_{j,i}-X_i\|}{R_j}\right)^2} \quad (4)$$

where yr_m represents the model for each output variable, $XC_{j,i}$ indicates the number j of fuzzy sets which corresponds to each input variable i , R_j indicates the size of each of the j fuzzy sets, C_{jm} : indicates the output weights of the neuro-fuzzy model for j according to the dynamic variable m and S_{jn} indicates the normalized output values for each one of neurons of the hidden layer of the ANFIS model as is shown in (5):

$$S_{jn} = \frac{S_j}{S_1 + S_2 \dots + S_{ne}} \quad (5)$$

In (5), ne is the number of multidimensional fuzzy sets that covers the solution problem space. In this way, the ANFIS neuro-

fuzzy model configures a first order Takagi-Sugeno inference system, taking into account that the conformation of the fuzzy sets, which compose the input variables of the rules antecedent, is obtained through a Cartesian decomposition of the clusters formed in the hidden layer.

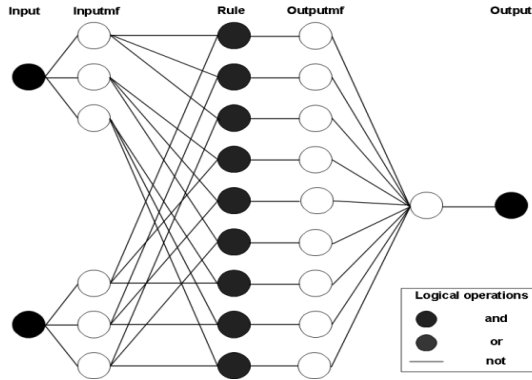


Fig. 3. ANFIS structure for the proposed control system. Source: Authors

Fig. 4 shows the form of a cluster obtained in the hidden layer of an ANFIS model considering a model with two input variables (I_{pv}, V_{pv_ref}) and one output variable (K_p). Such a figure corresponds to the proportional gain K_p , integral and derivative gains are constant.

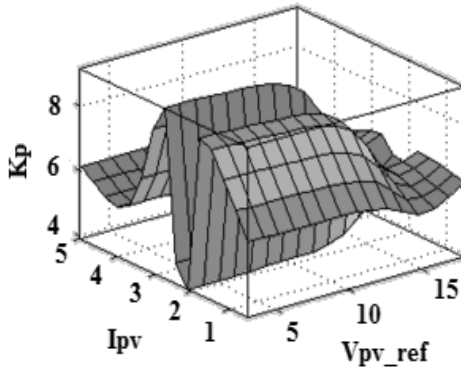


Fig. 4. Clusters form in the hidden layer of the ANFIS identification model in the space. Source: Authors

The training of the network consists in 9 rules *if-then* and the optimization is carried out by using the backpropagation method (Valencia et al., 2006). The network has been trained to reach an error less or equal to 10^{-3} with a limit of 100 epochs.

3. RESULTS AND DISCUSSION

The system was simulated in Simulink®. The parameters of the converter were: $L=56$ uH, $C=44$ uF, $V_b=33.5$ V. Fig. 5 presents the P-V characteristic for different irradiance levels, where it can be noted that only one maximum power point exists for each condition.

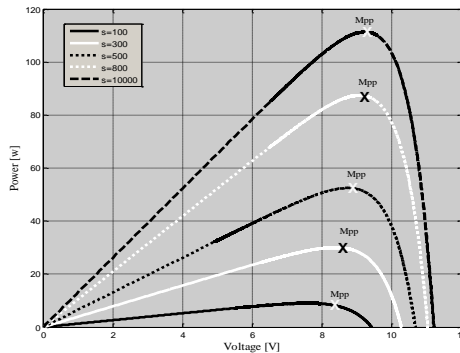


Fig. 5. P-V characteristics. Source: Authors

Fig. 6 presents the behavior of the system in presence of different perturbations at the reference voltage, irradiance and load voltage, where it is observed the satisfactory response of the proposed controller. In such results, the constant settling time required for the MPPT algorithm is guaranteed, while all the perturbations are effectively rejected. In addition, the adaptability of K_p to the system operating conditions are also observed.

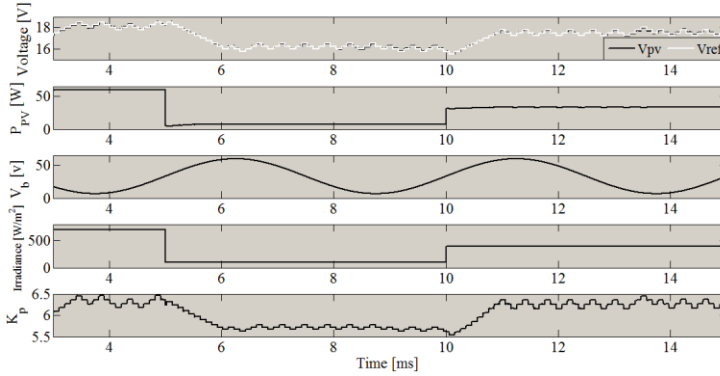


Fig. 6. System response with irradiance changes. Source: Authors

Fig. 7 shows the comparison between the PID and ANFIS controllers. It must be noted that the response of the system controlled by the PID controller changes depending on the operating point, which causes instability and power losses. Instead, the Fuzzy proposed controller provides a uniform performance despite the operation conditions change.

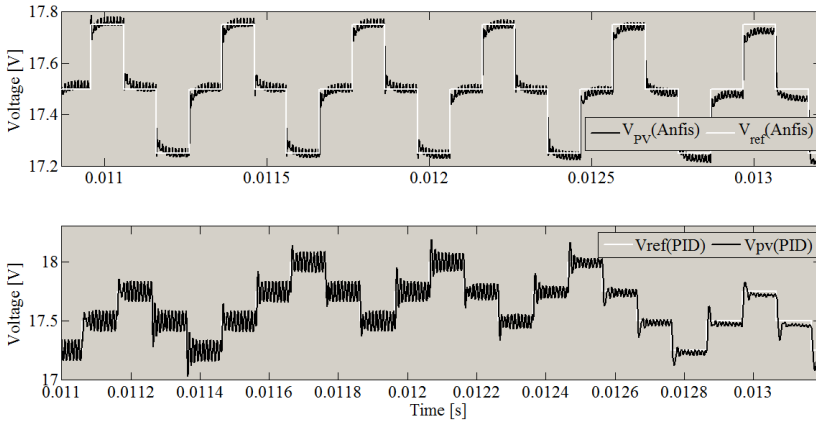


Fig. 7. Comparison between V_{pv} and V_{ref} obtained with ANFIS and classical PID controller. Source: Authors

4. CONCLUSION

This paper has presented the design of a PID ANFIS controller and its application on a PV system. The proposed controller does not require a linear model of the PV system, hence its performance is not constrained to work around a given operating point. The application of the ANFIS controller guarantees that the system adapts to a pre-established dynamic and responds accurately to irradiance changes and load perturbations. The behavior of the system under the operation of the ANFIS controller allows to define a suitable perturbation time which is required for the P&O algorithm in order to avoid instability and power losses as in the case of classical PI and PID controllers which only guarantee a correct operation around the design operating point. Simulation results validate the proposed solution, which exhibits a suitable performance under system perturbations. In addition, the proposed controller was contrasted with a typical PID controller under changes in the irradiance and the load, where a good performance of the proposed controller was observed.

5. ACKNOWLEDGMENT

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