Power Conversion Performance of a Single-Phase PV Inverter with Fuzzy Logic Algorithm

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Abstract. The paper presents a low-power conversion system focusing on implementing new solar inverter control techniques implemented with Fuzzy Logic. The power generated by a solar panel requires robust approaches and efficient methods to be used at its maximum. Therefore, a promising strategy is a Fuzzy Logic based on the Maximum Power Point Tracking (MPPT) algorithm. To gather efficient power conversion, our proposed model uses a control loop composed of Fuzzy Proportional Integrative (PI) regulators, Clarke and Park transform, followed by a synchronization grid mechanism Second-order generalized integrator (SOGI) based phase-locked loops (PLLs). The proposed technique examines photovoltaic system (PV) performance with respect to its non-linearities and eventual shaded conditions that can occur in the PV array. The shading effect is tested by varying the irradiance, which determines the variation of the output current and implicitly of the output power. The simulation results show that the inverter control system is very efficient, generating stable and nearly sinusoidal current and voltage characteristics. Thus, the inverter converts over 99 % of the power generated by PV arrays.

1. Introduction

Developing alternative energy resources with high efficiency and low emission has become very important by increasing concerns about fossil fuel deficit, high oil prices, global warming, and environmental and ecosystem damage [1].

The photovoltaic (PV) system has become an important renewable energy source due to its availability and easy access. Since it is a DC power source, an inverter must convert it to AC power, powering up AC loads or transport it to the utility grid. The level of difficulties of the system implementation is associated with inverter topology, switching topology, and system environment or platform. The success of PV power usage is associated with proper control techniques of the inverter. Researchers have focused on various inverter control issues, including self-consumption losses, nonlinearity behaviour, output fluctuation, weather dependence, and low PV efficiency [1].
There are more than two PI controllers in grid-connected systems, and they usually require high-quality transit performance that is defined. Thus, it is necessary to adjust the value of PI gains during the transit process to achieve better performance. One of the most effective methods for adjusting PI gains is fuzzy logic control (FLC) [2]. In general, the FLC applies to intelligent control systems, nonlinear systems, and other complex applications due to its simplicity and flexibility [2].

MPPT algorithms are essential because PV arrays have a nonlinear voltage-current characteristic with a unique point where the produced power is highest. This point depends on the temperature of the panels and the irradiance conditions. Furthermore, the increase of average PV system size may lead to new strategies like eliminating the DC-DC converter, usually placed between the PV array and the inverter, and moving the MPPT to the inverter, resulting in increased simplicity, overall efficiency, and a cost reduction.

The goal is to implement control techniques based on Fuzzy logic for single-phase inverter in low-power photovoltaic systems [3].

2. PV System Design

The configuration of the grid-connected PV inverter system considered in this paper is illustrated in figure 1. The system contains a control system based on Fuzzy Logic, solar panel, inverter, and RL-load. The control system consists of several sub-control modules: MPPT and current-control Fuzzy logic functions, Park and Inverse Park transformations, SOGI-PLL grid synchronization and pulse width modulated (PWM) signal generator.

The PV array is composed of two 75W Suntech Power STP075S-12/Bp panels, series-connected. The solar panels block has two inputs for both irradiance (varying) and temperature (constant).

The PV’s output fits into a Fuzzy Logic MPPT block which provides a voltage reference for the inverter. The single-phase inverter is formed of a DC link (two 10mF capacitors), a power stage (inverter IGBT), and filters. Its high capacitance helps stabilize the input voltage for the inverter. Therefore, the obtained signal goes to the Fuzzy Logic PI controller, giving the current in regulated form. This current, \( I_{d_{ref}} \), represents a Park transform parameter, which controls the system’s active power.

The method generates the feedback currents \( I_d \) and \( I_q \) using the inverter’s current \( I_{inv} \). \( I_q_{ref} \) is initialized with 0 to avoid reactive power in the PV system. The Fuzzy logic PI controllers amplify and integrate the signals and adjust the error to fulfill the reference currents’ equality conditions. The obtained control currents are transformed back to inverse Park transformation and fed to the PWM generator to send the inverter’s command pulses. The inverter feeds current into the grid through an interconnecting load RL. Finally, a phase-loop (SOGI-PLL) synchronizes the reference current injected by the inverter with the grid voltage. Consequently, a phase-frequency alignment takes place between the inverter’s sinusoidal current and the grid’s voltage. Given this, the inverter converts and delivers maximum power to the grid.

![Figure 1. The block diagram of the PV system.](image-url)
2.1. Maximum power point tracking algorithm (MPPT)
In the past decades, the most used algorithms for PV inverters in commercials are Perturb & Observe and Incremental Conduction. The results obtained for these two algorithms are similar, so it is difficult to say which one is the best. Lately, Fuzzy Logic Control (FLC) proved to perform more rapidly than the Perturb and Observe or Incremental Conductance algorithm. In figure 2 is presented the flow chart of the Fuzzy MPPT method. The main elements that make up an FLC system are the fuzzifier unit at the input terminal, knowledge-based (rule base) and the inference engine, and defuzzifier at the output terminal [4].

The Fuzzy MPPT block's inputs are the voltage (VPV) and the current (IPV) provided by the solar panel, while the output terminal is the voltage reference for the inverter (Vmppt) [4].

![Figure 2. FLC MPPT flow chart.](image)

Inside the Fuzzy MPPT block, the calculated power and voltage variation (∆V) to the fuzzy logic controller. The following equations determine the parameters of the Fuzzy MMPT:

\[
P_{PV} = I_{PV} \times V_{PV}
\]

\[
\Delta V_{PV} = V(k) - V(k-1)
\]

Figure 3 illustrates the implementation of the algorithm using the elements available in Simulink.

![Figure 3. Simulink implementation of the MPPT fuzzy algorithm.](image)

To implement the MPPT algorithm, we use the Fuzzy Logic Designer function, and the fuzzy inference method used is the Mamdani method, which uses Max-min composition. The fuzzy set includes 49 statements (if/then rules), representing the membership functions of input/output variables, ∆VPV, PPV, and Vmppt. Each variable has seven fuzzy subsets. The input variables are normalized to
match certain intervals, $\Delta V_{pv}$ between $[-1,1]$, respectively $P_{pv}$ between $[0, 150]$. The output variable $V_{mppt}$ belongs to the interval $[34,35]$. Any input value that does not belong to the domain is considered too large and generates signal errors. For simplicity, we use triangular and trapezoidal membership functions, through which the Fuzzy controller allows the rapid reduction of signal errors, which improves the transient response of the system [5].

2.2. Grid synchronization
Because of its advantages and wide practical usage, SOGI-based PLL circuits will be implemented in the simulation model. SOGI-based PLL is a highly efficient method for synchronizing PV inverter systems into single-phase, easy-to-design, and implement networks capable of running close to a filter without delay with the required bandwidth [6]. Second-Order Generalized Integrator (SOGI) is used to generate Quadrature signals. These quadrature signals are given as input to the Parks Transform block. Parks transform is used to transform stationary frame of reference to rotation frame of reference. PI controller behaves as a low pass to cancel our higher frequency parts. The PI controller parameters are crucial as altering either of the parameters will lead the system to lose synchronism [6].

2.3. Current control loop
The control provides two nested loops: one slower outer and one inner faster. Its output is the reference for the outer one. Generally, in the control of the inverter, PI controllers are used. The main issues for these classical regulators are related to the transient regime of the controlled signals. In our model, the traditional controllers were replaced with PI controllers based on Fuzzy logic thanks to their efficiency. In the first step, we configure the fuzzy inference system (FIS) to produce a linear control surface from the E (error) and CE (error change) inputs to the output the peak positions corresponding to the input sets [7].

The rule base includes 9 rules expressed in terms: If ...Then, using the logical AND operator. Membership functions are the input variables E and CE, each with three fuzzy subsets. The membership functions corresponding to the output variable are of singleton type and are expressed by linguistic terms.

We calculate the gains $k_p$, $k_i$, corresponding to the conventional PI regulators. The controller's gains, PI in the voltage loop were obtained using the trial and error method, reaching the values $k_p = -5$ and $k_i = -30$. The calculation PI gains corresponding to the current loop involves the choice of a constant time, $\tau_i$, of 50 $\mu$s, a value of the load inductance of 200 $\mu$H and a value of the load resistance of 20 m$\Omega$. The value of the inductance is sufficient because the work involves modelling a low-power photovoltaic system. The parameters $k_p$ and $k_i$ are estimated as below (3), (4):

$$k_p = \frac{L}{\tau_i} = \frac{200 \times 10^{-6}}{50 \times 10^{-6}} = 4$$

$$k_i = \frac{R \times \tau_i}{\tau_i} = \frac{20 \times 10^{-2}}{50 \times 10^{-6}} = 400$$

In order to be able to model the PI Fuzzy controller, we need the scaling factors $GE$ (error gain), $GCE$ (error change gain), and $GCU$ output (output gain). These scaling factors are calculated based on the gains $k_p$, $k_i$, assuming the maximum reference step 1, the maximum error E is 1. Since the input range of the error E is $[-10,10]$, the error gain is chosen $GE = 10$ and the rest scaling factors are calculated with the following formulas [8]:

$$GCE = GE \cdot \left(\frac{k_p - \sqrt{k_p^2 + 2k_iE}}{2k_i}\right)$$

$$GCU = \frac{k_i}{GE}$$
After calculations for the first PI Fuzzy controller corresponding to the voltage control loop, the following values are obtained for the scaling factors: $GE = 10$, $GCE = 1.66$, and $GCU = -3$. In figure 4, we have the Simulink implementation of the PI Fuzzy controller.

![Figure 4](image)

Figure 4. The PI fuzzy controller corresponding to the voltage control loop.

3. Experimental setup

The Matlab model of the Fuzzy Logic Control implementation on PV modules is shown in figure 5. The temperature is constant at 25 °C, together with the irradiance represents inputs of the PV system. The solar power (PPV) and active power (POUT) is used to show the power conversion of the PV system [9]. We use a varying irradiance input to test the effectiveness of the proposed FLC algorithm. The irradiance varies from 1000 W/m² to 750 W/m² and 500 W/m². The parameters used for the PV panel are shown in table 1 [10-12].

![Figure 5](image)

Figure 5. Matlab model of PV system with Fuzzy Logic Control.

**Table 1.** The main features of solar panel

| Parameter                        | Value  |
|----------------------------------|--------|
| Open circuit voltage (Voc)       | 21.7 V |
| Voltage at maximum power point (Vmp) | 17.3 V |
| Short-circuit current (Isc)      | 4.72 A |
| Current at maximum power (Imp)   | 4.35 A |
| Maximum Power (Pmax)             | 75 W   |
4. Simulation results
The following figures illustrate the simulation results of the system presented in figure 5. Figure 6 shows the variation of irradiance to produce the partial shading effect. Figure 7 and figure 8 show current and power characteristics from the solar panel at different values of irradiance and fixed values for temperature. The MPPT controller was under the same operating conditions as illustrated in figure 9. At the initial moment, for the maximum irradiance value (1000 W/m2), the Vmppt voltage is at 34.8 V. If the irradiance drops to 500 W/m2, there is a slight decrease in the voltage to 34.5 V, corresponding to the new maximum power point. So, it can be stated that the inverter reference voltage (VMPPT) is constant at constant irradiance and varies very small with irradiation changes. This shows that the Fuzzy-based MPPT algorithm offers a very good precision in establishing the maximum power point.

![Figure 6. Variation of iradiance.](image6)

![Figure 7. Irradiance effect in I_PV characteristics from the solar panel.](image7)

![Figure 8. Irradiance effect in P_PV characteristics from the solar panel.](image8)

![Figure 9. Inverter reference voltage generated by the Fuzzy MPPT controller.](image9)

The current and power extracted from the panel are the parameters that vary the most with irradiation change, and the voltage remains nearly constant. The output current and power of the inverter are also proportional to the irradiance. The current characteristics of the inverter are used in the current control loop to obtain maximum power (figure 10). Figure 11 illustrates the power transfer performance at different values of irradiance and fixed values for temperature. It can be seen that the power output of the solar panel (PPV), varies between 149.8 W and 150.2 W and the active power (POUT) varies between 149.5 W and 149.9 W in the case of 1000 W/m2. That means that the systems have an efficiency greater than 99.5 %, due to the Fuzzy MPPT algorithm and the control loop based on PI Fuzzy controllers.
Figure 10. Output inverter current ($I_{\text{inv}}$), inverter voltage ($V_{\text{inv}}$) and grid voltage ($V_{\text{grid}}$).

Figure 11. Power conversion performance.

5. Conclusions
The modeling and real-time testing of a single-phase PV inverter control based on Fuzzy logic have been presented in this paper. The simulation results showed that the inverter control system employing Fuzzy MPPT and Fuzzy PI controller effectively produces stable and nearly sinusoidal waveforms of both voltage and current. Moreover, the inverter can transfer the available excess PV power to the utility grid.

6. References
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