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MPPT & Power Factor Control for Grid Connected PV Systems with Fuzzy Logic Controllers

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ABSTRACT

Two fuzzy logic controllers are proposed in this paper to control a three phase inverter for grid connected photovoltaic system. The first controller was used to predict the DC voltage that allows the three phase inverter to track the maximum power point of photovoltaic array under different environmental conditions such as irradiances and temperature. The second was used to control the active power and reactive power injected into the grid in order to inject the maximum active power produced by photovoltaic systems into grid with high efficiency and low total harmonic distortion using the same three phase inverter. The system components are photovoltaic array, DC link voltage, three-phase inverter, inverter control, LC filter, transformer and grid. To verify the effectivnesse of the introdueced system, modeling and simulation are verified in Matlab/Simulink due to its frequent use and its effectiveness.

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1. INTRODUCTION

In recent years, however, the number of solar powered homes connected to the local electricity grid has increased dramatically. These grid connected photovoltaic (PV) systems have solar panels that provide some or even most of their power needs during the day time, while still being connected to the local electrical grid network during the night time. Solar powered PV systems can sometimes produce more electricity than is actually needed or consumed, especially during the long hot summer months. This extra or surplus electricity is either stored in batteries or as in most grid connected PV systems, fed directly back into the electrical grid network. Governments and utility companies support programs which focus on grid connected PV systems. So, the number of PV installation has an exponential growth.

PV energy is a green renewable source. PV cell is the most basic of PV modules. It consists of a P-N junction fabricated in a layer semiconductor. The current-voltage (I-V) and power–voltage (P-V) outputs characteristics of solar cell are similar to that of a diode [1]. Under sun, photons with energy greater than the band gap energy of the semiconductor are absorbed and create an electron–hole pair that creates a current proportional to the irradiation. It is the interface which converts light into electricity. Modeling this device requires taking environmental conditions (irradiance and temperature) as input variables and current, voltage or power as outputs. Any change in the inputs immediately implies changes in outputs. Consequently, to extract the maximum power point from the PV array under different inputes we use a MPPT algorithm [2]-[6]. In this paper, a fuzzy logic controller was used in MPPT for a three phase inverter in ordre to pridect the DC link voltage which extracts the maximum power from PV array. For that, using an accurate model for the PV module is important [2], [7]. It is a single diode model with both series and parallel resistors for greater accuracy.

In grid connected PV systems, the inverter which converts the output direct current (DC) of the solar modules to the alternate current (AC) is receiving increased interest in order to generate power to utility. Many topologies are used to this purpose [8]-[13].

This paper present two fuzzy logic controllers using a three phase inverter, first one track the maximum power point of PV array and the second one for current regulator. Based on the current references (direct current) and (quadratic current), the regulator determines the required reference voltages for the inverter. The reference is set to zero. In first section, photovoltaic was described. The second section presents a fuzzy logic control to track the maximum power point array under different conditions (irradiance, temperature and load). In the next section, fuzzy logic controller for current control was described with a Phase Locked Loop to synchronize the Park fram to grid voltage. In the forth section, simulations in Matlab/Simulink of grid connected photovoltaic systems are presented and analyzed. The last section is a global conclusion about this work.

2. GRID CONNECTED PV SYSTEMS

Figure 1 shows a detailed model of a 250-kW PV array connected to a 25-kV grid via a three-phase inverter. This model is described as follow:

PV Array: it consists of 86 parallel strings. Each string has 7 modules connected in series. Three-phase inverter: it is modeled using a 3-level IGBT bridge PWM-controlled. The inverter chokes RL and a small harmonics filter C are used to filter the harmonics generated by the IGBT Bridge. A 250-kVA 250V/25kV three-phase transformer is used to connect the inverter to the utility grid. Inverter Control: The control system contains sex major subsystems. Utility grid: it included two 25-kV feeders, loads, grounding transformer and an equivalent 120-kV transmission system.

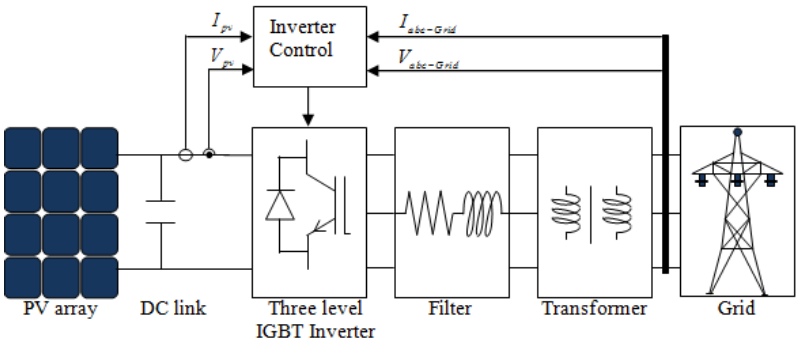


Figure 1. Grid connected photovoltaic system

Inverter Control sub systems are:

- MPPT Controller: the Maximum Power Point Tracking (MPPT) based on the Fuzzy logic control. This MPPT system automatically varies the VDC reference signal of the inverter VDC regulator in order to obtain a DC voltage which will extract maximum power from the PV array.
- V_{DC} Regulator: determine the required I_d reference for the current regulator.
- The VSC converts the 500V DC link voltage (VDC) to 260V AC and keeps unity power factor. The VSC control system uses two control loops: an external control loop which regulates DC link voltage to +/-250 V and an internal control loop which regulates I_d and I_q grid currents. I_d current reference is the output of the DC voltage external controller. I_q current reference is set to zero in order to maintain unity power factor. V_d and V_q voltage outputs of the current controller are converted to three modulating signals $U_{abc\text{-}ref}$ used by the PWM Generator. The control system uses a sample time for voltage and current controllers as well as for the PLL synchronization unit. Pulse generators of VSC converters use a fast sample time in order to get an appropriate resolution of PWM waveforms.
- Current regulator: based on the current references I_d and I_q, the regulator determines the required reference voltages for the inverter. A second Fuzzy logic controller was used for current regulator.
- PLL: required for synchronization and voltage/current measurements.
- PWM Generator: generate firing signals to the IGBTs based on the required reference voltages.

2.1. PV System

The PV circuit model is based on the following equation:

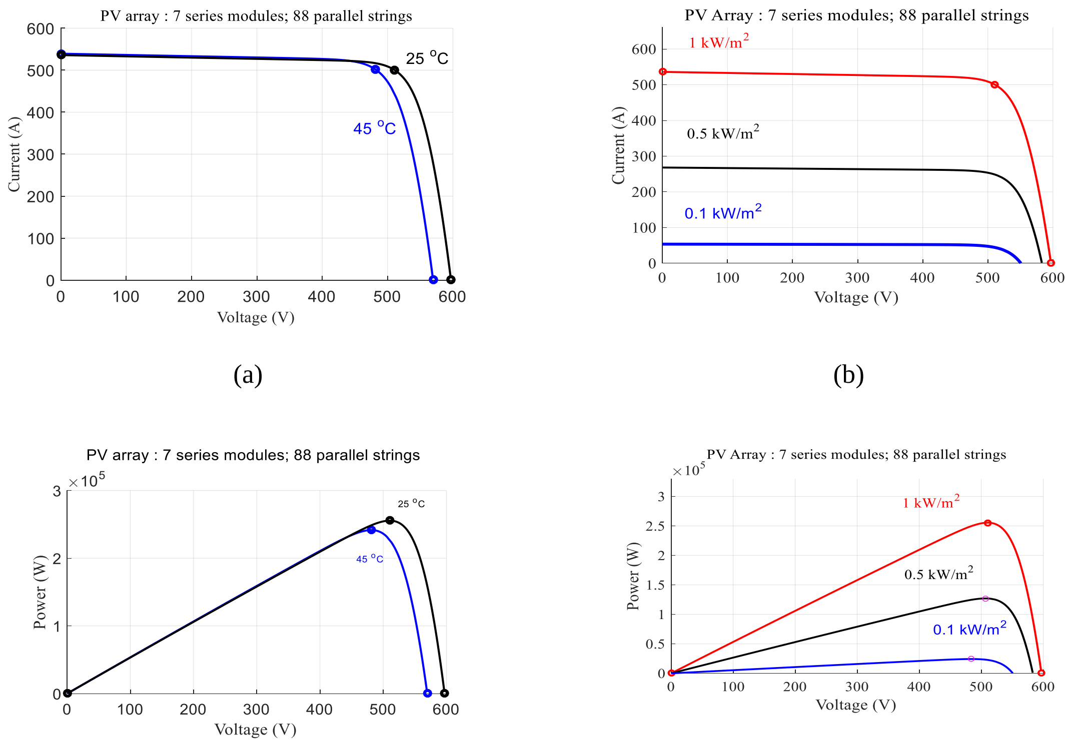
$$I_{pv} = i_{pv} - I_0 \left[\exp\left(\frac{V_{pv} + I_{pv} R_s}{\eta N_s \frac{K_b T}{e}} \right) - 1 \right] - \frac{V_{pv} + I_{pv} R_s}{R_{sh}} \tag{1}$$

In order to apply this model in simulation, the key specifications are given in Table 1.

Table 1. Photovoltaic Parameters

At Temperature	T	25	°C
Open circuit voltage	V_{oc}	597.1	V
Short circuit current	I_{sc}	535.9	A
Voltage, maximum power	$V_{p\max}$	510.3	V
Current, maximum power	$I_{p\max}$	500.7	A
Maximum power	$P_{\max}$	255500	W

As the solar irradiance varies over time and depending on the climatic conditions, the power output also varies. The performance of a photovoltaic cell is usually presented by its I(V) and P(V) curves which are produced for several irradiance levels and several cell temperature levels. The variation of current and power versus voltage curve under various irradiation levels and temperatures are shown in Figure 2. We can observe that the weak sunlight and raising the cell temperature will reduce the power conversion capacity.



(a) (b)

(c) (d)

Figure 2. Variation of current and power versus voltage curve under various irradiation levels and temperatures. (a). Current–Voltage at 1kW.m² and specified temperatures. (b). Power–Voltage at 1kW.m² and specified temperatures. (c). Current–Voltage at 25°C and specified Irradiances. (d). Power–Voltage at 25°C and specified Irradiances

3.1. MPPT with Fuzzy Logic Controller

The Maximum Power Point Tracking (MPPT) controller is based on the Fuzzy logic control. This MPPT system automatically varies the V_{DC} reference signal of the inverter V_{DC} regulator in order to obtain a DC voltage which will extract maximum power from the PV array.

Fuzzy logic controller has the advantage to working with imprecise inputs, not needing an accurate mathematical model, and handling nonlinearity. Generally, it consists of three stages: fuzzification, rules base table lookup, and defuzzification. During fuzzification, numerical input variables are converted into linguistic based on membership function similar to Figure 3. In this case five fuzzy levels are used: NB (Negative Big), NS (Negative Small), ZE(Zero), PS (Positive Small) and PB (Positive Big).

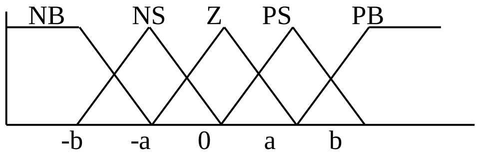


Figure 3. Membership function for inputs and output of fuzzy controller

The inputs to a MPPT fuzzy logic controller are usually an error E and a changing error CE .

$$E(n) = \frac{P_{pv}(n) - P_{pv}(n-1)}{V_{pv}(n) - V_{pv}(n-1)} \quad (2)$$

$$CE(n) = E(n) - E(n-1) \quad (3)$$

The output of MPPT fuzzy controller is a desired DC voltage.

Table 2 shows the rules table of fuzzy controller; where all the entries of matrix are fuzzy sets of error, changing error and desired DC voltage.

Table 2. Fuzzy Rules Base Table

E/CE	NB	NS	ZE	PS	PB
NB	ZE	ZE	NB	NB	NS
NS	ZE	ZE	NS	NS	NS
ZE	NS	ZE	ZE	ZE	PS
PS	PS	PS	PS	ZE	ZE
PB	PB	PB	PB	ZE	ZE

If, for example, the operating point is far to the left to the maximum power point (MPP) that is E is PB and CE is ZE, then we need to largely increase the DC voltage, that V_{dc-ref} should be PB to reach the MPP. Figure 4 shows the fuzzy logic controller algorithm.

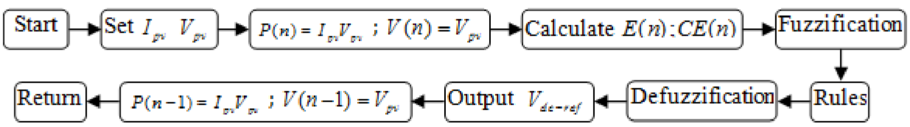


Figure 4. Algorithm for fuzzy logic controller

In Simulink we use the bloc shown in Figure 5

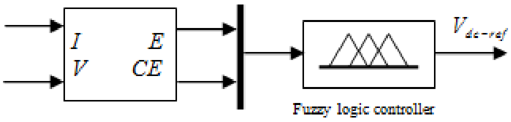


Figure 5. Simulink bloc for fuzzy logic controller

3. CURRENT CONTROL WITH FUZZY LOGIC CONTROLLER

The voltage and current equations of the grid using $abc \mapsto \alpha\beta \mapsto dq$ transformations are given by:

$$\begin{bmatrix} d \\ q \end{bmatrix} = \begin{bmatrix} \cos(wt) & \sin(wt) \\ -\sin(wt) & \cos(wt) \end{bmatrix} \cdot \begin{bmatrix} \alpha \\ \beta \end{bmatrix} \quad (4)$$

$$\begin{bmatrix} \alpha \\ \beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} a \\ b \\ c \end{bmatrix} \quad (5)$$

$abc \mapsto \alpha\beta \mapsto \mathrm{dq}$ are replaced by $V_{abc} \mapsto V_{\alpha\beta} \mapsto V_{\mathrm{dq}}$ for voltage or by $I_{abc} \mapsto I_{\alpha\beta} \mapsto I_{\mathrm{dq}}$ for current measurement. The rotating reference frame at the grid frequency gives:

$$\begin{cases} \mathrm{V}_d = \mathrm{V}_{d-Grid} + \mathrm{R}\mathrm{I}_{d-Grid} + \mathrm{L}\dfrac{dI_{d-Grid}}{dt} - \omega L I_{q-Grid} \\ \mathrm{V}_q = \mathrm{V}_{q-Grid} + \mathrm{R}\mathrm{I}_{q-Grid} + \mathrm{L}\dfrac{dI_{q-Grid}}{dt} + \omega L I_{d-Grid} \end{cases} \quad (6)$$

Using dq transformation, the active and reactive powers (P, Q) are given by:

$$\begin{cases} P = \dfrac{3}{2}\left(V_d I_d + V_q I_q\right) \\ Q = \dfrac{3}{2}\left(V_q I_d - V_d I_q\right) \end{cases} \quad (7)$$

Therefore, active and reactive power can be controlled by controlling direct and quadrature current components i_{dg-ref} , i_{qg-ref} , which is given as:

$$\begin{cases} I_d = \dfrac{2\left(PV_d + QV_q\right)}{3\left(V_d^2 + V_q^2\right)} \\ I_q = \dfrac{2\left(PV_q - QV_d\right)}{3\left(V_d^2 + V_q^2\right)} \end{cases} \quad (8)$$

The second fuzzy logic controller was used to control direct and quadrature currents. And a Phase Locked Loop (PLL) is used to synchronize the Park transformation to the pulsation of the measured voltage across the grid. Thus, when the system is in an established regime, the direct component V_d at the output of the Park transformation is an image of the amplitude of the measured voltage and the quadratic component V_q is zero. Thus, the equations (8) show I_d as a direct image of the active power and I_q as an image of the reactive power. Figure .6 shows the proposed inverter control.

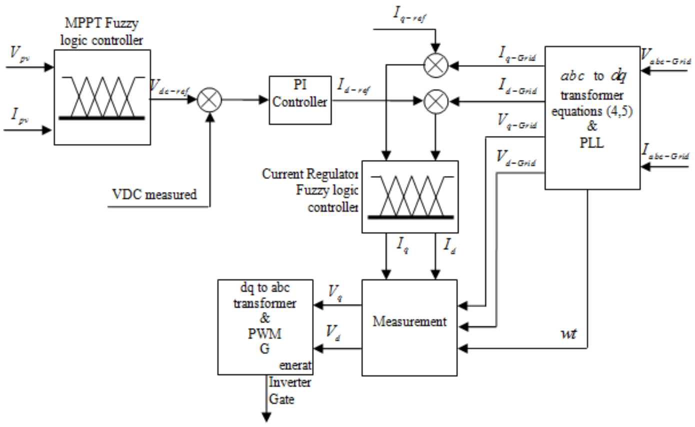


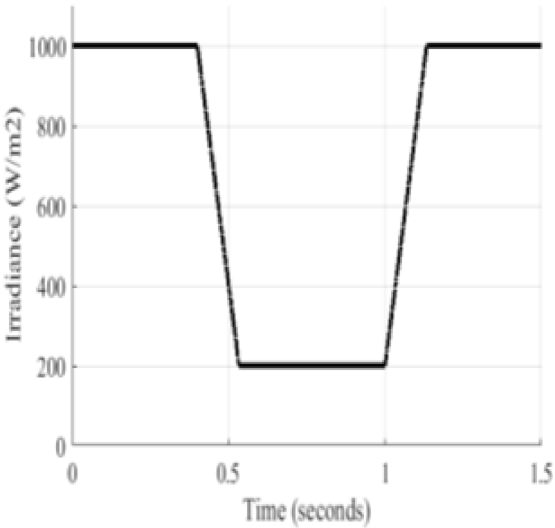
Figure 6. Proposed inverter control with two fuzzy logic controllers

4. SIMULATION AND RESULTS

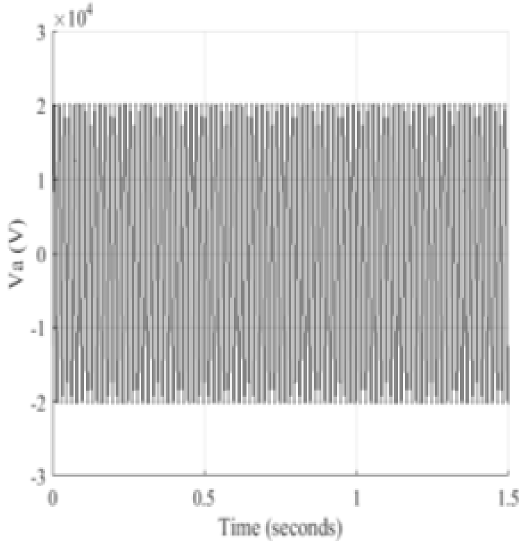
The operating temperature is 45 deg. C. When steady-state is reached, we get a PV voltage and the power extracted from the array. These values correspond to the expected values from the PV module manufacturer specifications. Figure 7 shows variation of current, voltage and power versus time curve under various irradiance levels.

Sun irradiance is rapidly ramped down. Due to the MPPT operation, the control system reduces the VDC reference in order to extract maximum power from the PV array.

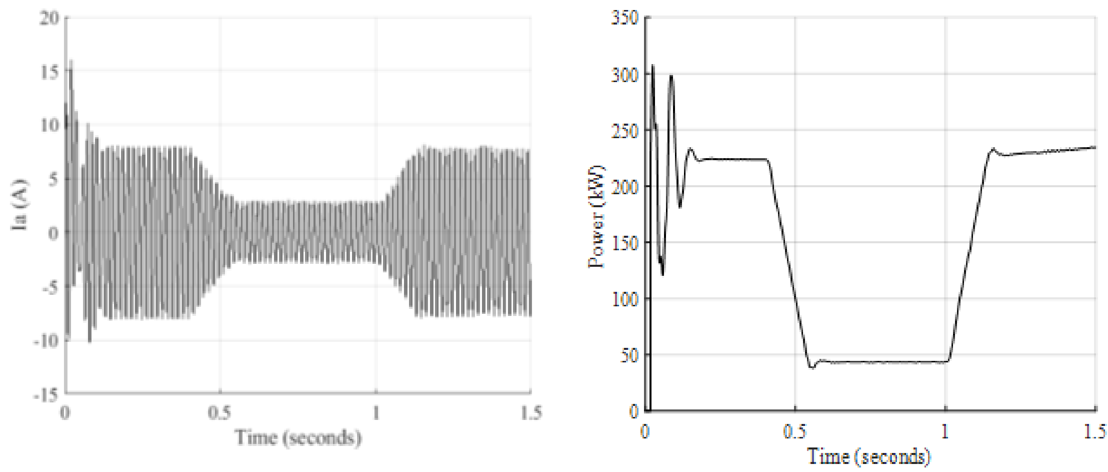
As it can be seen, Maximu Power Point was reahed under irradiance changes. Also, the value of the voltage injected into grid is stable and equal to that of the grid. The third resut is that voltage and current are in phase which proves that the reactive power injected into grid is zero. So we obtained the objectives of two fuzzy logic controllers. Figure 8 show Phase difference between voltage and current of grid under various irradiation levels



(a)



(b)



(c) (d)

Figure 7. Variation of current, voltage and power versus time curve under various irradiance levels. (a). Irradiance. (b). Voltage inverter output. (c). Current inverter output. (d). Power inverter output

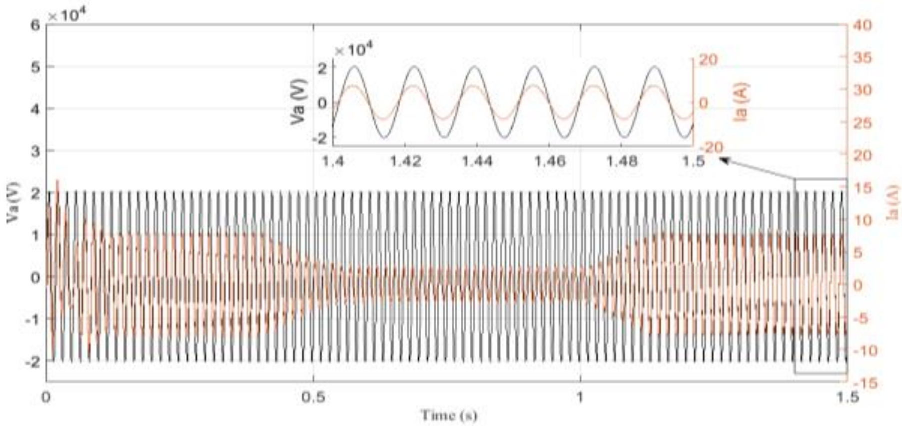


Figure 8. Phase difference between voltage and current of grid under various irradiation levels

5. CONCLUSION

Usuelly a MPPT technique is applied to a DC–DC converter and then a second PFC commande is applied to an inverter. In this work, two fuzzy logic controllers are described for grid connected photovoltaic systems using a three phase inverter without DC–DC converter. The first one was applied to track maximum power point and the second was applied to control the power factor. The fuzzy logic controller for MPPT algorithms track the maximum power point under two steps in irradiance with good stabilty. A vector control strategy for photovoltaic side inverter and grid side inverter using fuzzy logic controllers give a good performances of MPPT and Power Factor Control.

NOMENCLATURE

e	Electron charge	K_b	Boltzmann's constant
I_0	Reverse saturation current	N_s	Number of solar cells
$I_{abc-Grid}$	Grid three phase current	P_{pv}	Output power of solar cell
I_d	Desired direct current	R_s	Series resistance

I_{d-ref}	Grid reference direct current	R_{sh}	Shunt resistance
i_d	Diode current	V_{d-Grid}	Grid direct voltage
I_{pv}	Output current of solar cell	V_{dc-ref}	DC voltage witch extract MPP
i_{pv}	Photocurrent	V_{pv}	Output voltage of solar cell
I_q	Desired quadratic current	V_q	Quadratic voltage
I_{q-ref}	Grid reference quadratic current	η	Diode quality
I_{sc}	Short circuit current		
i_{sh}	Shunt resistance current		

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