Maximum Power Point Tracking Control for Grid-Connected Photovoltaic System under Partial Shading Conditions

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Abstract—This manuscript uses an active bypass circuit to preserve the photovoltaic (PV) modules from a significant reduction in power generation, which is transferring from partial shading. The active bypass circuit controls each PV module separately, including the shaded ones, by detecting the shaded region on these modules using an image processing technique. The active bypass circuit ensures that every PV module on the solar system is working at its maximum power operating point. Under partial shading conditions, the conventional maximum power point tracking (MPPT) methods have usually failed to track the global MPP. In order to overcome this limitation, this paper attempts to combine a fuzzy logic technique and an active bypass circuit to ensure the detection of a unique global power point (GMPP). A current source inverter (CSI) is used with a double-tuned resonant filter to eliminate the undesirable harmonics on the direct current (DC) side. In addition, an LC filter is used in the AC side to reduce the switching harmonics. The simulation results demonstrate improvement in the performance of the proposed MPPT method under partial shading conditions. Hence, the combination of the active bypass circuit and the image processing technique, based on a fuzzy logic decision-making approach, provides an effective process for the detection of the shaded region on the surface of the PV module. In addition, this combination ensures a unique global maximum power point (GMPP)for the proposed PV solar system.

Index Terms— Photovoltaic (PV) Module, Image Processing, Active by Bass Circuit, Shadow Detection, Fuzzy Logic, Maximum Power Point Tracking (MPPT), Grid-Connected.

I. INTRODUCTION

The performance of a photovoltaic (PV) module mainly depends on the amount of solar irradiance that can be absorbed by each module. PV modules must commonly be connected in series in order to generate the desired power. If any part of these modules is prohibited from receiving light by means of partial shading, their power generation will be reduced. As a result of partial shading on a PV module, a significant decrease in the total PV power generation is observed. To solve this problem, conventional approaches commonly connect a bypass diode in parallel with each PV module [1- 4]. However, the shaded PV modules cannot produce their inherent power and the overall power generation solar system is still smaller than the power generation without shading conditions [5].

In order to handle the problem of partial shading on PV modules, this manuscript uses an active bypass circuit, a generation control circuit (GCC) [6-7]. In fact, the active bypass circuit controls each PV module separately, including the shaded ones, by detecting the shadow region on these modules based on the image processing technique [8-9]. The active bypass circuit ensures that every PV module of the solar system is working at its maximum power operating point [10-11]. To track the maximum power point of the proposed solar system, a new method, based on a combination of an active bypass circuit and a fuzzy logic technique, is proposed. This manuscript is organized as follows: In Section 2, the proposed PV solar system is presented. Section 3 presents the shadow detection method on a PV array using a digital image processing technique. Section 4, explores the proposed configuration of the active bypass circuit and its control principle. Section 5 presents the fuzzy logic control technique for tracking the maximum power point. Section 6, presents the simulation results. Finally, in Section 7 conclusions are given and discussion.

II. PROPOSED PV SOLAR SYSTEM DESCRIPTION

Fig.1 illustrates the circuit configuration for the proposed PV solar system, where two PV modules consist of ten solar cells are connected in series in order to generate the required voltage and circuit. monitoring camera gives a quick indication of an existing shadow on these modules by using the proposed digital image processing technique. The digital processing technique is based on a fuzzy logic decision, making system permitting the determination of the shadow type. The proposed technique enables the active bypass circuits, which are connected in parallel with each PV module, to generate a control signal from a pulse width modulator (PWM) to ensure the detection of unique MPP for solar system. A current source inverter (CSI) with a double tuned parallel resonant circuit is connected to the DC side of the solar system to boost the DC input voltage with very reduced value of unwanted harmonics. The AC side of the system is connected to the grid using

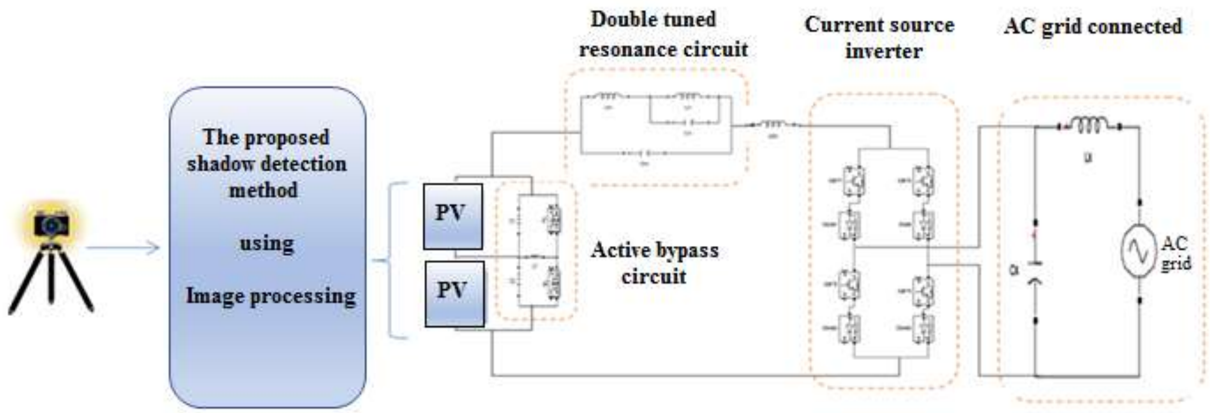


Fig.1. Proposed Grid-Connected PV Solar System.

an LC filter to avoid switching harmonics on the AC side.

III. Proposed Method of Shadow Detection on a PV Array Using Digital Image Processing

The need for an effective process, to detect the shadow on PV panels, becomes a necessity especially in a massive PV solar system where the shadow can cover a large part of panel. The main motive for using digital image processing technique is to establish a dynamic and effective way to detect the shadow on PV panels and to determine the its type [8-9]. The first step depends on installing a camera system to continuously monitor the PV arrays. The image obtained by the monitoring camera is then treated by a digital processing technique, based on a fuzzy logic decision- making system, and the shadow type is determined.Fig.2 illustrates the different stages of the overall system which will be discussed in details.

A. Background of the Subtraction Method

Background subtraction consists of extracting a foreground mask from the preserved background model using the stationary camera. This technique is widely used for detecting objects or tracking targets by subtracting the input from the background model, which also known as the reference frame. The background subtraction method can be represented by the mathematical formula [12]:

$$Mt(x,y) = \begin{cases} 1, & \text{if } D\big(I(x,y,t), R(x,y,t)\big) > T \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

Where:
M_t (x, y) is the motion mask at time t, x and y are the pixel location variables, D is the distance between the input frame I (x, y, t) and the reference frame R(x, y, t), and T is the threshold value, which is an empirically selected value.
The distance between the input frame and the reference frame is compared with the threshold value T, if the distance value is geater than that of the threshold, then this indicates a difference in pixels between foreground and background which means the presence of a new object in the image. This distance can be presented by the following formulas:

$$D_0 = |I(x,y,t) - R(x,y,t)| \tag{2}$$
$$D_1 = |I^R(x,y,t) - R^R(x,y,t)| + |I^G(x,y,t) - R^G(x,y,t)| + |I^B(x,y,t) - R^B(x,y,t)|$$

Where D0 is the distance for the gray image, and D1 is the distance for the RGB image.
The flowchart of the background subtraction method is illustrated in Fig.2. The main steps of this method can be summarized as follow:

1. Estimate the reference frame R(x, y, t) at time t.
2. Subtract the reference frame from the input frame I(x, y, t).

Apply a threshold T to the absolute difference to get the foreground mask.

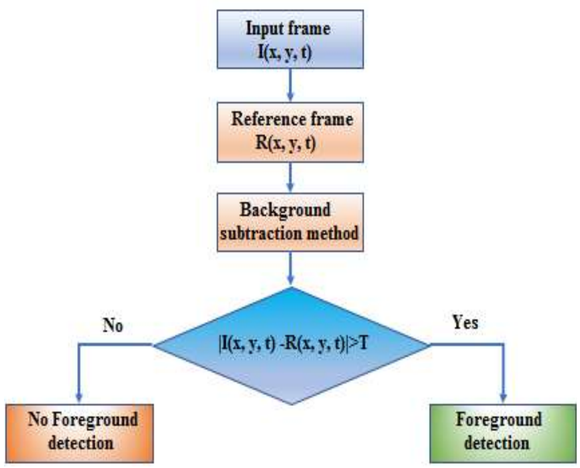


Fig. 2. Flowchart of the background subtraction method.

The background subtraction method is sensitive to noise and illumination changes and it depends on the threshold value T, which is empirically selected value and is not a function of time similar to the input and reference frame. In order to improve the results of background subtraction, the dissertation uses a Blob detection method that highlights the new object in the reference image, based on the hypothesis that a new object has different properties, such as color distribution and brightness, as opposed to the surrounding regions.

The Blob detection method returns a zero-pixel value if both inputs are equal and one-pixel value if they are different. The detection method uses a median filter to remove any unexpected noise from the gray image. Finally, it traces the region boundaries in a binary image. The input and the reference images of the proposed PV solar panels and the results of applying background subtraction and Blob detection methods are shown in Fig.3.

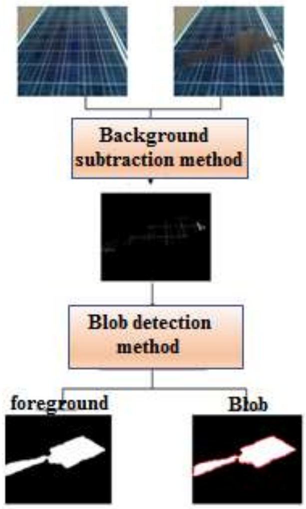


Fig. 3. The proposed detection methods for a PV solar panel.

A. Edge Detection Method

Edge detection is one of the essential steps in digital image processing. It depends on finding the boundaries of objects within images by detecting the sudden changes of intermission in the brightness of an image. There are many common edge detection algorithms such as Roberts, Sobel, Prewitt, and Canny [13-18].

Before applying the edge detection method, this dissertation uses a morphological process to reduce the unexpected noise of the image obtained from background subtraction by applying dilation and erosion operations. Dilation adds pixels to the boundaries of the shaded area in a PV image, while erosion removes pixels from these boundaries. The morphological process depends on the shape and size of the construction element used to treat the image [19]. Then, Canny algorithm will be applied to detect the shadow boundaries of a PV solar panel [17]. The Canny edge detector is an image processing technique used to detect edges in an image with the minimum effect of noise and more likely to detect the weak edges [20]. It consists of a multistage edge detection algorithm; the main steps for this algorithm are shown in Fig.4. The main goal of using the Canny algorithm is to reduce the amount of data to be treated in the digital image and preserves the only significant structural properties of the shaded area of the PV image. The proposed edge detection method is shown in Fig.5.

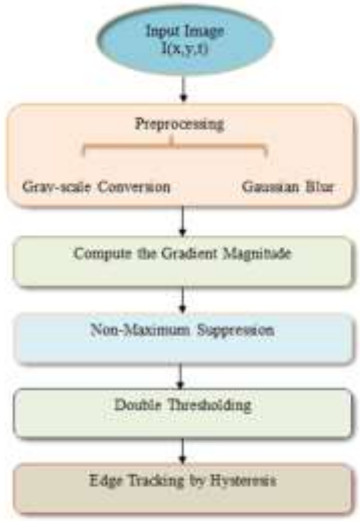


Figure 4. A flowchart of Canny Edge Detector.

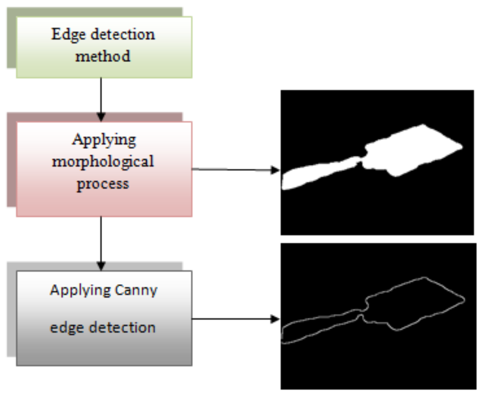


Fig. 5. The proposed Edge Detection Method.

A. Fuzzy Logic Method

Fuzzy logic is one of the artificial intelligent approaches that are based on human reasoning rather than the Boolean logic. This approach treats the levels of possibilities of input to obtain the obvious output. In order to benefit from the flexibility of fuzzy logic approach, the manuscript uses this method as a decision-making process to classify the type of shadow on the PV solar panel. The proposed fuzzy logic method takes the values of brightness (B) and color distortion (CD) of the shaded area on the PV solar panel as an input parameter and the type of this shaded area as an output parameters. Brightness is a relative expression of the intensity of the output energy of a visible light source. It can be represented as the total energy value, or as the amplitude where is the greatest value of intensity occurs at the wavelength of the visible light. In other words, brightness represents the intensity value of every pixel in the digital image. In the RGB color space, the amplitudes of red, green, and blue for a specific color can tack a range from 0 to 100 percent of full brightness. These level values are represented by the range of decimal numbers from 0 to 255 or hexadecimal numbers from 00 to FF. When the brightness value is 0, then the color space brightness is completely black. However, with the increase in the value, the brightness of the color space increases and shows different colors. In this manuscript, the normalized value of R, G, and B is used in the range [0, 1]. The following equation is used to calculate the value of brightness of the image by finding the weighted mean of intensity value for all pixels of the shaded are. Some data points count more strongly than others, in that they are given more weight in the calculation:

$$B_{shaded} = \frac{\sum_{i=1}^{m} (0.3Ri + 0.3Gi + 0.4Bi)}{m} \quad (3)$$

where B_{shaded} is the brightness value of the shaded region, and m is the number of pixels in the RGB color space.
Color distortion is a deflection from rectilinear dropping of pixels in an image; it is a type of optical deviation. Color distortion can be calculated by using Mahalanobis distance between the arithmetic mean of red, green and blue pixel values of the shaded area and the arithmetic mean of pixel values of the reference image for PV solar panel. Mahalanobis distance gives a useful method of measuring how similar some set of pixels is to an ideal set of pixels. The following formula is used to calculate the value of color distortion for the shaded region:

$$CDshaded = Maha\_Dis\ (Mean\ (RGBshaded\ , Ref\ )) \quad (4)$$

where CD_{shaded} is the color distortion of the shaded region, RGB_{shaded} is the red, green and blue pixel value of the shaded area, and R_{ef} is the pixel value for the reference image.

Mahalanobis distance is based on arithmetic mean of RGB of the shaded region and the variance of the expectation variables, with tacks the covariance matrix of all the variables in consideration. The region of constant Mahalanobis distance around the mean forms an ellipse in 2D space when only two variables are measured, or an ellipsoid or hyper ellipsoid when more variables are used. This distance is zero if the pixel of RGB_{shaded} at the mean of the reference image, and it increases as the pixel moves away from the mean. The Mahalanobis distance is given by the following equation:

$$Maha\_Dis = [(\mu_{shaded} - \mu_R)\, S^{-1}\, (\mu_{shaded} - \mu_R)^T]^{1/2} \quad (5)$$

Where μshaded is the arithmetic mean of the shaded region, μR is the arithmetic mean of the reference image, and S is the covariance matrix. This matrix is calculated by using the standard deviations of pixel values for the shaded region.

The input membership functions of brightness and color distortion and the output membership function of the proposed fuzzy logic method are represented in Fig.6. The fuzzy logic rules are shown in Table 1.
B_{shaded} is the brightness value of the shaded region, CD_{shaded} is the color distortion of the shaded region, s is small, m is medium, and b is big.

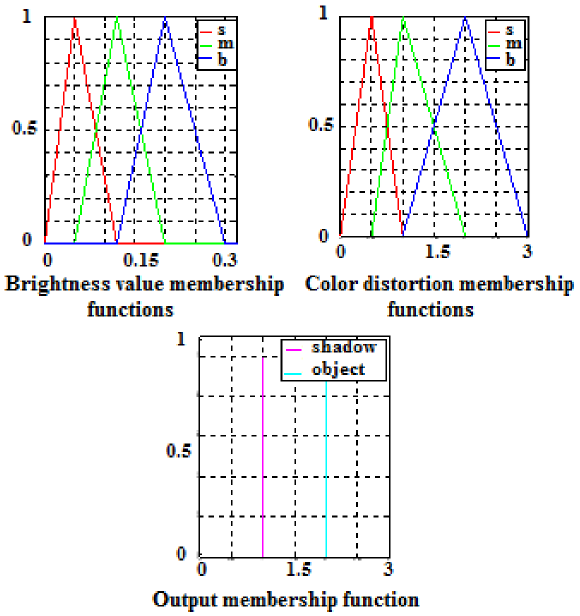


Fig. 6. The input and output membership functions of the proposed fuzzy logic method.

To ensure the effectiveness of applying a digital image processing technique in shadow detection for PV solar system and classifies the type of this shadow, two different images were obtained from a mobile camera. The results of using the proposed digital image processing method based on Matlab are shown in Fig. 7 (a) and (b). In the first case, a shadow caused by a human hand covers the PV panel whereas in the second case, a piece of sacking covers the PV panel.
As Figure 7 (a) illustrates, the brightness and color distortion values of the shaded region are calculated using the proposed image processing method based on Matlab. The results are as follows:
$B_{shaded} = 0.1068$, $CD_{shaded} = 0.2388$
By applying rule number 6 on these values of brightness and color distortion, the output will be a shadow.
For the second input image in Figure 8 (b), the brightness and color distortion values are:
$B_{shaded} = 0.1323$, $CD_{shaded} = 2.7019$
By applying rule number 4 on these values of brightness and

color distortion, the output will be an object.

The fuzzy logic decision-making approach defines the type of the shaded region on the PV input image, and then this information will be used as an input parameter for active by-pass circuit. In addition, when the type of shadow has been determined the cleaning purpose will be used. If the shadow is an object, it should be removed. On the other hand, if a shadow is detected, it should be cleaned using any cleaning method.

TABLE 1
Fuzzy Logic Rules.

Rule No	Rules
1	B_{shaded} = b & CD_{shaded} = b , then output = object
2	B_{shaded} = b & CD_{shaded} = m , then output = object
3	B_{shaded} = b & CD_{shaded} = s , then output = object
4	B_{shaded} = m & CD_{shaded} = b , then output = object
5	B_{shaded} = m & CD_{shaded} = m , then output = shadow
6	B_{shaded} = m & CD_{shaded} = s , then output = shadow
7	B_{shaded} = s , then output = shadow

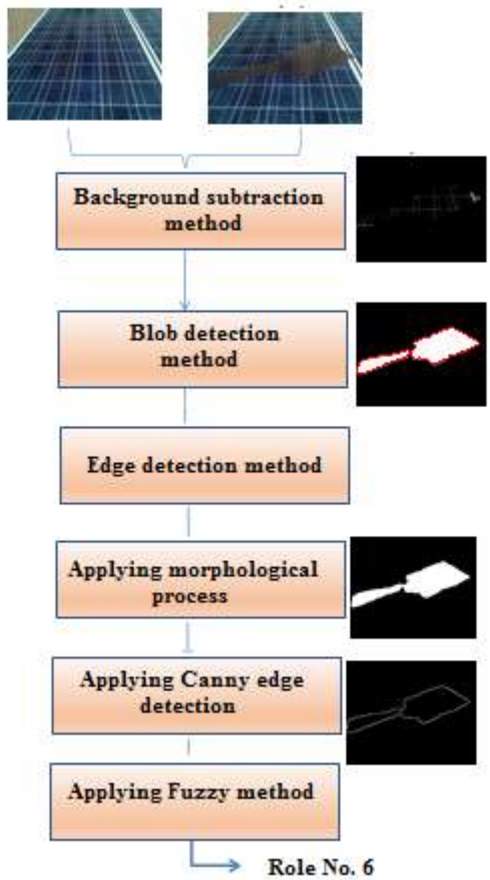


Fig. 7. The proposed shadow detection method. (a)Shadow region

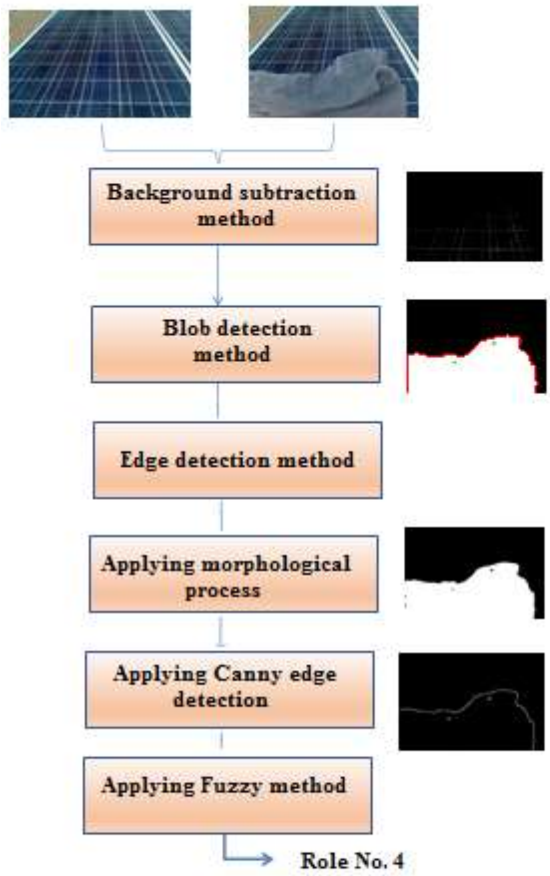


Fig. 7. The proposed shadow detection method.
(b) Object region.

IV. Proposed Configuration of the Active Bypass Circuit and Its Control Principle

Fig.8 illustrates the proposed configuration of the active bypass circuit where a chopper circuit consists of capacitor, inductor, and MOSFET are connected in parallel with each PV module. The arrangement forms a buck-boost converter which converts the fixed DC input voltage to the variable DC output voltage directly. Fig.9 shows the gate signals for the multistage chopper circuit.

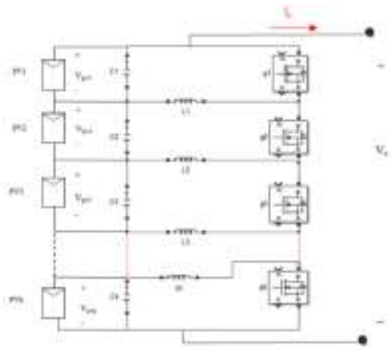


Fig. 8. The proposed configuration of the active bypass circuit.

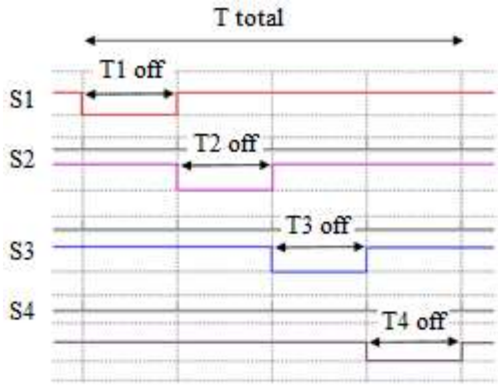


Fig. 9. The gate signals for the multistage chopper circuit.

The generation control voltage, for each PV module (V_{PVk}), depends upon the switching frequency of the buck-boost converter which can be given as follow:

$$V_{PV1} : V_{PV2} : \ldots\ldots\ldots : V_{PVk} = D_1 : D_2 : \ldots\ldots\ldots : D_k \quad (6)$$

The switching duty ratio is given by:

$$D_k = \frac{T_{k(off)}}{T_{total}}$$

$$\sum_{j=1}^{K} Dj = 1 \quad (7)$$

$$D_k = \frac{V_o}{V_o + V_{pvk}} \quad (7)$$

Where D_k is the switching duty ratio, $T_{k(off)}$ is the OFF-time of switch g_k, T_{total} is total switching interval, K is the number of PV modules, V_{PVk} is the generation control voltage and V_o is the output voltage.

In order to benefit from the active bypass features, with accreditation of shadow detection method which based on digital image processing technique, this approach uses a pulse width modulator (PMW) to control the active bypass circuit by defining the gate signals of the MOSFET. The proposed PWM for the active bypass circuit is shown in Fig.10 where the PWM can be controlled by the input value of brightness and color distortion of the shaded area which is obtained from the shadow detection method based on digital image processing techniques. Fig.11 shows the gate signals g_1 and g_2 for the active bypass circuit.

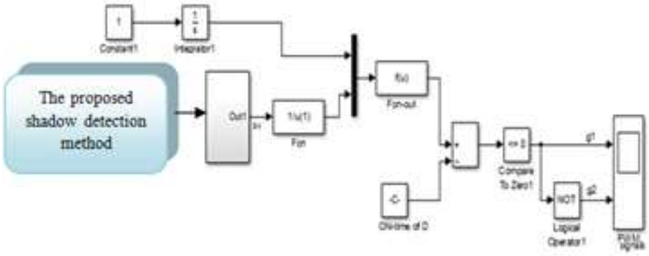


Fig. 10. The proposed pulse width modulator.

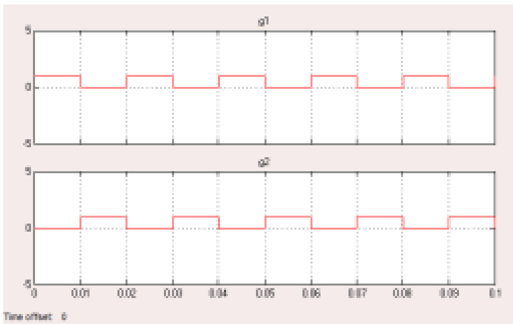


Fig.11. The gate signals for the proposed active bypass circuit.

V. Fuzzy Logic Control Technique for Tracking MPP

In order to track the MPP of the proposed grid-connected PV solar system, this paper uses a fuzzy logic controller (FLC). This type of controller achieves a quick location to the MPP by controlling the gate signals of the MOSFET of the proposed active bypass circuit. Fig.12 shows the proposed simulation model of the FLC based on Mamdani method using the

Matlab/Simulink/Fuzzy Logic Toolbox. Fig. 13 illustrates the inductor current (I_{L1}) waveform in the active bypass circuit when the signal has been received from the fuzzy logic controller.

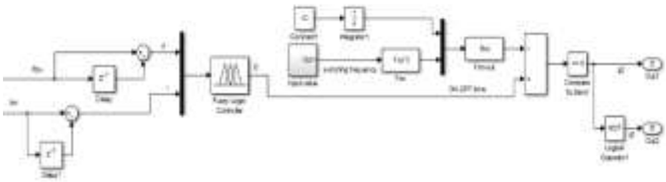


Fig. 12. Block diagram of the proposed FLC.

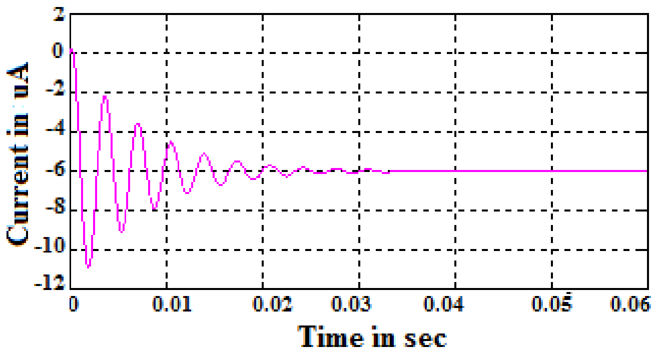


Figure 13: The inductor current waveform in the active bypass circuit.

The inputs of the proposed FLC are the PV array output power and current:

$$\Delta P_{pv} = P_{pv}(j) - P_{pv}(j\text{-}1)$$

$$\Delta I_{pv} = I_{pv}(j) - I_{pv}(j\text{-}1)$$

where

ΔP_{pv} is the change in the output power of the PV array, ΔI_{pv} is the change in the output current of the PV array, and j is the sampling instant.

The output of the proposed FLC is the duty ratio value (D) of the active bypass circuit which controls the ON-OFF time of switching period for the gate signal of each MOSFET. The input membership functions, the change in power and change in current of the PV array, and the output membership function of the proposed fuzzy logic method are presented in Fig.14. The fuzzy logic rules are shown in Table 2, where 16 fuzzy control rules are used to get the desired value of the MPP. The surface view for the proposed FLC is shown in Fig.15.

where:

NB: Negative Big, NS: Negative Small, PB: Positive Big, and PS: Positive Small.

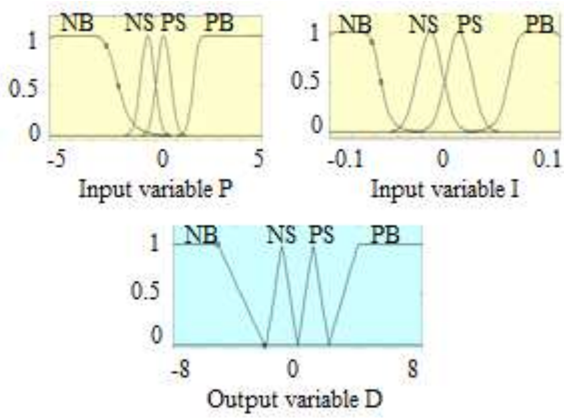


Fig. 14. The input and output membership functions of the proposed FLC.

TABLE 2

Fuzzy Logic Rules.

ΔP_{pv} \ ΔI_{pv}	NB	NS	PS	PB
NB	PB	PB	NB	NB
NS	PS	PS	NS	NS
PS	NS	NS	PS	PS
PB	NB	NB	PB	PB

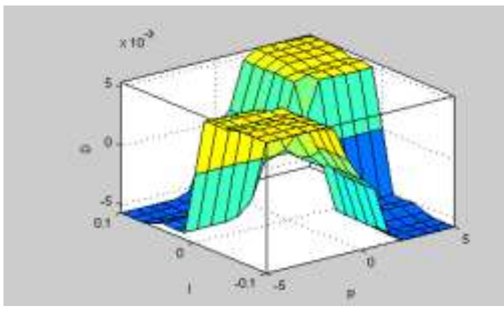


Fig. 15. Surface viewer for the proposed FLC.

The CSI output current is illustrated in Fig. 16. In order to reduce the output harmonics on the AC side, the LC filter is connected between the CSI and the grid.

The proposed fuzzy logic based MPPT controller includes three basic components, fuzzification module, inference engine and defuzzification module as shown in Fig. 17. The fuzzification makes it possible to pass fromthe crisp variables to the linguistic variables. The actual voltage(V_{pv}) and current (I_{pv}) of the PV module can be measured continuously and the power can then be calculated

(P_{pv} = V_{pv}× I_{pv}). The control is determined on the basis of satisfaction of two criteria relating to the two input variables of the proposed controller, namely ΔP_{pv} and ΔI_{pv} at the sampling instant j.

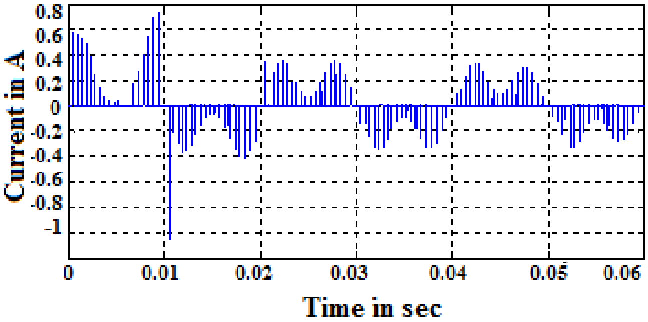


Fig. 16. The CSI output current.

The output is the duty ratio value (D) of the active bypass circuit which controls the ON-OFF time of the switching period for the gate signal of each MOSFET

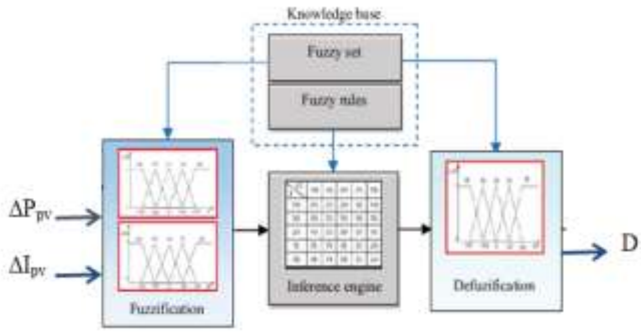


Fig. 17. Structure of fuzzy logic controller.

The inference engine applies the rules to the fuzzy inputs (that were generated from the fuzzification process) to determine the fuzzy outputs. Therefore, before the rules can be evaluated, the crisp input values must be fuzzified to obtain the corresponding linguistic values (that are necessary to determine the active or fired rules) and the degree to which each part of the antecedent has been satisfied for each rule.

It is noticed that the inference methods provide a function for the resulting membership variable; it thus acts on fuzzy information. As the DC-DC converter requires a precise control signal D at its entry, it is the necessary to envisage a transformation of this fuzzy information into deterministic one, this phase is called defuzzification. Defuzzification can be performed normally by two algorithms: Center of Area (COA) and the Max Criterion Method (MCM). The most used defuzzification method is that of the determination of the center of area (COA) of final combined fuzzy set. The fin union of all rule output fuzzy set using the maximum aggregation method.

To validate the performance of the proposed PV solar system shown in Fig.1, the maximum power point tracking design is simulated using a Matlab/Simulink. The circuit specifications are given in Table 3. The output power and current of the proposed PV solar system under uniform condition (with irradiance level 500W/m^2) are shown in Fig.18

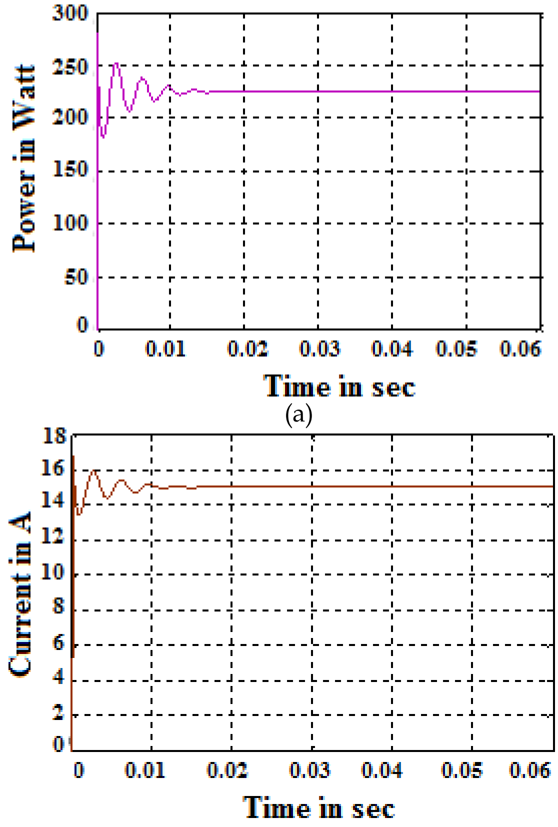
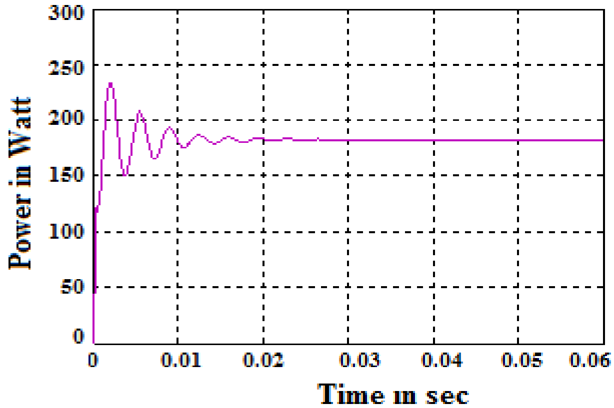
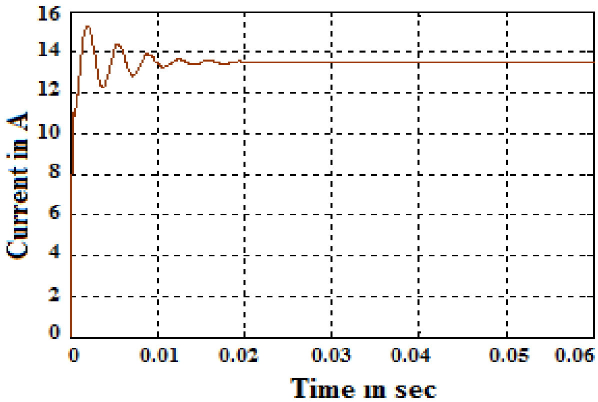


Fig. 18. (a) PV output power. (b) PV output current under the uniform conditions.

When the second PV module in Fig. 1 is partially shaded (with irradiance level 250W/m^2), the output power and current of the proposed PV solar system are shown in Fig. 19.



(a)



(b)

Fig. 19. (a) PV output power. (b) PV output current under partially shaded conditions.

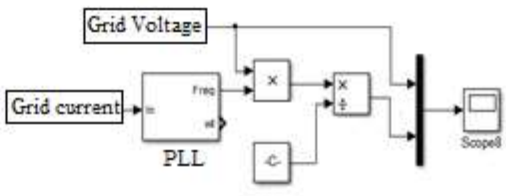


Fig. 20. Block diagram of the grid voltage and current.

TABLE 3
The PV solar system specifications.

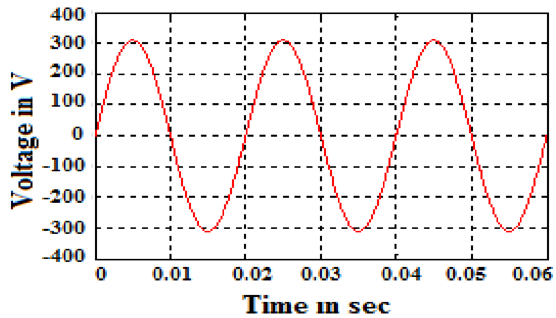
Item	Symbol	Value
PV module open-circuit voltage	V_{oc}	8V
PV module short-circuit current	I_{sc}	15A
Irradiance used for measurements	I_r	500(W/m^2)
Active bypass capacitor	C1	100µF
Active bypass capacitor	C2	100µF
Active bypass inductor	L1	0.01mH
Resonant circuit inductor	L_m	10mH
Resonant circuit inductor	L_n	5mH
Resonant circuit capacitor	C_m	125µF
Resonant circuit capacitor	C_n	250µF
DC – link inductor	L_{dc}	5mH
AC - filter capacitor	C_k	20µF
AC – filter inductor	L_k	1mH
AC – grid voltage	V_{rms}	220V

The comparison between the results of output power and current for the PV modules under the normal conditions and partial shading conditions with using the proposed MPPT control method is shown in Table 4.

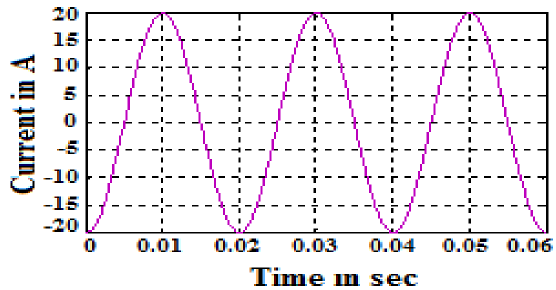
TABLE 4
PV output power and current

PV output power without a shadow	225w
PV output power with shadow	182.35w
PV output current without a shadow	15A
PV output current with shadow	13.5A

The AC grid voltage and current are shown in Fig. 21, where the two signals are out of phase. In order to make both signals in phase, a phase-locked-loop is used as shown in Fig. 22. The ac grid voltage and current with using phase-locked-loop are shown in Fig. 23.



(a)



(b)

Fig. 21. (a) The grid voltage. (b) The grid current.

Fig. 24 shows the simulation result of the proposed MPPT control method under different shadow conditions. The power generated from the two PV modules under the uniform conditions at T_1 is equal to 225W. When the second module is partially shaded at T_2, the PV output power decreases to 158.77W. When the shadow is removed at T_3, the PV output power increases again to the same value. This result shows that the proposed MPPT control method is stable under the different shadow conditions.

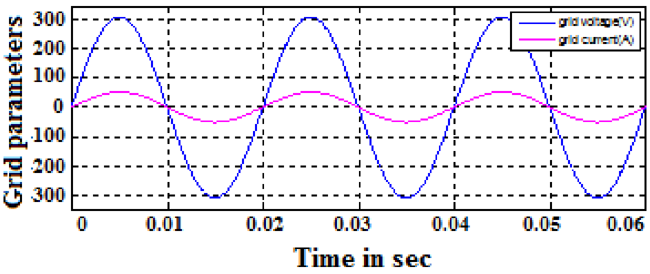


Fig. 23. The AC grid voltage and current with using phase-locked-loop.

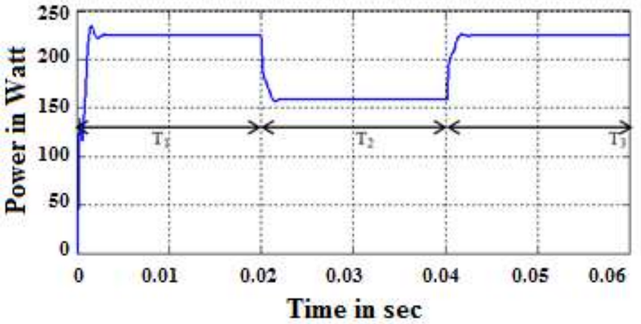


Fig. 24. Simulation results of the proposed MPPT under different shadow conditions.

VI. CONCLUSION

With the increased demand for renewable energy resources especially the solar energy, it is important to preserve the performance of the PV array of the solar system on its maximum power point under the partial shading conditions. In this thesis, the partial shading problem of the photovoltaic solar system has been investigated and addressed. Specifically, the global maximum power point has been tracked. In fact, the conventional algorithms cannot solve the problem of multiple peaks that appear in the P-V curve when the solar irradiance on the PV array is changed as a consequence of partial shading. To overcome that problem, this thesis has used an artificial intelligence algorithm that based on a fuzzy control algorithm. Furthermore, this thesis presented an effective process to detect the shaded region on a PV module. This process uses a digital image processing technique to tack an image for the PV. module, and then this process determines the existence of a shadow or not on PV array. Finally, using a fuzzy design making method, this thesis has introduced a practical method to discriminate the type of this shadow. The results obtained from the shadow detection method have been used to design a pulse width modulator which can enable the gate drive of the active bypass circuit. This active bypass circuit ensures that every PV module on the solar system is working at its maximum operating point. This should increase the power generation of the PV solar system. Consequently, an effective method to track the maximum power point under the partial shading conditions has been developed based on the combination between the fuzzy logic technique and active bypass circuit which ensured a unique MPP for the solar system. In order to connect the PV array of the proposed solar system to ac grid, a current source inverter (CSI) has been used with a double tuned resonant filter which showed up eliminations in the undesirable harmonics on the DC side. In addition, an LC filter has been used in AC side to reduce the switching harmonics

The simulation results showed an improvement in the performance of the proposed MPPT method under partial shading conditions. Hence, the combination of active bypass circuit and the image processing technique, which relies on fuzzy logic decision-making approach, provides an effective approach to detect the shaded region on the PV module. In addition, this combination ensures a unique MPP of the proposed PV solar system. The proposed fuzzy control system can reach the maximum power in a short time and can maintain its stability under any partial shading conditions.

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