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FUZZY BASED MAXIMUM POWER POINT TRACKING IN GRID CONNECTED PV SYSTEMS UNDER PARTIALLY SHADING CONDITIONS

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Abstract— To convert solar energy more viable, the efficiency of solar array systems should be maximized. An easier approach to maximizing the efficiency of solar array systems is Maximum Power Point Tracking (MPPT). MPPT is used in photovoltaic (PV) systems to maximize the output power of photovoltaic array, irrespective of the irradiation and temperature conditions. Many conventional MPPT fails to attain global maximum power point due to presence of multiple maxima points in shaded solar PV panel. This work proposes a fuzzy based controller which always attains the global maximum point in shaded panels and to develop a control techniques for three phase grid connected PV system including a method for DC link voltage control that can stabilize the voltage at the inverter input. The proposed MPPT has been implemented by combining fuzzy logic based MPPT with a scanning and storing system. The proposed MPPT is able to reach the global maximum power point (MPP) under any partial shading conditions. Moreover, the controller exhibits a fast speed of convergence, having small oscillation around the MPP during steady state.

***Keywords* — MPPT, PV, Fuzzy Logic.**

I. INTRODUCTION

Renewable energy sources play an important role in electric power generation. There are various renewable sources which used for electric power generation, such as solar energy, wind energy, geothermal etc. Solar Energy is a good choice for electric power generation, since the solar energy is directly converted into electrical energy by solar photovoltaic modules. These modules are made up of silicon cells. When many such cells are connected in series we get a solar PV module. The current rating of the modules increases when the area of the individual cells is increased, and vice versa. When many such PV modules are connected in series and parallel combinations we get a solar PV arrays, that suitable for obtaining higher power output.

Main factors that affect the efficiency of the collection process are solar cell efficiency, intensity of source radiation and storage techniques. The efficiency of a solar cell is limited by materials used in solar cell manufacturing. It is particularly difficult to make considerable improvements in the performance of the cell, and hence restricts the efficiency of the overall collection process. Therefore, the increase of the intensity of radiation received from the sun is the most attainable method of improving the performance of solar power. There are three major approaches for maximizing power extraction in solar systems. They are sun tracking, maximum power point (MPP) tracking or both. These methods needs controllers may be intelligent such as fuzzy logic controller or conventional controller such as PID controller.

The advantage of the fuzzy logic control is that it does not strictly need any mathematical model of the plant. It is based on plant operator experience, and it is very easy to apply. Hence, many complex systems can be controlled without knowing the exact mathematical model of the plant. In addition, fuzzy logic simplifies dealing with nonlinearities in systems. The nice thing about fuzzy logic control is that the linguistic system definition becomes the control algorithm.

Modified fuzzy-logic controller for maximum power point (MPP) tracking was proposed to increase photovoltaic (PV) system performance during partially shaded conditions [1]. In place of perturbing and observing the PV system MPP, the controller will scan and stores the maximum power during the perturbing and observing procedures. The controller provides accurate convergence to the global maximum operating point under different partial shadowing conditions.
A technique based on GA was developed to extract the global maximum point for PV panel under shade [2]. The characteristics of PV array are affected by shading, temperature and solar insolation. In reality, under partially shaded conditions, the P-V and I-V characteristics of solar array gets more complex with multiple maxima in the characteristic curves. A new method to track the global MPP based on controlling a dc to dc converter connected to the output of PV array, such that it behaves as a constant input-power load. The power–voltage characteristic of PV arrays operating under partial-shading conditions exhibits multiple local MPP[3]. A novel strategy of maximum power point tracking for photovoltaic power generation systems based on Fibonacci search algorithm to realize simple control system to track the real maximum power point even under non-uniform or for rapidly changing insolation conditions [4].

1.1 Solar PV Characteristics

The solar cell is the semiconductor device that directly converts the light energy to the electrical energy. Specifically, the output power of a solar array strongly depends on the irradiance level of sunlight and ambient temperature. The conventional model of a solar cell is the one diode model. During uniform solar insolation, the output power of the solar PV array is equal the total output power of all solar cells. MPPT is used to track maximum power from a Solar PV panel. But in non uniform insolation condition like shadow on the solar panel, the region of shaded solar module starts working as a load, and it can be expeled by using the bypass and blocking diode[9]. If even one full cell is shaded, the voltage of that module will drop to half of its un-shaded value in order to protect itself. If enough cells are shaded, the module will not convert any energy and will in fact become a tiny drain of energy on the entire system. The effect of shading is occurrence of multiple local maxima points. The conventional algorithms like Perturb and Observe method and Incremental conductance method cannot be applied, as the algorithm stops when they get first local maximum point. These algorithms fail to extract global maximum power point resulting in significant reduction of both the generated power and the PV energy production system reliability.

Photovoltaic modules have a very low conversion efficiency of around 15% for the manufactured ones. The PV plant efficiency is affected mainly by three factors: the efficiency of the PV panel, the efficiency of the inverter and the efficiency of the MPPT algorithm. Improving the efficiency of the PV panel and the inverter is not easy as it depends on the technology available, it may require better components, which may increase extremely the cost of the installation. Instead, improving the tracking of the MPP with new control algorithms is easier, which is not expensive and could be done even in plants which are in use already by updating their control algorithms, which would lead to an effective increase in PV power generation and consequently a reduction in its price. MPPT algorithms are necessary because PV arrays have a non linear voltage-current characteristic with a unique point where the power produced is maximum. This point will depends on the irradiance conditions and temperature of the panels. Both conditions change during the day and are also different depending on the season of the year. In addition, irradiation can change rapidly due to changing atmospheric conditions such as clouds.

Conventional MPPT techniques find the maximum power point voltage (V_{MPP}) and current (I_{MPP}) at which the PV array operates at the MPP. The functioning of a photovoltaic array is impacted by solar irradiance, temperature, array configuration and shading. However, these techniques may malfunction for non uniform insolation of the PV array. Frequently, the PV arrays get shadowed, wholly or partially, by means of moving clouds, adjacent buildings and towers, nearby trees, utility and telephone poles. The situation is of special interest in case of large PV installations such as those used in distributed power generation systems.

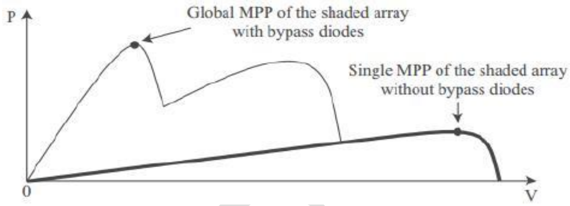

Fig 1: P-V Characteristics of Shaded PV Solar Cell

Solar PV panel is a power source having non linear internal resistance. A major challenge in using a solar PV source containing a number of cells in series is to deal with its non-linear internal resistance. The problem will be more complex when the array receives non-uniform solar radiation. The shaded cells absorb a large amount of electric power generated by cells receiving high insolation and convert it into heat. This heat under certain conditions may damage the low illuminated cells . To mitigate the stress on shaded cells, bypass diodes are connected across the modules. In such case, power-voltage characteristic curve shows multiple peaks under non uniform illumination. Under partially shaded conditions, the PV characteristics get more tangled with more than one peak. Yet, it is very crucial to understand and predict them in order to draw out the maximum possible power. A MATLAB-based modeling and simulation scheme is desirable for studying the I-V and P–V characteristics of a photovoltaic array under a non-inhomogeneous insolation due to partial shading[8]. It can also be used for assessing and acquiring new maximum power point tracking methods, particularly for partially shaded conditions.

The new method offers a mean to study the effects of shading patterns on PV panels having different forms. It is observed that, for a set number of PV modules, the array configuration (refers to the number of series and parallel connections) importantly bears on the maximum usable power under partially shaded conditions[7]. The PV and IV characteristic of shaded solar PV panel is given in Figure 1 and Figure 2.

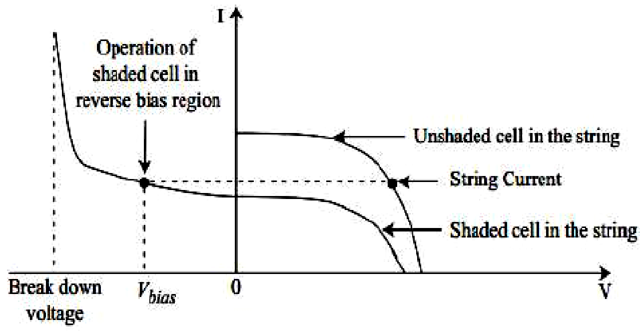

Fig 2: I-V Characteristics of Shaded PV Solar Cell

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The photovoltaic generator model can be found from the electrical equivalent to the source. The equivalent circuit of solar cell is shown in Fig.3.

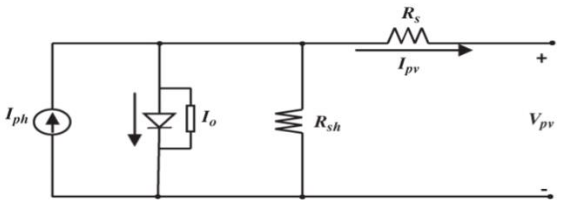


Fig 3: Equivalent Circuit of PV Cell

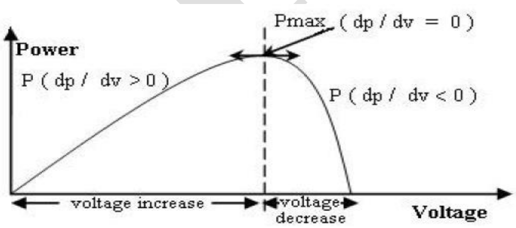
By using single diode model, the equivalent circuit for the solar module in Ns series cells or parallel cells can be studied. The specifications of solar module are illustrated in Table 1.

Table 1. Solar Module Specification

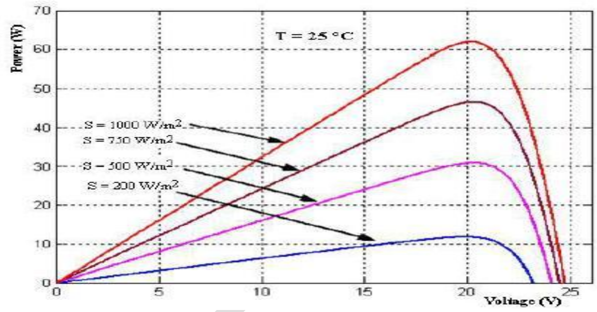
Parameter	Value
Voltage at maximum point(V_m)	26.3 V
Current at maximum point(I_m)	7.61 A
Open circuit voltage(V_{oc})	32.9 V
Short circuit current(I_{sc})	8.21 A
N_s	54
G_{ref}	1000W/m^2
T_{ref}	(25+273.15) K
R_s	0.001Ω
R_{sh}	5Ω

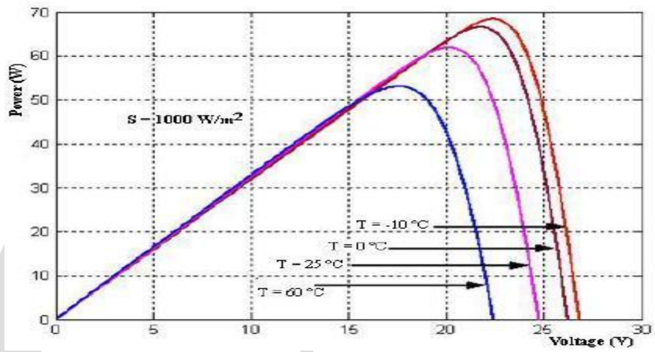
1.2 Maximum Power Point Tracking

A typical characteristic curve of PV model's current and voltage curve is shown in Figures 2,and the power and voltage curve is shown in Figures 2. The characteristics of a PV system vary with temperature as shown in Figures 2 and with irradiation as shown in Figures 2; there exists a single maxima power corresponding to a particular voltage and current [34].



So, when a direct connection is carried out between the source and the load, the output of the PV module is seldom maximum and the operating point is not optimal. To avoid this problem, it is necessary to add an adaptation device, MPPT controller with a DC-DC converter, between the source and the load (Figure 2).



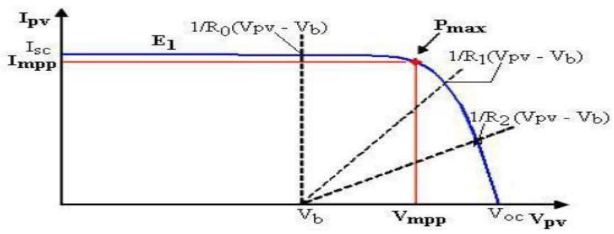


Maximum power point tracker (MPPT) tracks the new modified maximum power point in its corresponding curve whenever temperature and/or insolation variation occurs. MPPT is used for extracting the maximum power from the solar PV module and transferring that power to the load. A dc/dc (step up/step down) converter acts as an interface between the load and the module.

The MPPT changing the duty cycle to keep the transfer power from the solar PV module to the load at maximum point[34].

II. FUZZY LOGIC CONTROLLER

Unlike conventional MPPTs where the PV system operating power is perturbed and observed to track the MPP. Scanning, storing, perturbing and observing the operating power of the PV system are used for the proposed MPPT. The proposed method is able to track the MPP under any weather conditions,



particularly partial shadowing where local and global maximum points exist. During the initial condition or varying weather conditions, the proposed MPPT makes a wide range search to scan and store the maximum power value on the PV system. A preset value which represents the accepted difference between the identified maximum power and the operated power is stored to decide the controller rules. If the difference between the identified maximum power and the operated power is greater than the pre-set value, the duty cycle is increased, or-else, fuzzy-logic-based MPPT is applied[11]. In this case, the algorithm ensures that the MPPT is not trapped by local maxima and quickly recovers the new global maximum point during varying weather conditions.

The flowchart of the proposed method is shown in Fig.4, where V_{PV}, I_{PV} are the PV output voltage and current respectively, D is the duty cycle, P_{max} is the global MPP, and ΔP_{max} is a constant that identifies the allowable difference between the global maximum point and the operating power point.

Three scanning and storing techniques are proposed to identify the global maximum power during initial conditions or varying weather conditions. The first technique is to initialize the system with maximum duty cycle since the PV output power usually takes some samples before reaching the operating point at maximum duty cycle. The P–V characteristic curve is scanned, and the global MPP is stored. The second technique is to increase the duty cycle from a minimum to a maximum value with a fixed step. In this case, the P–V curve is scanned, and the global MPP is stored. The last technique is to apply a large initial perturbation step to make a wide search range on the PV power locus. The scanning and storing the PV power are accomplished during perturbation and observation.

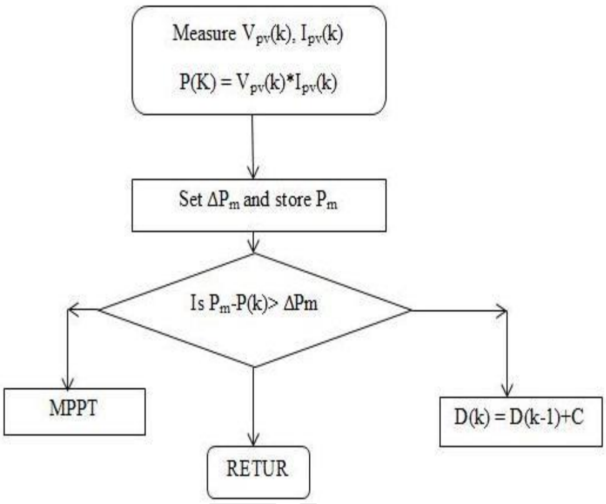


Fig 4: Proposed method flowchart

Any conventional MPPT method can be used with the proposed method however, fuzzy-logic-based MPPT is preferred specially when using the third technique because the tracking speed is not constant. Therefore, during initial conditions or varying weather conditions, the initial tracking speed should be fast enough to make a wide range power scan and store the maximum available power. On the other side, when the operating point reaches the global maximum, the tracking speed decreases to minimize any oscillation around the global maximum point. The PV system block diagram along with proposed MPPT controller is shown in Fig.5.

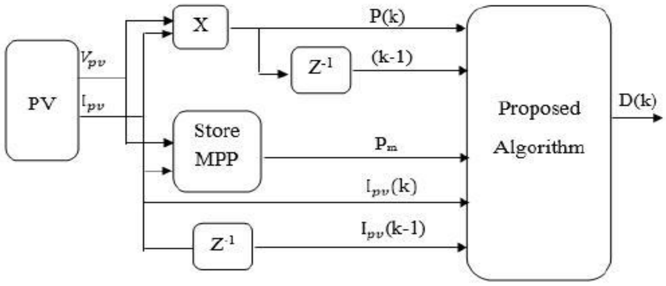


Fig 5: PV System Block with proposed MPPT Controller

Modification to the fuzzy-logic-based MPPT algorithm using the scanning and storing procedures, is proposed to quickly locate the global MPP. The inputs to the fuzzy logic controller (FLC) are:

$$\Delta P = P(k) - P(k\text{-}1)$$
$$\Delta I = I(k) - I(k\text{-}1)$$
$$\Delta P_{max} = P_{max}(k) - P(k)$$

where ΔP, ΔI are the PV array output power change and current change respectively, ΔP_{max} is the difference between the stored global maximum power (P_{max}) and the current power, ΔD is the perturbation variation size. To ensure that the PV global maximum power is stored during the scanning procedure, a fast initial tracking speed is used. The change in variable inputs ΔP and ΔI are divided into four fuzzy subsets: positive big (PB), positive small (PS), negative big (NB), and negative small (NS). The variable input ΔP_{max} is divided into two fuzzy subsets: PB and PS. The output variable ΔD is divided into six fuzzy subsets: PB, positive medium (PM), PS, NB, negative medium (NM), and NS. Therefore, the fuzzy algorithm requires 32 fuzzy control rules. To operate the fuzzy combination, Mamdani's method with max–min combination is used. The fuzzy rules are shown in Table 2.

Table 2 Fuzzy Logic Rules

ΔI / ΔP	NB	NS	PS	PB	ΔP_{max}
NB	PM	PM	NM	NM	**PS**
NS	PS	PS	NS	NS	
PS	NS	NS	PS	PS	
PB	NM	NM	PM	PM	
NB	PB	PB	PB	PB	**PB**
NS	PB	PB	PB	PB	
PS	PB	PB	PB	PB	
PB	PB	PB	PB	PB	

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III. THREE-PHASE GRID-CONNECTED INVERTERS

Control of three phase grid connected pv system

This chapter covers the control system developed to operate a grid connected PV system. First, the structure of the system and its control blocks are introduced. Then, the function of each block is examined in detail. An overview of the dq transformation and sinusoidal PWM technique are presented for their importance in building the inverter control system. The boost DC converter is controlled using an open loop maximum power point tracking technique in order to achieve fast control response to transients and changes in weather conditions. The control system is assessed based on: the quality of the injected AC current into the grid, as determined by the Total Harmonic Current Distortion (THDI) limits specified by the IEEE Std. 929-2000; and the speed of the control system in tracking the maximum power point as weather conditions, mainly solar irradiation, change. The system was studied under grid-side fault conditions to examine the effect of the transformer topology selection on the propagation of zero sequence currents to the grid. These currents can intervene with the correct operation of the utility protection relays.

3.1 System structure

The PV system under study is shown in figure 3-1. A photovoltaic array is used to convert sunlight into DC current. The output of the array is connected to a boost DC converter that is used to perform MPPT functions and increase the array terminal voltage to a higher value so it can be interfaced to the distribution system grid at 6.6 kV. The DC converter controller is used to perform these two functions. A DC link capacitor is used after the DC converter and acts as a temporary power storage device to provide the voltage source inverter with a steady flow of power. The capacitor's voltage is regulated using a DC link controller that balances input and output powers of the capacitor. The voltage source inverter is controlled in the rotating *dq* frame to inject a controllable three phase AC current into the grid.

To achieve unity power factor operation, current is injected in phase with the grid voltage. A phase locked loop (PLL) is used to lock on the grid frequency and provide a stable reference synchronization signal for the inverter control system, which works to minimize the error between the actual injected current and the reference current obtained from the DC link controller. An adjustable speed drive (ASD) and an RL load are connected to the grid to simulate some of the loads that are connected to a distribution system network. An LC low pass filter is connected at the output of the inverter to attenuate high frequency harmonics and prevent them from propagating into the power system grid. A second order LCL filter is obtained if the leakage inductance of the interfacing transformer is referred to the low voltage side. This provides a smooth output current which is low in harmonic content.

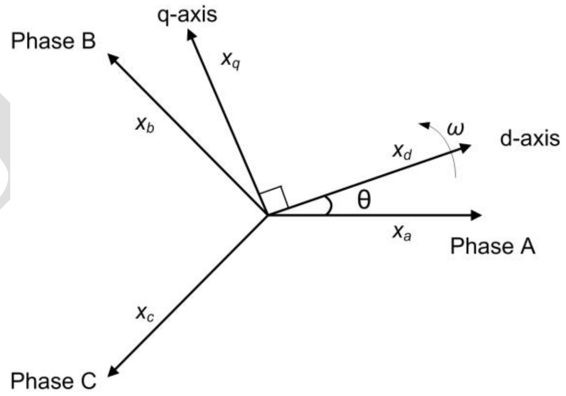
The abc/dq Transformation

The *dq* transformation is used to transform three phase system quantities like voltages and currents from the synchronous reference frame (*abc*) to a synchronously rotating reference frame with three constant components when the system is balanced. The relationship that govern the transformation from the *abc* to *dq* frame is

$$\begin{bmatrix} x_d \\ x_q \\ x_0 \end{bmatrix} = T * \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix}$$

$$T = \sqrt{\frac{2}{3}} * \begin{bmatrix} \cos(\omega t) & \cos(\omega t - \frac{2\pi}{3}) & cos(\omega t + \frac{2\pi}{3}) \\ -\sin(\omega t) & -\sin(\omega t - \frac{2\pi}{3}) & -\sin(\omega t + \frac{2\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}$$

where *x* can be either a set of three phase voltages or currents to be transformed, *T* is the transformation matrix and *ω* is the angular rotation frequency of the frame [23]. The angle between the direct axis (d-axis) and phase a-axis is defined as θ as shown in figure 3-2.



3.2 Relationship between the abc and dq reference frames

The result of this transformation is three constant rotating components: the direct (d), quadrature (q) and zero (0) components. In balanced three phase systems, the zero component can be ignored since

xa □□*xb* □□*xc* □□0

The inverse transformation from the *dq* frame to the *abc* frame can be obtained by applying

$$\begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} = T^{-1} * \begin{bmatrix} x_0 \\ x_d \\ x_q \end{bmatrix}$$

$$T = \sqrt{\frac{2}{3}} * \begin{bmatrix} \cos(\omega t) & -\sin(\omega t) & \frac{1}{\sqrt{2}} \\ \cos(\omega t - \frac{2\pi}{3}) & -\sin(\omega t - \frac{2\pi}{3}) & \frac{1}{\sqrt{2}} \\ cos(\omega t + \frac{2\pi}{3}) & -\sin(\omega t + \frac{2\pi}{3}) & \frac{1}{\sqrt{2}} \end{bmatrix}$$

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This transformation is useful in developing the control system for the voltage source inverter under current control to regulate the output of the PV system. Active and reactive powers injected from the PV system can be calculated using the following relationships

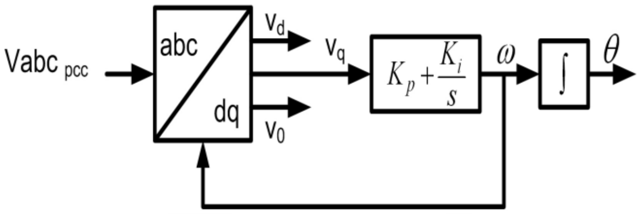
$P=V_dI_{d,injected}+V_qI_{q, injected}$
$Q= -V_dI_{q,injected}+V_qI_{d, injected}$

where *Vd*, *Vq* are the *dq* voltages at PCC at the grid side of the transformer, *Id,injected* and *Iq,injected* are the *dq* components of the injected current at the grid side. It is evident that in the computation of reactive power *Q*, there is cross coupling between the direct and quadrature current and voltage components. This can be eliminated through the use of a phase locked loop (PLL) that locks on the grid frequency in such a way that the quadrature component of the voltage at the point of PV system connection is forced to zero. In this case, equation 3.4 simplifies to

$P=V_dI_{d,injected}$
$Q=-V_dI_{d,injected}$

This means that the direct and quadrature components of the inverter output current can be used to control the active and reactive output powers from the PV array system, as they are related to the injected currents by the transformer turns ratio. This is based on the assumption that the voltage at the point of common coupling (PCC) is relatively constant. In current practice, distribution systems have regulation mechanisms to keep voltage within specified limits.

3.3 Phase Locked Loop (PLL)



The role of the phase locked loop is to provide the rotation frequency, direct and quadrature voltage components at the point of common coupling (PCC) by resolving the grid voltage *abc* components. Multiple control blocks of the PV system rely on this information to regulate their output command signals. As stated earlier, the PLL computes the rotation frequency of the grid voltage vector by first transforming it to the *dq* frame, and then force the quadrature component of the voltage to zero to eliminate cross coupling in the active and reactive power terms [23]. A proportional-integral controller is used to perform this task as shown in figure 3-3. The proportional (Kp) and integral (Ki) gains of the controller were set through an iterative process to achieve a fast settling time.

Schematic diagram of the phase locked loop (PLL)

The output from the PI controller is the rotation frequency ω in rad/s. Integrating this term results in the rotation angle θ in radians. The operation of the PLL is governed by

$\omega=K_pV_q + K_I\int V_q dt$
$\theta =\int \omega dt$

IV. RESULTS AND DISCUSSION

The given shaded solar PV panel under study have three maximum power points, out of which only one is global maximum power point. Due to the effect of shading, there is an occurrence of more than one maximum point.

In this work, the Simulink model has been developed for 6 cases. The first 3 cases are under constant irradiation and next 3 cases are under varying irradiation conditions. Each case differs in terms of placement of the proposed controller and its actuating signal.

Case I-Individual MPPT Controllers for Shaded & Illuminated PV Arrays,
Case II- MPPT controller based on Illuminated PV Array,
Case III - MPPT Controller based on Shaded PV Array.

The conventional MPPT techniques like Perturb & Observe method fails to converge to global maximum power point. In fact it converges to local maximum point and its convergence rate is slower. But the fuzzy logic controller used here converges at global maximum point at a faster manner. The presence of multiple maximum points in shaded solar panel makes the conventional MPPTs to converge at local maxima point instead of global maximum point.

The fuzzy logic controller perturbs and observes the operation at the optimum duty cycle. A wide duty cycle range search is applied to scan for the global maximum point. Once the global maximum power is found, the controller stores the value and compares it with the current operation power. If the difference between the stored global maximum power and the current operating power is greater than a preset value, the duty cycle increases.

During varying weather conditions, the controller resets the stored global maximum value and repeats the same process to find the new global MPP. This technique is slightly faster with less power losses during the initial and varying weather conditions. The duty cycle must return to a minimum value

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whenever it exceeds the maximum value to track the global MPP.

The proposed fuzzy-logic-based MPPT with a large initial perturbation step scans and stores the power locus during perturbation and observation. The local maxima in the P–V characteristic do not prevent the proposed MPPT from successfully capturing the global MPP in a relatively short time, with small oscillation around the MPP.

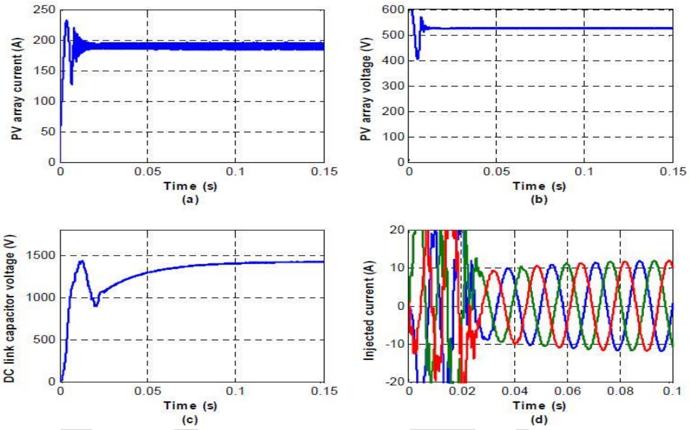
Fig.6 gives the designed structure of the MATLAB Simulink model for Case 1. Fig.7 shows the obtained Power from the PV by implementing various MPPT algorithms and comparing them for constant Irradiation condition. Similarly Fig.8 shows the obtained Power from the PV by implementing various MPPT algorithms and comparing them for varying Irradiation condition.

Table 3 gives a quantitative comparison of various performance measures in applying various MPPT algorithms and the proposed Fuzzy Logic Controller based MPPT. In Table 3, P_{ILA} is Power Produced by illuminated array, P_{SH} is the Power Produced by Shaded Array, P_{TOTAL} is the Total Power Produced by both arrays, V_{MIL} is Maximum Power Point Voltage of Illuminated Array, V_{MSH} is Maximum Power Point Voltage of Shaded Array and V_M is Maximum Power Point Voltage

Simulation of the PV system at *G* = 1000 W/m2 and *T* = 25°C

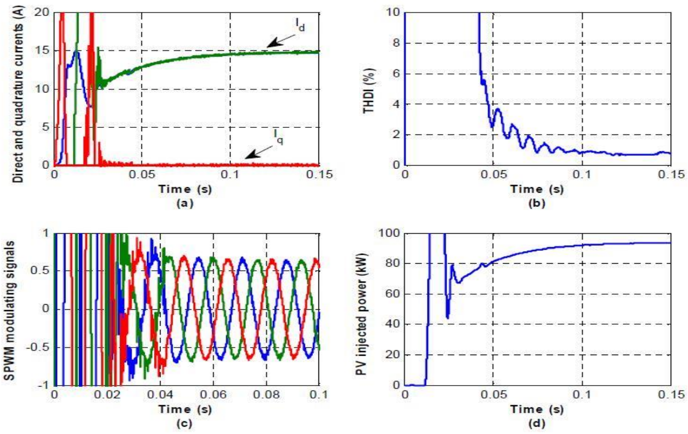
The PV system was constructed using a 100 kW array connected in centralized mode. The array composed of 25 parallel strings each containing 20 modules in series to obtain a terminal voltage suitable for grid connection purposes. To simulate the control system and the resulting output currents and voltages of the VSI, the array was subjected to a 1000 W/m2 of solar irradiation and a temperature of 25° C. The DC output current and terminal voltage of the array were monitored during simulation to determine the current operating conditions at the specified atmospheric conditions. These two quantities are shown in figure 4-1 (a) and (b) respectively.

The switching action of the DC converter caused some ripple in the output current with an average value of about 190 A, the ripple magnitude can be reduced by increasing the size of the inductor used in the boost converter. There are some initial transients in the current waveform at the beginning of simulation as the system started operation and the DC converter drove the array to the estimated maximum power point. The array terminal voltage also suffered initially from these transients. The array voltage stabilized at 526 V estimated by measuring the test cells voltages. Error during the estimation process may result due to the fact that actual voltages of the array modules might vary slightly rom the theoretical value. This error can be adjusted by taking that fact into account.



(a) DC current output of the PV array (b) Terminal voltage of the array (c) DC link capacitor voltage and (d) injected AC currents at the secondary side of the transformer (grid)

The DC link voltage was monitored to verify the operation of the DC link controller and make sure it reached a constant value for the VSI to operate correctly and generate the required output currents. The purpose of the controller was to force the mismatch between the capacitor input and output DC power to zero. The output of the controller was the reference direct current responsible for setting the output power from the inverter. It took about 0.1 seconds or 6 cycles for the capacitor to reach a steady state voltage of 1400 V as shown in figure 4-1 (c). This fixed voltage DC bus would feed the required power to the inverter to inject the sinusoidal AC currents shown in figure 4-1 (d). These currents suffered from transients at the start of system operation as the PLL synchronized the control system and due to having a changing DC link capacitor voltage.



(a) dq components of the injected current (b) total harmonic distortion of the output AC current (c) SPWM modulation signals used to drive the VSI and (d) real power delivered tothe grid from the PV system

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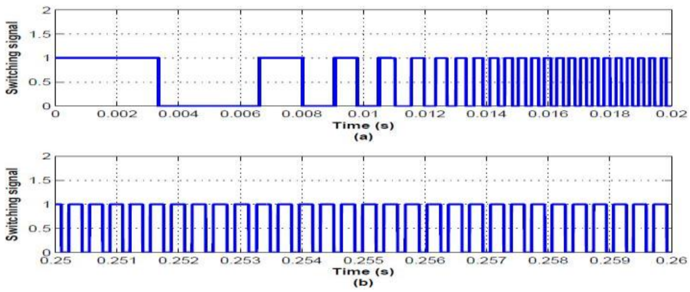
The dq components of the output current are shown in figure 4-2 (a). The quadrature current component responsible for controlling the reactive power output from the inverter was forced to zero in order to achieve unity power factor operation. The direct component was controlled to follow the reference signal set by the DC link voltage controller.

The THD level in the output current was below the limits specified by the IEEE standard 929-2000 which is 5%. The filter connected to the inverter was a low pass type set to attenuate harmonics above 612 Hz in the output. The value of THDI was 1% during steady state operating conditions as shown in figure 4-2 (b). The sinusoidal pulse width modulation signals obtained from the inverter current controller were used to provide the triggering pulses for the inverter switches. The amplitudes of the signals were below unity to ensure over modulation did not occur causing undesirable harmonics in the output.

The signals are shown in figure 4-2 (c). The output real power in kW injected into the grid is shown in figure 4-2 (d). The maximum output power form the array under the stated conditions (1000 W/m2 and 25 C) should have been 100 kW. However, due to the estimation of the maximum power point and power losses in harmonics at the inverter output, the actual injected power to the system was 94 kW. From initial results, the open loop MPPT algorithm based on the fractional open circuit voltage technique proved its quick response at system start up in a short time of about 6 cycles as compared to the modified incremental conductance algorithm used in [14]. The switching signal of the boost converter was monitored to examine its duty cycle and switching frequency.

In figure 4-3 (a), the duty cycle of the switching signal is about 0.5 during the initial transient phase of the simulation. The switching frequency is around 150 Hz at that point but it increases as the converter drove the PV array close to the maximum power point voltage. During the steady state operation phase which is achieved after the MPP has been located, the switching frequency settles at about 3 kHz.

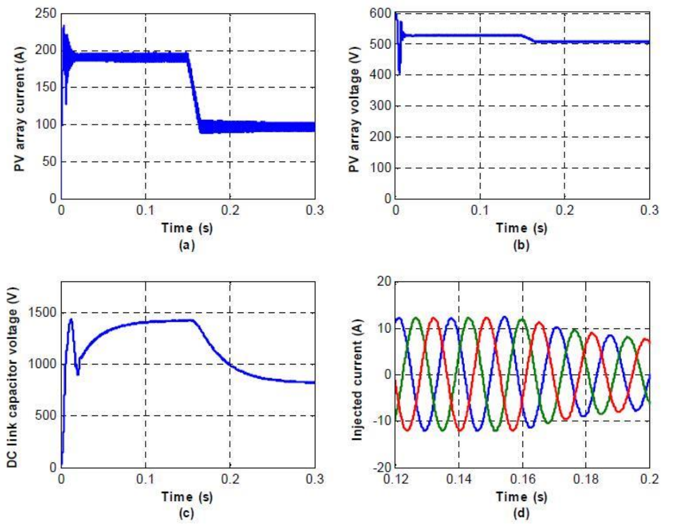
This is shown in figure 4-3 (b) where the duty cycle of the switching signal is at 0.67. In this case, the duty cycle is controlled indirectly by monitoring the PV array terminal voltage and the estimated MPP voltage. Direct control of the duty cycle can be achieved by augmenting this MPPT tracking technique with the IncCond technique in order to fine tune the obtained MPP estimated voltage.



(a) switching signal of the boost converter during the tracking phase of the MPP (b) switching signal during steady state after locating the maximum power point of the PV array

Simulation when *G* changes from 1000 to 500 W/m2

The goal of the simulation study in this section was to verify the dynamic and steady state response of the control system of the PV array as solar irradiation level dropped rapidly. This is a situation that can happen when a cloud passes by and blocks direct sunlight from hitting the PV array. The array was subjected to a sudden drop in solar irradiation from 1000 to 500 W/m2 while monitoring the DC and AC voltages and currents in the PV array and the associated power conditioning system. Irradiation level dropped at 0.15 seconds and had an immediate effect on the array DC output current and voltage as shown in figure 4-4 (a) and (b) respectively.



(a) DC output current from the array taking into account the change in solar irradiation (b) PV array terminal voltage (c) DC link capacitor voltage and (d) injected AC currents to the grid.

The estimated voltage changed due to shading of the array causing the DC converter to move the operating voltage to a new value that corresponded to the new maximum power point, around 500 volts. Array current, which is heavily dependent on solar irradiation level, dropped to half its initial value at 1000 W/m2 to about 94 A. This caused the maximum theoretical output power to be halved as well to 50 kW. As the input power to the DC link capacitor decreased, the DC link controller

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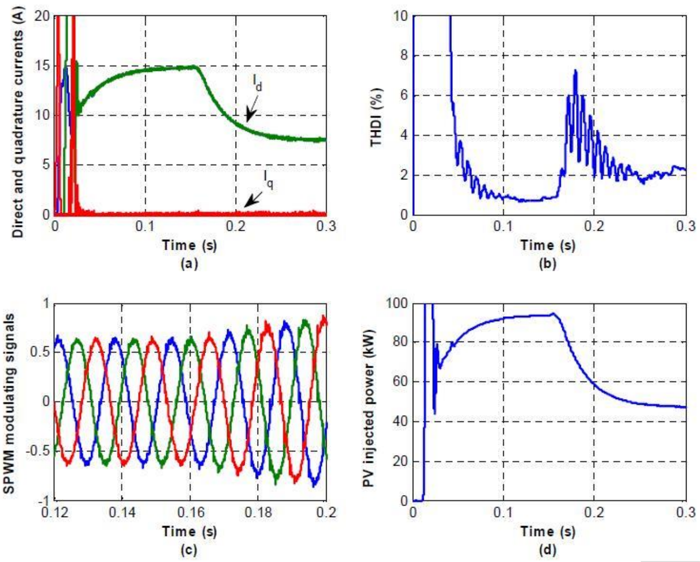
worked on setting a new reference current for the inverter to match the output power to a new control set point. The capacitor voltage decreased as shown in figure 4-4 (c). It took the controller about 6 cycles to stabilize the capacitor voltage. The injected AC currents experienced a change in amplitude as the reference current was set to a lower value due to the drop in input power, as shown in figure 4-4 (d)



(a) dq components of the injected current after the drop in solar irradiation (b) total harmonic distortion in the injected current (c) SPWM modulating signals that drive theinverter switches and (d) real power injected into the grid.

The direct component of the injected current was controlled to follow the new reference value dictated by the DC link controller at 7 A, which dropped from 15 A when solar irradiation was at 1000 W/m2. The reference for the quadrature component, however, stayed at zero to maintain unity PF operation. The dq components of the injected current are shown in 4-5 (a). The total harmonic distortion in the output current increased during the transition caused by changes in irradiation level as shown in figure 4-5 (b). The current waveform was distorted as it changed to a lower magnitude because of PV power drop. After the transition was complete, the THD reached a level of 2%, an increase of 1% from the case when solar irradiation was at 1000 W/m2. The increase in THDI was attributed to the decrease in the magnitude of the injected current where the effect of harmonics was more pronounced.

As the magnitude of the DC link voltage decreased, the sinusoidal PWM signals magnitudes increased to control the inverter to inject the required maximum power to the grid. The signals are shown in figure 4-5 (c). The real output power of the system was recorded to verify the operation of the MPPT technique. Before the drop in solar irradiation, output power from the array was 94 kW from a theoretical maximum of 100 kW. After irradiation dropped, output power was at 47 kW from a theoretical maximum of 50 kW as in figure 4-5 (d). The control system kept track of the approximate maximum power point and responded quickly to the irradiation level change in 0.1 seconds.

V. CONCLUSION

The conventional MPPT techniques like Perturb & Observe method fails to converge to global maximum power point. In fact it converges to local maximum point and its convergence rate is mentally dull. But the fuzzy logic controller used here converges at global maximum point at a faster manner. The presence of multiple maximum points in shaded solar panel makes the conventional MPPTs to converge at local maxima point instead of global maximum point. The fuzzy logic controller perturbs and observes the operation at the optimum duty cycle. A wide duty cycle range search is applied to scan for the global maximum point. Once the global maximum power is founded, the controller stores the value and compares it with the current operation power. If the difference between the stored global maximum power and the current operating power is greater than the preset value and the duty cycle increases. During varying weather conditions, the controller resets the stored global maximum value and repeats the same process to find the new global MPP. The proposed fuzzy-logic based MPPT with a large initial perturbation step scans and stores the power locus during perturbation and observation. The local maxima in the P–V characteristic do not prevent the proposed MPPT from successfully capturing the global MPP in a relatively short time, with small oscillation around the MPP.

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