CHAPTER-6

FUZZY BASED MAXIMUM POWER
POINT TRACKING
OF PV CELLS
6. Fuzzy Based Maximum Power Point Tracking of PV Cells

6.1 Introduction

In recent years, the number and variety of applications of fuzzy logic have increased significantly. The applications range of consumer products such as cameras, camcorders, washing machines, and microwave ovens to industrial process control, medical instrumentation, decision-support systems, and portfolio selection.

Fuzzy logic has two different meanings. In a narrow sense, fuzzy logic is a logical system, which is an extension of multivalve logic. However, in a wider sense fuzzy logic (FL) is almost synonymous with the theory of fuzzy sets, a theory which relates to classes of objects with a sharp boundary in which membership is a matter of degree. In this perspective, fuzzy logic in its narrow sense is a branch of fuzzy logic. Even in its more narrow definition, fuzzy logic differs both in concept and substance from traditional multivalve logical systems.

A trend that is growing in visibility relates to the use of fuzzy logic in combination with neuro computing and genetic algorithms. More generally, fuzzy logic, neuro computing, and genetic algorithms may be viewed as the principal constituents of what might be called soft computing. Unlike the traditional, hard computing, soft computing accommodates the imprecision of the real world[108]. The guiding principle of soft computing is: Exploit the tolerance for imprecision, uncertainty, and partial truth to achieve tractability, robustness, and low solution cost. In the future, soft computing could play an increasingly important role in the conception and design of systems who’s MIQ (Machine IQ) is much higher than that of systems designed by conventional methods.

Among various combinations of methodologies in soft computing, the one that has high visibility at this juncture is that of fuzzy logic and neuro computing, leading to neuro-fuzzy systems. Within fuzzy logic, such systems play a particularly important role in the induction of rules from observations. An effective method developed by Dr. Roger Jang for this purpose is called ANFIS (Adaptive Neuro-Fuzzy Inference System). This method is an important component of the toolbox. The fuzzy logic toolbox is highly impressive in all respects [108]. It makes fuzzy logic an
effective tool for the conception and design of intelligent systems. The fuzzy logic toolbox is easy to master and convenient to use. And last, but not least important, it provides a reader friendly and up-to-date introduction to the methodology of fuzzy logic and its wide ranging applications.

6.1.1 Review of Fuzzy Logic Concepts

Fuzzy logic uses fuzzy set theory, in which a variable is a member of one or more sets, with a specified degree of membership. Fuzzy logic allows us to emulate the human reasoning process in computers, quantify imprecise information, make decision based on vague and incomplete data, yet by applying a “defuzzification” process, and arrive at definite conclusions.

A fuzzy controller can be designed to roughly emulate the human deductive process i.e. the process whereby one successively infers conclusions from their knowledge. The functional architecture of the fuzzy system is composed of four basic elements; a fuzzy knowledge base (rule base and database), an inference mechanism, a Fuzzification interface and a defuzzification interface. The basic block diagram of fuzzy controller is given in Figure 6.1 where a fuzzy controller is embedded in a closed loop control system.

The FLC mainly consists of three blocks

- Fuzzification
- Inference Engine
- Defuzzification
- Rule base Unit

![Figure-6.1: General Block diagram of a fuzzy controller](image-url)
(i) Fuzzification

The fuzzy logic controller requires that each input/output variable which define the control surface be expressed in fuzzy set notations using linguistic levels. The linguistic values of each input and output variables divide its universe of discourse into adjacent intervals to form the membership functions. The member value denotes the extent to which a variable belong to a particular level. The process of converting input/output variable to linguistic levels is termed as Fuzzification.

(ii) Inference Engine

The behavior of the control surface which relates the input and output variables of the system is governed by a set of rules. A typical rule would be IF x is A THEN y is B When a set of input variables are read each of the rules that has any degree of truth in its premise is fired and contributes to the forming of the control surface by approximately modifying it. When all the rules are fired, the resulting control surface is expressed as a fuzzy set to represent the constraints output. This process is termed as inference.

(iii) Defuzzification

Defuzzification is the process of conversion of fuzzy quantity into crisp quantity. There are several methods available for defuzzification. The most prevalent one is centroid method, which utilizes the following formula:

\[ \frac{\int (\mu(x))x \, dx}{\int \mu(x) \, dx} \]

Where \( \mu \) is the membership degree of output x.

(iv) Rule base Unit

Fuzzy rule base is a collection of IF and THEN rules that contain all the information for the controlled. Fuzzy inference engine is an operating method that formulates a logical decision based on the fuzzy rule setting and transforms the fuzzy
rule base into fuzzy linguistic output. In this chapter Mamdani’s fuzzy inference method, with Maximum and Minimum operation fuzzy combination has been used.

6.2 Different Schemes for Implementing MPPT

1. Fuzzy logic based MPPT with PWM technique for uniform insolation of a PV Cell.
2. Fuzzy Logic Based Controller of MPPT for Partial Shadow condition of a PV Cell.
3. GA Enhanced Fuzzy Logic Based Controller of MPPT under Partially Shaded Condition

METHOD -1

6.3 Fuzzy logic based MPPT with PWM technique for uniform insolation of a PV Cell

The proposed MPPT controller presents the fuzzy logic based MPPT algorithm. A fuzzy logic based MPPT control technique is implemented to generate the optimal voltage from the photovoltaic system by modulating the duty cycle applied to the buck boost DC-DC converter. The proposed algorithm gives a good maximum power operation of the PV system. The fuzzy logic based MPPT can track the maximum power point faster and also it can minimize the voltage fluctuation after MPP has been recognized.

6.3.1 Proposed Method

The block diagram of the proposed solar PV system is shown in Figure-6.2. It mainly consists of a PV Module, a boost DC-DC converter, MPPT control unit and a load. The PV panel contains 100 solar cells in series and four solar cells in parallel. When the modules are wired in parallel, their current rating is increased while the voltage remains constant. When the modules are wired together in series, their voltage is increased while the current remains constant. A pure resistive load is connected to the PV module through the boost DC-DC converter. The Photovoltaic module generates the DC voltage from the solar PV array.

The voltage supplied by the PV array does not have constant values, but fluctuates according to the surrounding conditions such as intensity of solar rays and
temperature. These supplies are therefore supplemented by additional converters. The DC to DC boost converter is used to regulate a chosen level of the solar photovoltaic module output voltage and to keep the system at the maximum power point. It is mainly useful for PV maximum power tracking purposes, where the objective is to draw maximum possible power from solar panels at all times, regardless of the load. It can able to regulate the perturbed voltage by increasing or decreasing the voltage reference of the PWM (Pulse width modulation) signal [112].

Figure-6.2: Fuzzy logic based MPPT solar PV panel

The output voltage and current of the PV panel are measured and fed to the fuzzy based MPPT control unit for MPP tracking. Based on the change of power with respect to the change of voltage dp/dv and \( \Delta dp/dv \) fuzzy determines the voltage reference of the PWM (Pulse Width Modulation) signal.

In the proposed fuzzy logic based technique the error (E) and changing error (CE) are taken as input variables which are as below for \( k_{th} \) sample time

\[
E(k) = \frac{dP}{dV} = \frac{P_{ph}(k) - P_{ph}(k-1)}{V_{ph}(k) - V_{ph}(k-1)} \quad \text{--- (6.2)}
\]

\[
CE(k) = E(k) - E(k-1) \quad \text{--- (6.3)}
\]
Where, $P_{ph}(k)$ is the power of the photovoltaic generator. The input $E(k)$ shows the change of power with respect to the change of voltage. Another input $CE(k)$ expresses the change of error.

### 6.3.2 Membership Functions of Proposed Fuzzy Logic Controller

![Membership functions of error](image1)

**Figure-6.3: Membership functions of error**

![Membership functions of changing error CE](image2)

**Figure-6.4: Membership functions of changing error CE**

![Membership functions of Voltage reference Vref](image3)

**Figure-6.5: Membership functions of Voltage reference Vref**
To design the FLC, variables which can represent the dynamic performance of the system to be controlled, should be chosen as the inputs to the controller. In the proposed method, the derivative of the change of power with respect to the change of voltage ($\frac{dP}{dV}$) and change of $\Delta$ ($\frac{dP}{dV}$) are considered as the inputs of the FLC and the voltage reference for a modulated signal generation is taken as the output of the FLC.

The input and output variables are converted into linguistic variables. In this case, five fuzzy subsets, NB (Negative Big), NS (Negative Small), ZE (Zero), PS (Positive Small) and PB (Positive Big) have been chosen. Membership functions used for the input and output variables are shown in Figure-6.5. As both inputs have five subsets, a fuzzy rule base formulated for the present application is given in Table 6.1. The performances of fuzzy logic based MPP tracking are able to reduce the perturbed voltage after the MPP operating voltage has been recognized.

<table>
<thead>
<tr>
<th>E</th>
<th>CE</th>
<th>NB</th>
<th>NS</th>
<th>ZE</th>
<th>PS</th>
<th>PB</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>ZE</td>
<td>ZE</td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
<td></td>
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<tr>
<td>NS</td>
<td>ZE</td>
<td>ZE</td>
<td>PS</td>
<td>PS</td>
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<tr>
<td>ZE</td>
<td>PS</td>
<td>ZE</td>
<td>ZE</td>
<td>ZE</td>
<td>NS</td>
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<tr>
<td>PS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>ZE</td>
<td>ZE</td>
<td></td>
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<tr>
<td>PB</td>
<td>NS</td>
<td>NB</td>
<td>NB</td>
<td>ZE</td>
<td>ZE</td>
<td></td>
</tr>
</tbody>
</table>

Figure-6.6: FLC surface rules viewer
6.3.3 Simulink Diagram of the Proposed Method

In the simulation diagram Fuzzy Logic Controller of the Triangular and Gaussian membership functions are used, from this figures, it can be observed that the fuzzy can track the maximum power point at 0.01s and also it generates constant voltage without any deviations. In the simulation diagram there are 480 cells are used, which are connected in four parallel paths in each path is having seven PV modules and each module is having 120 cells in serial, insolation level of 1000W/m² and 25°C temperature. A pure resistive load is connected to the PV module through the boost dc-dc converter. The boost converter consists of a 0.2 mH inductor and a 1 mF capacitor. This boost converter is used to step up the voltage to the required value. The gating signal to the boost converter is generated by comparing the signal generated by the MPPT algorithm to a repeating sequence operating at a high frequency. The load is a 10 ohm resistance.

Figure-6.7: Simulation circuit diagram with FLC and PWM controller
Figure-6.8: PWM sub system

Figure-6.9: PV module sub system
6.4 Fuzzy Logic Based Controller of MPPT for Partial Shadow condition of a PV Cell

6.4.1 Proposed Photovoltaic Array

During partially shaded conditions, the system P–V characteristic curve has multiple peaks. Therefore, a conventional Maximum Power Point (MPP) Tracker (MPPT) such as Hill Climbing, Incremental Conductance, and Ripple Correlation could miss the global maximum point. Modified techniques have also been proposed, with the objective of minimizing the hardware or improving the performance. For this proposed method the following system and cases are to be considered.

Figure-6.10: PV array system with nine modules connected in series and parallel

There are different possibilities for the radiation distribution among the PV modules; the following five cases are randomly considered.

Case-1: One module in each column is completely shaded (viz., modules 1, 4, and 7).

Case-2: One module in each column is partially shaded with equal radiation levels (viz., modules 2, 5, 8).

Case-3: One module in each column is partially shaded with unequal radiation levels (viz., modules 3, 6, 9)
Case-4: Two modules in the first column and one module in each other column are partially shaded with equal radiation levels (viz., modules 1, 2, 4)

Case-5: All modules are partially shaded with different radiation levels. Simulation results of the five cases indicate that a completely shaded module causes a reduction of the PV output power without creating local maxima. However, partially shaded modules result in a reduction of the PV output power, creating local maxima, where the number of local maxima increases as the variation of the radiation levels on each module increases. The PV output power characteristics of the five different cases are shown in Figure-6.11.

6.4.2 PV modules output power characteristics under the five cases

![Figure-6.11: PV output power characteristics under the five cases.](image)

The system is modelled based on the data for the Shell SP150-PC, the short-circuit current and the open-circuit voltage for each PV module under rated radiation level are 4.4 A and 43.4 V, respectively. One PV module is partially shaded, and it receives a radiation of 500 W/m², while the other two modules receive the rated radiation, which is 1000 W/m². The three points are considered: point 1: where the current equals Isc and the voltage equals zero, point 2: where the current equals I_{step} and the voltage equals V_{step}, and point 3: where the current equals zero and the voltage equals Voc. By inspecting, the previous variables, it can be defined.
1) $I_{sc}$ is the short-circuit current of the un-shaded PV modules.

2) $I_{\text{step}}$ is the short-circuit current of the shaded PV module.

3) $V_{\text{step}}$ is the summation of the open-circuit voltages of the un-shaded modules.

4) $V_{oc}$ is the summation of the open-circuit voltages of the shaded and un-shaded modules.

When the radiation distribution levels increase, the number of voltage/current step increases. The PV system is tested under different partial shadowing conditions. Two PV modules are partially shaded and receive two different radiation levels, which are 500 and 300 W/m$^2$, and the third module receives rated radiation, which is 1000 W/m$^2$. The following two more observations are to be added to the previous observations.

1) $I_{\text{step2}}$ is the short-circuit current of the shaded PV modules with the highest radiation level.

2) $V_{\text{step1}}$ is the open-circuit voltage of the un-shaded modules plus the summation of the shaded module open circuit voltages without the open-circuit voltage of the low radiation module.

$$I_{\text{PVTOTAL}} = I_{\text{branch1}} + I_{\text{branch2}}$$  \hspace{1cm} (6.4)

From Equation (6.3), the general mathematical model of $N$ parallel connected PV modules in the PV system is

$$I_{\text{PVTOTAL}} = I_{\text{branch1}} + I_{\text{branch2}} + \ldots + I_{\text{branchN}}$$  \hspace{1cm} (6.5)

$N$ is the number of distributed radiation levels. Usually, the PV system consists of parallel-/series-connected PV modules. Therefore, to derive a mathematical model for the overall PV system, the previous three series-connected PV modules are connected in parallel with another three series connected PV modules, as for simplicity, the radiation levels are distributed as follows. In the first branch, modules 1 and 2 receive a radiation of 1000 W/m$^2$, and the shaded module receive 500 W/m$^2$. 

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6.4.3 Flow Chart of Proposed Method

If the difference between the identified maximum power and the operated power is greater than the present value, the duty cycle is increased; otherwise, fuzzy-logic-based MPPT is applied. In this the algorithm ensures that the MPPT is not trapped by local maxima and quickly recovers the new global maximum point during varying weather conditions.

Unlike conventional scanning MPPT, the essentiality of using a long time delay is not required because the controller scans the $P-V$ curve while perturbation and observation are carried out [108]. Figure 6.12 shows the flowchart of the proposed method, where $V_{pv}$ and $I_{pv}$ are the PV output voltage and current, respectively, $D$ is the duty cycle, $P_M$ is the global MPP, and $\Delta P_M$ is a constant that identifies the allowable difference between the global maximum point and the operating power point.

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 of the PV power locus.

<table>
<thead>
<tr>
<th>Table – 6.2 Parameters of Shell SP150-PC Solar Cell data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
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<tr>
<td>Typical peak power ($P_p$)</td>
</tr>
<tr>
<td>Voltage at peak power ($V_{pp}$)</td>
</tr>
<tr>
<td>Current at peak power ($I_{pp}$)</td>
</tr>
<tr>
<td>Short-circuit current ($I_{sc}$)</td>
</tr>
<tr>
<td>Open-circuit voltage ($V_{oc}$)</td>
</tr>
<tr>
<td>Temperature coefficient of open-circuit voltage</td>
</tr>
<tr>
<td>Temperature coefficient of Short-circuit current</td>
</tr>
<tr>
<td>Approximate effect of temperature on power</td>
</tr>
<tr>
<td>Normal operating temperature of cell</td>
</tr>
</tbody>
</table>

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6.4.4 Fuzzy Logic Controller Design

Modification to the Fuzzy-logic-based MPPT algorithm, using the scanning and storing procedures, is proposed to quickly locate the global MPP. Fuzzification of the flowchart in Figure-6.12 is considered in the proposed MPPT design. The inputs to the Fuzzy-logic controller (FLC) are

\[
\begin{align*}
\Delta P &= P(k) - P(k-1) \\
\Delta I &= I(k) - I(k-1) \\
\Delta P_M &= P_m(k) - P(k-1)
\end{align*}
\]

And the output equation is

\[
\Delta D = D(k) - D(k-1)
\]

Where, \(\Delta P\) and \(\Delta I\) are the PV array output power change and current change, respectively, \(\Delta P_M\) is the difference between the stored global maximum power \((P_M)\) and the current power, and \(\Delta D\) is the boost converter duty cycle change. To ensure
that the PV global maximum power is stored during the scanning procedure, a fast initial tracking speed is used.

Figure-6.13: PV array system blocks diagram and the proposed MPPT controller.

The variable inputs $\Delta P$ and $\Delta I$ are divided into four fuzzy subsets: positive big (PB), positive small (PS), negative big (NB), and negative small (NS). The variable input $\Delta PM$ is divided into two fuzzy subsets: PB and PS. The output variable $\Delta D$ 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, the shapes and fuzzy subset attritions of the membership function in both of the inputs and output are shown in Figure-6.14.

Table-6.3: FUZZY-LOGIC RULES

<table>
<thead>
<tr>
<th>$\Delta I$</th>
<th>NB</th>
<th>NS</th>
<th>PS</th>
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<th>$\Delta P_M$</th>
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<td>NB</td>
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The last fuzzy controller stage is defuzzification where the center-of-the-area algorithm is used to convert the fuzzy subset duty cycle changes to real numbers

\[ \Delta D = \frac{\sum_{i} \mu(D_i)D_i}{\sum_{i} \mu(D_i)} \]  

Where \( \Delta D \) is the fuzzy controller output and \( D_i \) is the center of the max–min composition at the output membership function. The surface view of the fuzzy logic controller is as shown in the Figure-6.15.
6.4.5 Simulink Diagrams of MPPT with and without Fuzzy Logic Controller

A Fuzzy-logic-based MPPT has been proposed to extract the global MPP under partially shaded PV system conditions. The proposed MPPT has been implemented by combining fuzzy-logic-based MPPT with a scanning and storing system. Three scanning techniques have been proposed to scan the PV power characteristic curve and store the Maximum power value, during initial and varying weather conditions. The simulation circuit as shown in the figure below with a temperature of 20°C and the irradiance is 400 w/m². The simulation diagram of MPPT without Fuzzy logic controller and its sub system of PV cells are shown in Figures-6.16, 6.17. The simulation diagram of MPPT with Fuzzy logic controller and its sub system of PV cells are shown in Figures-6.18, 6.19.

Figure-6.16: Maximum power point tracking without fuzzy logic controller.
Figure-6.17: PV module sub system

Figure-6.18: Maximum power point tracking with fuzzy logic controller.
The ever-increasing demand for low-cost energy and growing concern about environmental issues has generated enormous interest in the utilization of non-conventional energy sources such as the solar energy. The freely and abundantly available solar energy can be easily converted into electrical energy using photovoltaic (PV) cells. A PV source has the advantage of low maintenance cost, absence of moving/rotating parts, and pollution-free energy conversion process. However, PV systems suffer from a major drawback which is the nonlinearity between the output voltage and current particularly under partially shaded conditions.
During partially shaded conditions, the system P–V characteristic curve has multiple peaks. Therefore, a conventional maximum power point (MPP) tracker (MPPT) such as Hill Climbing, Incremental Conductance, and Ripple Correlation could miss the global maximum point. In general, a PV source is operated in conjunction with a DC–DC power converter, whose duty cycle is modulated in order to track the instantaneous MPP of the PV source. Several tracking schemes have been proposed. Among the popular tracking schemes are the perturb and observe (P&O) or hill climbing, incremental conductance, short circuit current, open-circuit voltage, and ripple correlation approach[110].

An MPPT scheme for a PV system under partial shadowing conditions is proposed based on this observation. In a simulation of a partially shaded PV system rejects the observation in an MPPT based on conventional P&O and a partial shadowing identifier has been proposed. Also, it is observed that the global maximum point of a PV system under non uniform conditions is always located to the left of maximum power at normal weather conditions. Therefore, a trajectory line of the PV system under different isolation levels is stored in a data-based memory to identify the partially shaded conditions.

6.5.1 Proposed Fuzzy Based System

A fuzzy based system is designed in the proposed work for tracking the maximum power point under non uniform shading and partial shadowed conditions. To achieve this objective Simulink and fuzzy logic toll boxes available in the Matlab environment are put to good use. To simulate the effect of partial shadow and nonuniform insolation 6 PV modules are considered.

From the Figure-6.20 it can be observed that modules 1-5 are subjected to one amount of insolation and module 6 is subjected to a different level of isolation as may be required to emulate different environmental condition. As can be observed the model can also be subjected to randomly varying insolation as a time varying signal. The random variation can be subjected to a single module or all the six modules. These types of arrangement help us to simulate rapidly varying insolation conditions to study the effectiveness of the proposed setup in tracking the maximum power points under such conditions.
In this work, the efficacy of the proposed system is compared with the performance of a standard MPPT controller designed on the basis of P&O method. The job of controllers both fuzzy and P&O is to supply the necessary reference current value so that the system shall be operated at its maximum power point in spite of the changes in the insolation values. The idea is to supply the optimum value of reference current so that the PV panels operate at their maximum efficiency. A fuzzy logic controller with rule viewer is used in the proposed system.

The fuzzy controller tracks the operating reference current value compared to the standard P & O method enabling better stability of the system. This feature enables the proposed system to track maximum power points under partially shading and rapidly varying insolation conditions. To validate the above we have used PV array comprising of 6 PV cells connected in series. For validation 4 panels are considered to have uniform insolation and remaining 2 panels having different insolation.
The PV characteristics clearly exhibit the occurrence of multiple peaks for partial shadow conditions. A GA function is used to extract maximum power points for different temperature and irradiance values. This data is used to create the knowledge base for the proposed fuzzy controller. The fuzzy controller feeds on the insolation as input and gives the reference current value for operating the DC to DC converter.

The Mamdani fuzzy solver is used for Fuzzification, triangular membership functions are used for creating the knowledge base and a centroid function is used for defuzzification. The fuzzy controller tracks the operating reference current value compared to the standard P&O method enabling better stability of the system. This feature enables the proposed system to track maximum power points under partially shading and rapidly varying insolation conditions.

Figure-6.21: Fuzzy MPPT Simulink Diagram
6.5.3 Rule base view diagrams under different insolation

The Rule Viewer displays a road map of the whole fuzzy inference process. It's based on the fuzzy inference diagram described in the previous section. You see a single figure window as shown in Figure-6.22 with 10 small plots nested in it. The three small plots across the top of the figure represent the antecedent and consequent of the first rule. Each rule is a row of plots, and each column is a variable. The first two columns of plots show the membership functions referenced by the antecedent, or the if-part of each rule.

Figure-6.22: Rule base view diagrams
The third column of plots shows the membership functions referenced by the consequent, or the then-part of each rule. If you click once on a rule number, the corresponding rule will be displayed at the bottom of the figure. Notice that under food, there is a plot which is blank. This corresponds to the characterization of none of the variable food in the second rule. The fourth plot in the third column of plots represents the aggregate weighted decision for the given inference system. This decision will depend on the input values for the system.

The Rule Viewer allows you to interpret the entire fuzzy inference process at once. The Rule Viewer also shows how the shape of certain membership functions influences the overall result. Since it plots every part of every rule, it can become unwieldy for particularly large systems, but, for a relatively small number of inputs and outputs, it performs well (depending on how much screen space you devote to it) with up to 30 rules and as many as 6 or 7 variables. This diagram depicts the rule base for different insolation values. In regard to the above mentioned rule base it depicts the change in the value of the reference current being provided by the controller for different set of insolation variations.

6.5.4 Results and Discussions

In the simulation diagram Fuzzy Logic Controller of the Triangular and Gaussian membership functions are used, from this figures, it can be observed that the fuzzy can track the maximum power point at 0.01s and also it generates constant voltage without any deviations. The performance of the fuzzy based MPPT. Hence from the results it is clear that the PV power which is controlled by the fuzzy controller is more stable than the conventional MPPT techniques. In without controller case the voltage of PV Cells is maintain constant about 68V, this voltage is of one module as shown in Figure 6.23. The current and power of PV Cells in case of without controller are about 13.2A and 920W as shown in Figures 6.24 and 6.25.

The duty cycles which are generated by Fuzzy Logic Controller (FLC) are also have some harmonics and steady state errors. These harmonics and steady state errors are reduced by using of Pulse Width Modulation (PWM). The PWM is applied to the carrier frequency of Fuzzy Logic Controller, to generate output signals and duty cycles. The voltage of PV Cells is increased to 134.4V as shown in Figure 6.26, and
the current of PV Cells is decreased to 6.71A as shown in Figure 6.27. The power of PV Cells is reached to maximum is about 903.2W as shown in Figure 6.28.

Fuzzy Logic Controller of the Triangular and Gaussian membership functions, respectively. From this figures, it can be observed that the fuzzy can track the maximum power point at 0.01s and also it generates constant voltage without any deviations. The performance of the fuzzy based MPPT. Hence from the results it is clear that the PV power which is controlled by the fuzzy controller is more stable than the conventional MPPT techniques.

Figure-6.23: Output voltage without FLC and PWM controller

Figure-6.24: Output current without FLC and PWM controller
Figure-6.25: Output power without FLC and PWM controller

Figure-6.26: Output voltage with FLC and PWM controller

Figure-6.27: Output current with FLC and PWM controller
The voltage supplied by the PV array does not have constant values, but fluctuates according to the surrounding conditions such as intensity of solar rays and temperature. These supplies are therefore supplemented by additional converters. The DC to DC boost converter is used to regulate a chosen level of the solar photovoltaic module output voltage and to keep the system at the maximum power point. It is mainly useful for PV maximum power tracking purposes, where the objective is to draw maximum possible power from solar panels at all times, regardless of the load. It can able to regulate the perturbed voltage by increasing or decreasing the voltage reference of the PWM (Pulse width modulation) signal [112].

The Fuzzy Logic Controller (FLC) generates the duty cycles and stored in memory and the signals from Fuzzy Logic Controller is low. To increase the strength of signals by increase the gain then the voltage and current of PV Cells is increased. The PV Cells are operating at maximum power. For without Fuzzy Logic Controller, all PV Cells are operated at the voltage of about 50V. If some of cells are partially shaded the voltage is reduced to 40V as shown in Figure 6.29. Similarly current is reduced from 9A to 4.689A as shown in Figure 6.30 and power is reduced from 400W to 187.3W as shown in Figure 6.31. The Fuzzy Logic Controller is provided in simulation for some of cells are partially shaded the voltage is about 80V as shown in Figure 6.32. Similarly current is 4.2A as shown in Figure 6.33 and power is 320W as shown in Figure 6.34.
Figure-6.29: PV Output Voltage without Fuzzy Logic Controller

Figure-6.30: PV Output Current without Fuzzy Logic Controller

Figure-6.31: PV Output Power without Fuzzy Logic Controller
Figure-6.32: PV Output Voltage with Fuzzy Logic Controller

Figure-6.33: PV Output Current with Fuzzy Logic Controller

Figure-6.34: PV Output Power with Fuzzy Logic Controller
The following shows the results of maximum power point tracking under the fuzzy approach discussed in the work. The system is tested for different grouping of insolation values like 4 modules are subjected to an irradiance of 1000 W/m² and the remaining 2 modules subjected to 900 W/m². Two panels which are subjected to variable insolation are tested for different insolation values like 850 W/m², 800 W/m² and 750 W/m². The results clearly point to the fact the reference value of the current being DC To AC converter varies as the insolation varies and the system is able to operate at its maximum power point.

It can be deduced that the fuzzy controller is faster than the P&O controller in the transition state and presents also a much smoother signal with less fluctuations in steady state. The controllers by fuzzy logic can provide an order more effective than the traditional controllers for the nonlinear systems, because there is more flexibility. A fast and steady fuzzy logic MPPT controller was obtained. It makes it possible indeed to find the point of maximum power in a shorter time runs compared to the well known P&O controller.

![Figure-6.35: PV Characteristics under constant isolations (6modules 1000 W/m²)](image)
Figure-6.36: PV Characteristics under different isolations (4 modules 1000 W/m², 2 Modules 900W/m²)

Figure-6.37: PV Characteristics under different isolations (4 modules 1000 W/m², 2 modules 850W/m²)
Figure-6.38: PV Characteristics under different isolations (4 modules 1000 W/m², 2 modules 800W/m²)

Figure-6.39: PV Characteristics under different isolations (4 modules 1000 W/m², 2 modules 750W/m²)
Table-6.4 Results Comparison of With and without FLC with PWM Technique

<table>
<thead>
<tr>
<th>Output Parameters of PV Cells</th>
<th>Without FLC with PWM</th>
<th>With FLC with PWM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>68V</td>
<td>134.4V</td>
</tr>
<tr>
<td>Current</td>
<td>13.2A</td>
<td>6.72A</td>
</tr>
<tr>
<td>Power</td>
<td>920W</td>
<td>903.2W</td>
</tr>
</tbody>
</table>

Table-6.5 Results Comparison of with and without FLC Under partial shadow Conditions of PV Cells

<table>
<thead>
<tr>
<th>Output Parameters of PV Cells</th>
<th>Without FLC</th>
<th>With FLC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>39.94V</td>
<td>80V</td>
</tr>
<tr>
<td>Current</td>
<td>4.689A</td>
<td>4.2A</td>
</tr>
<tr>
<td>Power</td>
<td>187.3W</td>
<td>320W</td>
</tr>
</tbody>
</table>

Table-6.6 Results Comparison of Current & Maximum Power of PV Cells under partial shadow conditions using GA Trained FLC

<table>
<thead>
<tr>
<th>Constant Insolation For 4 panels (W/m²)</th>
<th>Constant Insolation For 2 panels (W/m²)</th>
<th>I reference Supplied (Amps)</th>
<th>Maximum Power (Watts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>1000</td>
<td>4.96A</td>
<td>495W</td>
</tr>
<tr>
<td>1000</td>
<td>900</td>
<td>4.86A</td>
<td>495W</td>
</tr>
<tr>
<td>1000</td>
<td>850</td>
<td>4.2A</td>
<td>474W</td>
</tr>
<tr>
<td>1000</td>
<td>800</td>
<td>4.1A</td>
<td>454W</td>
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<tr>
<td>1000</td>
<td>750</td>
<td>3.9A</td>
<td>430W</td>
</tr>
</tbody>
</table>
6.6 Summary

This chapter explores the ambit of maximum power point tracking using three different techniques. One technique is a Fuzzy Logic based MPPT of PV cells with PWM technique results are presented in Table-6.4. Second is Fuzzy Logic based MPPT of PV cells under partial shadow condition results are presented in Table-6.5. Third is the GA enhanced Fuzzy Logic controller of MPPT under different insolation condition results are presented in Table-6.6.

For the above proposed methods a new mathematical model was designed to represent the behavior of the P–V characteristic under partial shadow conditions. MATLAB/SIMULINK simulations representing partially shaded conditions of PV system was carried out to validate the proposed MPPT. Most of the methods present in the literature feeds on the insolation as input and gives the reference current value for operating the DC to DC converter. The fuzzy controllers enhance the efficiency by providing better operating point for tracking the Maximum Power Point.

In comparison to the standard P & O method the fuzzy controller tracks the operating reference current value enabling better stability of the system. This feature enables the proposed system to track maximum power points under partially shading and rapidly varying insolation conditions. It is designed as a comprehensive system that has been generalized for maximum power point tracking under partially shadowed and nonuniform shadow conditions. An attempt is been made in this thesis to contribute for better maximum power point tracking. Unlike the existing methods that are based on periodically sweeping the entire I-V characteristic of the array our approach increases the optimization of this process enhancing the overall power output and efficiency.

The results are validating the fact that the proposed MPPT is capable of reaching the global MPP under any partial shading conditions. A GA function is used to extract maximum power points for different temperature and irradiance values. This data is used to create the knowledge base for the proposed fuzzy controller. Moreover; the controller exhibits a fast convergence speed, with small oscillation around the MPP during steady state conditions. This feature enables the system to track maximum power points under partially shading and rapidly varying insolation conditions.