CHAPTER 2

ANALYSIS OF PHOTOVOLTAIC ARRAY

2.1 INTRODUCTION

In recent years, renewable energy sources become more significant source of energy. Among the renewable energy sources, solar energy is sustainable with less carbon emissions [123-124]. The output power of a PV array varies according to the sunlight conditions such as solar irradiations, shading and temperature. To obtain maximum power from photovoltaic array, photovoltaic power system usually requires maximum power point tracking (MPPT) controller [125, 128-130].

Various approaches have been reported to implement MPPT such as perturb and observe (P&O) method [126-127], the incremental conductance method, constant voltage method and short-circuit current method [121]. Using these methods, the maximum power point can be found for specified solar irradiation and temperature condition but they display oscillatory behaviour around the maximum power point under normal operating conditions. Moreover, the system will not respond quickly to rapid changes in temperature or irradiance. On the other hand, the conventional proportional integral (PI) controllers are fixed-gain feedback controllers and they cannot compensate the parameter variations in the process and cannot adapt changes in the environment. Also, PI controlled system is less responsive to real and relatively fast alterations in state and so the system will be slower to reach the set point. Therefore, an intelligent control technique using fuzzy logic control associated with a
MPPT controller is proposed which improves the energy conversion efficiency of the photovoltaic systems. The proposed intelligent fuzzy logic process comprises of expert knowledge which extracts maximum power from a PV module under varying solar irradiation, temperature and load conditions. The shape of the membership functions of the fuzzy logic controller can also be adjusted such that the gap between the operating point and maximum power point can be optimized. The fuzzy logic controller based results are compared with the conventional techniques such as P&O and PI controllers which validate its merits. An experimental setup of the proposed scheme has been built and the results obtained on a PV array of 74.8W, 21.2V, 4.4A, (15 panels connected in series).

2.2 MODELING OF A PV ARRAY

A PV cell can be represented by an equivalent circuit of single diode model [131] as shown in Fig. 2.1. The characteristics of this PV cell can be obtained using standard equation (2.1).

\[
I_{PV} = I_0 \left[ \exp \left( \frac{V + R_{sel}}{V_{oc}} \right) - 1 \right] - \frac{V + R_{sel}}{R_p}
\]

\[
I_{PV} = \text{photovoltaic current}
\]
\[ \text{I}_0 = \text{saturation current} \]
\[ V_t = N_s k \frac{T}{q}, \text{thermal voltage of array} \]
\[ N_s = \text{Number of cells connected in series} \]
\[ T = \text{actual temperature} \]
\[ k = \text{Boltzmann constant} \]
\[ q = \text{electron charge} \]
\[ R_{se} = \text{equivalent series resistance of the array} \]
\[ R_P = \text{equivalent parallel resistance of the array} \]
\[ \text{ad} = \text{diode ideality constant} \]

A single solar cell will produce only a limited power. Therefore it is usual practice in order to get desired power rating the solar cells are connected in parallel and series circuits which form a module. Such modules are again connected in parallel and series to form a solar array or panel to get required voltage and current. The equivalent series and parallel resistance of the array are denoted by the symbol \( R_{se} \) and \( R_P \) respectively in the equivalent circuit.

From the general \( I-V \) characteristic of the practical photovoltaic device, one can observe that the series resistance \( R_{se} \) value will dominate in the voltage source region and the parallel resistance \( R_P \) value will dominate in the current source region of operation.

The general equation of a PV cell describes the relationship between current and voltage of the cell. Since the value of shunt resistance \( R_P \) is high compared to value of series resistance \( R_{se} \) the current through the parallel resistance can be
neglected. The light generated current of the photovoltaic cell depends linearly on the solar irradiation and is also influenced by the temperature \cite{132} given by the equation (2.2)

\[
I_{PV} = \left[ I_{PV,n} + K_I \Delta_T \right] \frac{G}{G_n} \tag{2.2}
\]

\[
I_{PV,n} = \text{light generated current at nominal condition (25^0C and 1000 W/ m}^2) \]

\[
\Delta_T = T - T_n
\]

\[
T = \text{actual temperature [K]}
\]

\[
T_n = \text{nominal temperature [K]}
\]

\[
K_I = \text{current coefficient}
\]

\[
G = \text{irradiation on the device surface [W/m}^2) \]

\[
G_n = \text{nominal irradiation}
\]

The current and voltage coefficients \(K_V\) and \(K_I\) are included as shown in equation (2.3) in order to take the saturation current \(I_0\) which is strongly dependent on the temperature.

\[
I_0 = \frac{I_{sc,n} + K_I \Delta_T}{\exp\left(\frac{V_{oc,n} + K_V \Delta T}{K_T}ight) - 1} \tag{2.3}
\]

\[
K_V = \text{voltage coefficient}
\]

\[
K_I = \text{current coefficient}
\]

The output voltage is increased (where the current remains unchanged) proportionally on the number of identical PV modules connected in series \((N_{ser})\).
Similarly the output current is increased (where the voltage remains unchanged) proportionally on the number of identical PV modules connected in parallel ($N_{par}$).

It can be noted that the equivalent series and parallel resistance are directly proportional to the number of series modules and inversely proportional to the number of parallel modules respectively.

Therefore a general equation for array composed of $N_{ser} \times N_{par}$ is given by equation (2.4)

$$I = I_{PV}N_{par} - I_0N_{par}\left[\exp\left(\frac{V+R_{ser}\left(N_{ser}\right)}{V_{catN_{ser}}}I\right) - 1\right] - \frac{V+R_{ser}\left(N_{ser}\right)}{R_p\left(N_{par}\right)} I \quad (2.4)$$

### 2.3 EXPERIMENTAL SETUP AND PV ARRAY PARAMETERS

The PV array in the proposed scheme shown in Fig. 2.2 consists of PV array of 74.8W, 21.2V, 4.4A (19 panels connected in series).

![Fig 2.2 Experimental set up of solar panel with (MPPT) DC-DC converter-inverter](image)
A load of 80Ω per-phase is connected in star across the inverter terminals. A DC-DC converter (L=40μH, C=0.025F) is constructed with IGBT (5 A, 440 V) as a switch with a switching frequency of 2 KHz shown in Fig. 2.2. The closed loop firing scheme is employed to trigger the DC-DC converter. A 50Hz, three phase IGBT inverter is fabricated, and a microcontroller PIC 16F877A is used to trigger the IGBT in 120 degree conduction mode. The above scheme is tested for different conditions of irradiations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>I_{mp}</td>
<td>4.40 A</td>
</tr>
<tr>
<td>V_{mp}</td>
<td>17.00 V</td>
</tr>
<tr>
<td>P_{max}</td>
<td>74.8 W</td>
</tr>
<tr>
<td>I_{sc}</td>
<td>5.02 A</td>
</tr>
<tr>
<td>N_{a}</td>
<td>30</td>
</tr>
<tr>
<td>I_{o,n}</td>
<td>9.83 \times 10^{-3}A</td>
</tr>
<tr>
<td>V_{oc}</td>
<td>21.20 V</td>
</tr>
<tr>
<td>R_{sh}</td>
<td>0.511 Ω</td>
</tr>
<tr>
<td>R_{sh}</td>
<td>44.25 Ω</td>
</tr>
<tr>
<td>K_{V}</td>
<td>-74.7 mV/°C</td>
</tr>
<tr>
<td>K_{I}</td>
<td>2.80 mA/°C</td>
</tr>
</tbody>
</table>

The parameter of solar array (KCP-12075 at 25°C, 1000 W/m²) used for theoretical and experimental setup is given in table-2.1.

### 2.4 DC-DC BOOST CONVERTER

A dual stage power electronic system comprising a boost type DC-DC converter and an inverter is used to feed the power generated by the PV array to the load. To maintain the load voltage constant a DC-DC step up converter is introduced between the PV array and the inverter. The schematic diagram of the proposed scheme is shown in Fig. 2.3. In this scheme, a PV array feeds DC-DC converter used in step-up configuration. The voltage across the DC-DC converter is fed to a three phase, six-step, quasi-square-wave IGBT inverter which gives a three phase fixed amplitude and fixed frequency supply to feed an isolated load. For a DC-DC boost
converter, by using the averaging concept, the input–output voltage relationship for continuous conduction mode is given by

\[ \frac{V_o}{V_{in}} = \frac{1}{1 - D} \]  \hspace{1cm} (2.5)

Where, \( D \) = duty cycle. Since the duty ratio “D” is between 0 and 1 the output voltage must be higher than the input voltage in magnitude.

![Diagram](image)

**Fig 2.3 System configuration for PV-based system feeding power to the load**

It should be noted that the control logic of such DC-DC converter has to be different when it is fed from a stiff DC source. The duty ratio of the converter is found to increase linearly with increase in cell temperature and hence the intensity. It has been observed that when a PV array is connected to a boost converter, increasing the duty cycle, increases the average PV array current and as a result, PV array voltage decreases. Thus, an increase in duty-cycle result in shifting the operating point to the left on the V-I characteristics of the PV array. Similarly decreasing the duty cycle decreases the average PV array current and as the PV array voltage increases resulting in shifting the operating point of PV array to the right. As the input DC voltage varies with irradiation to obtain constant amplitude and constant frequency supply from the inverter, a closed loop fuzzy controller is incorporated to automatically vary the duty-
cycle of the DC-DC converter to obtain constant DC voltage at the inverter input terminals. The inverter output is then applied to an isolated load.

2.5 FUZZY LOGIC MPPT CONTROLLER

The conventional PI controllers are fixed-gain feedback controllers. Therefore they cannot compensate the parameter variations in the process and cannot adapt changes in the environment. PI-controlled system is less responsive to real and relatively fast alterations in state and so the system will be slower to reach the set point. On the other hand, P&O method for MPPT tracking will not respond quickly to rapid changes in temperature or irradiance. Therefore, a fuzzy control algorithm is proposed which is capable of improving the tracking performance as compared with the classical methods for both linear and nonlinear loads. Also, fuzzy logic is appropriate for nonlinear control because it does not use complex mathematical equation. The block diagram of fuzzy logic controller (FLC) is shown in Fig. 2.4. The two FLC input variables are the error (e) and change in error (Δe). The behavior of a FLC depends on the shape of membership functions of the rule base.

Fig 2.4 Block diagram of Fuzzy logic controller

A fuzzy logic control scheme proposed for maximum solar power tracking of the PV array with an inverter for supplying isolated loads is shown in (Fig. 2.5). They
have advantages such as robust and relatively simple to design since they do not require the knowledge of the exact model.

2.5.1 Fuzzification

The membership function values are assigned to the linguistic variables using seven fuzzy subsets called negative big (nb), negative medium (nm), negative small (ns), zero(zr), positive small (ps), positive medium (pm) and positive big (pb). Fuzzy associative memory for the proposed system is given in Table-2.2. Variable ‘e’ and ‘Δe’ are selected as the input variables, where ‘e’ is the error between the reference voltage (Vr) and actual voltage (Vo) of the system, and Δe is the change in error in the sampling interval. The output variable U is the reference signal for PWM generator. Triangular membership functions are selected for all these process. The range of each membership function is decided by the previous knowledge of the proposed scheme parameters.

2.5.2 Inference engine

Inference engine mainly consist of fuzzy rule base and fuzzy implication sub blocks. The fuzzified inputs are now, fed to the inference engine and the rule base is applied. The output fuzzy sets are then identified using fuzzy implication method. Here MIN-MAX fuzzy implication method is used.
2.5.3 Defuzzification

Once fuzzification is over, output fuzzy range is located. Since at this stage a non-fuzzy value of control is available a defuzzification stage is needed. Centroid defuzzification method [150] is used for defuzzification in the proposed scheme. The membership function of the variables ‘e’, ‘Δe’ and ‘U’ are shown in Figs. 2.6(a)-2.6(c) respectively.

Table 2.2
Fuzzy associative memory for the proposed system

<table>
<thead>
<tr>
<th>e</th>
<th>Δe</th>
<th>nb</th>
<th>nm</th>
<th>ns</th>
<th>zr</th>
<th>ps</th>
<th>pm</th>
<th>pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>nb</td>
<td>nb</td>
<td>nb</td>
<td>nb</td>
<td>nb</td>
<td>nb</td>
<td>nb</td>
<td>nb</td>
<td>nb</td>
</tr>
<tr>
<td>nm</td>
<td>nm</td>
<td>nm</td>
<td>nm</td>
<td>nm</td>
<td>nm</td>
<td>nm</td>
<td>nm</td>
<td>nm</td>
</tr>
<tr>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>zr</td>
<td>zr</td>
<td>zr</td>
<td>zr</td>
<td>zr</td>
<td>zr</td>
<td>zr</td>
<td>zr</td>
<td>zr</td>
</tr>
<tr>
<td>ps</td>
<td>ps</td>
<td>ps</td>
<td>ps</td>
<td>ps</td>
<td>ps</td>
<td>ps</td>
<td>ps</td>
<td>ps</td>
</tr>
<tr>
<td>pm</td>
<td>pm</td>
<td>pm</td>
<td>pm</td>
<td>pm</td>
<td>pm</td>
<td>pm</td>
<td>pm</td>
<td>pm</td>
</tr>
<tr>
<td>pb</td>
<td>pb</td>
<td>pb</td>
<td>pb</td>
<td>pb</td>
<td>pb</td>
<td>pb</td>
<td>pb</td>
<td>pb</td>
</tr>
</tbody>
</table>
2.6 ANALYSIS OF PHOTO VOLTAIC ARRAY

The proposed scheme (Fig. 2.4) is utilized for studying the $I-V$, $P-V$ characteristics of a PV array under a non-uniform irradiation and different temperature. The fuzzy logic controller based results are compared with the conventional techniques such as P&O and PI controllers which validate it’s merits.

2.6.1 Photovoltaic characteristics

The behavior the PV cells and its characteristics are discussed in this section. It is found that the set of $P-V$ & $I-V$ characteristics are highly nonlinear and dependent on solar irradiance of the PV array. The combination of $V$ and $I$ that maximizes the output depends on irradiation is also affected by the temperature of the cell.

![I-V Characteristics of a PV array for different irradiations](image)

Fig 2.7(a) shows $I-V$ characteristics of a PV cell for different irradiations. It can be observed that as the cell temperature remain constant; the PV output voltage remains nearly constant while the PV output current increases with increasing solar intensity. Fig. 2.7(b) & Fig. 2.7(c) show $P-V$ & $I-V$ characteristics of a PV cell respectively. Fig. 2.7(d) shows $P-V$ curve plotted for different values of temperature.
Fig 2.7(b): P-V Characteristics of PV array

Fig 2.7(c): I-V Characteristics of a PV array

Fig 2.7(d): P-V Characteristics of PV array for different temperature
2.6.2 Simulation of P&O, PI and Fuzzy logic MPPT Controllers

The results are presented with a comparison between the systems incorporating different configurations as P&O, PI and Fuzzy MPPT controllers.

It is clear that from Fig. 2.8, at a temperature of 25°C and at a solar irradiance of 500W/m², the solar panel output power is 38W. When there is a sudden raise in solar irradiance from 500W/m² to 1000W/m², the expected solar panel output power is 62W.

From Fig. 2.8, it is also observed that, for a sudden increase of irradiance from 500W/m² to 1000W/m², the PI controller settles to 62W at 0.6secs, P&O controller settles to 62W at 0.8secs, wherein the proposed fuzzy logic controller (FLC) settles to 62W at 0.4secs. This demonstrates the proposed FLC exhibit quicker settling.

It is clear that from Fig. 2.9, at a solar irradiance of 1000W/m² and at a temperature of 40°C, the solar panel output power is 58W. When there is a sudden decrease in temperature from 40°C to 20°C, the expected solar panel output power is 62W.
From Fig. 2.9, it is also observed that, for a sudden decrease in temperature from 40°C to 20°C, the PI controller settles to 62W at 0.3secs, P&O controller settles to 62W at 0.4secs, wherein the proposed FLC settles to 62W at 0.2secs. This demonstrates the proposed FLC exhibit quicker settling. Similar fast response of the proposed FLC has shown in Fig. 2.10, when there is a sudden raise in temperature from 20°C to 30°C.
2.7 CONCLUSION

A fuzzy logic controller for interfacing photovoltaic arrays with DC-DC converter has been developed. By applying the pulse width modulation (PWM) control scheme with appropriate MPPT algorithm to the power switches in the DC-DC converter that draws maximum power from photovoltaic array. The fuzzy logic is an effective tool to track and extract maximum power to the isolated load compared to conventional PI and P&O methods.

In order to develop a hybrid scheme employing the Solar-Wind energy, the PV characteristics and associated fuzzy logic based MPPT controller alone has been discussed in this chapter. Further to validate the suitability of wind driven self-excited induction generator in the hybrid scheme, the detailed steady state and dynamic characteristics of three phase and single phase induction generators are discussed in the following chapter.