Simulation of Fuzzy Logic Maximum Power Point Tracker for Standalone Photovoltaic System in MATLAB/SIMULINK Environment

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ABSTRACT

Electrical energy is obtained from Photovoltaic systems that utilize energy from the sun. The system also exhibits nonlinear characteristics that depend greatly on insolation level and temperature. At any instant, there exists a unique operating point on the I-V curve of Photovoltaic array called as the Maximum Power Point (MPP). This point has to be tracked continuously for the maximum transfer of power from solar PV panel to the load. In this paper Fuzzy logic method to track MPP is presented. A DC-DC converter is placed between the source and load and the duty cycle is varied based on fuzzy logic algorithm. Whole of the system is simulated in MATLAB/SIMULINK environment. The use of proposed MPPT improves the PV system performance and provides more of stable power.

INTRODUCTION

MPPT algorithms are indispensable because PV arrays exhibit a non linear voltage-current characteristic with a unique operating point where the power produced is maximum (N.Femia et al., 2005). The unique point changes based on the irradiance conditions and temperature of the panels. Irradiation change drastically due to changing atmospheric conditions. Maximum available power can be obtained by tracking MPP under all situations accurately. Various MPPT algorithms are categorised as direct and indirect methods that track the MPP effectively. Prior knowledge of characteristics of PV module is not required for Direct method of MPPT algorithms. MPPT algorithms under this category are Perturb and Observe method (P&O), Incremental Conductance method, feedback voltage or current, fuzzy logic method and neural network method. On the other hand, prior evaluation of PV generator is required for indirect method. These methods are based on mathematical relationship obtained from empirical data. Hence the result obtained will not be accurate (I. Houssamo et al., 2010).

Perturb and Observe(P&O) method is the commonly used method and it applies perturbation to the DC-DC converter by increasing or decreasing the duty cycle. P&O method fails to follow rapidly varying atmospheric conditions. The reason is it is unable to relate the change in the PV array power to the change in the atmospheric conditions (Chung-Yuen Won et al., 2007). Takagi and Sugeno fuzzy model described by fuzzy IF-THEN rules represent local input-output relations of a non-linear system. The main feature of a Takagi – Sugeno fuzzy model is to express the local dynamics of each fuzzy implication (rule) by a linear system model. The overall fuzzy model of the system can be obtained by blending the linear system models (R. Coelho et al., 2010). The generalized PV model can be simulated and analyzed in conjunction with power electronics for a maximum power point tracker using Matlab/Simulink software package. Consideration of the effect of solar insolation and cell temperature enables the dynamics of PV power system to be easily simulated, analyzed, and optimized (T.Esram et al., 2007).

Fuzzy is robust and is relatively simple to design as it does not require the knowledge of the exact model (D. Hohm et al., 2003). In this paper MPP tracker that uses Fuzzy logic is proposed. The error and change in error are computed and provided as inputs to the fuzzy inference system. Therefore the MPP can be tracked faster. More the number of membership functions (MFs), greater the correctness of the output. Therefore seven MFs are used in the work. Based on the changes of the inputs fuzzy can compute the duty cycle required for the boost converter used. Boost converter is used so as to minimize the long term system losses.
**Modeling Of Photovoltaic Systems:**

An ideal PV cell is modeled by a current source in parallel with a diode. None of the solar cell is ideal and thereby shunt and series resistances are added.

The ideal circuit of PV cell is shown in Fig.1. \( R_s \) is the intrinsic series resistance and \( R_p \) is the equivalent shunt resistance. \( R_s \) and \( R_p \) have to be of smaller and higher values respectively.

![Ideal circuit of PV Cell](image)

**Fig. 1: Ideal circuit of PV Cell**

Applying Kirchoff’s law to the node where \( I_{ph} \), diode, \( R_s \) and \( R_p \) meet, we get

\[
I_{ph} = I_D + I_{q} + I
\]

We get the following equation for the photovoltaic current

\[
I = I_{ph} - I_D - I_{r} \tag{1}
\]

\[
I = I_{ph} - I_D \left[ \exp \left( \frac{V+IR}{V_T} \right) - 1 \right] - \left[ \frac{V+IR}{R_p} \right] \tag{2}
\]

Where,

- \( I_{ph} \) is the Insolation current,
- \( I_D \) is the Cell current,
- \( I_{q} \) is the Reverse saturation current,
- \( V \) is the Cell voltage,
- \( R_s \) is the Series resistance,
- \( R_p \) is the Parallel resistance,
- \( V_T \) is the Thermal voltage
- \( K \) is the Boltzman constant,
- \( q \) is the Charge of an electron,
- \( T \) is the Temperature in Kelvin,
- \( c \) is the Temperature in Kelvin.

In the ideal PV Cell model \( I, I_D, R_p \) and \( R_s \) are related to cells temperature and radiation intensity, and are not easy to be determined. This makes the engineering application very difficult. Manufacturers of PV arrays provide only a few experimental technical parameters such as open-circuit voltage \( V_{oc} \), short-circuit current \( I_{sc} \), the maximum power point voltage \( V_{mp} \), the maximum power current \( I_{mp} \), and the maximum power point power \( P_{mp} \). To match with the parameters provided by industry the ideal PV model is simplified and \( R_p \) is found to be between 100\( \Omega \) and 10000\( \Omega \).

So, \( \frac{V+IR}{R_p} \) can be ignored compared with Photon current \( I \).

\( R_s \) is less than 1\( \Omega \),

So \( I = I_{sc} \)

Under open-circuit state, \( I = 0, V = V_{oc} \)

\[
I = I_{sc}(1 - C_1[ \exp \left( \frac{V}{E_{oc}} \right) - 1]) \tag{4}
\]

At the maximum power point, when \( V = V_{mp}, I = I_{mp} \)

\[
I_{mp} = I_{sc}(1 - C_1[ \exp \left( \frac{V}{E_{oc}} \right) - 1]) \tag{5}
\]

Under normal temperature,

\[
\exp \left( \frac{V_{mp}}{E_{oc}} \right) \gg 1, C_1 = \left( 1 - I_{mp} / I_0 \right) \exp \left( \frac{V_{mp}}{E_{oc}} \right) \tag{6}
\]

Under open-circuit state, when \( I = 0, V = V_{oc} \), therefore,

\[
0 = I_0(1 - \frac{V_{mp}}{I_0}) \exp \left( \frac{V_{mp}}{E_{oc}} \right) \left[ \exp \left( \frac{1}{E_{oc}} \right) - 1 \right] \tag{7}
\]

Under normal temperature,

\[
\exp \left( \frac{1}{E_{oc}} \right) \gg 1, C_2 = (V_m / V_{oc} - 1) / \ln \left( I_m / I_0 \right) \tag{8}
\]

Being seen, with common parameters like \( V_{oc}, I_0, V_{mp}, I_{mp}, C_1 \) and \( C_2 \) can be calculated and the PV cell model can be created.

Now, adjusting the model such that the above model is created under temperature 25 °C, 1000 W/m². Considering variable ambient temperature and solar radiation, the model can be modified as below

\[
DT = T_c - T_{ref} \tag{9}
\]

\[
DV = -\beta DT - R_c DI \tag{10}
\]

\[
DI = \alpha \frac{S}{S_{ref}} DT + (\frac{S}{S_{ref}} - 1) I_{sc} \tag{11}
\]

\[
I = I_{sc} \left( 1 - C_1 \left[ \exp \left( \frac{V-DV}{E_{oc}} \right) - 1 \right] \right) + DI \tag{12}
\]

**Tracking Of Maximum Power Point:**

A solar panel can convert only 35 to 45 percentage of solar irradiation into Electrical Energy. MPP tracking techniques are required for improving the efficiency of the solar panel. As per the maximum power transfer theorem the output power
will be maximum when the source impedance matches with that of the load impedance. To enhance the output voltage and to match source impedance with load resistance a dc-dc converter is used.

The load characteristics influence the operation of PV module. The solar PV module P-V characteristics and I-V characteristics are shown in Fig 2. From the P-V characteristics and I-V characteristics, two major points can be observed. (i) When the output voltage exceeds a maximum value, the current drops sharply with increasing voltage (ii) when the output voltage is less than a maximum value, the change in output current is very small with the change in voltage. In the first case PV cell operates as constant voltage source and in the next case it operates as a constant current source.

Fig. 2: I-V and P-V characteristics of PV cell

For a load having internal resistance $R_i$, the optimal adaptation takes place only at the Maximum Power Point. MPP is indicated as $P_{\text{max}}$. When the source is connected directly to the load, operating point of the PV module will not be an optimal one. To solve this problem a MPPT controller as shown in Fig. 3 is utilized. The controller generates duty cycle $D$ for the DC-DC converter placed between source and load. Also, the MPPT controller has to properly track MPP according to the variation in temperature and insolation.

Fig. 3: MPPT Solar PV system

The parameters of the solar PV panel used in the work is tabulated in Table I.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current at maximum power</td>
<td>$I_{oc}$</td>
<td>4.95A</td>
</tr>
<tr>
<td>Voltage at maximum power</td>
<td>$V_{oc}$</td>
<td>35.2V</td>
</tr>
<tr>
<td>Open circuit voltage</td>
<td>$V_{oc}$</td>
<td>44.2V</td>
</tr>
<tr>
<td>Short circuit current</td>
<td>$I_{sc}$</td>
<td>5.2A</td>
</tr>
<tr>
<td>Temperature coefficient of short circuit current</td>
<td>$\propto$</td>
<td>0.015A/K</td>
</tr>
<tr>
<td>Temperature coefficient of open circuit voltage</td>
<td>$\beta$</td>
<td>0.7V/K</td>
</tr>
<tr>
<td>Internal series resistance</td>
<td>$R_s$</td>
<td>0.21/Ω</td>
</tr>
<tr>
<td>Reference solar radiation</td>
<td>$S_{ref}$</td>
<td>1000W/m²</td>
</tr>
<tr>
<td>Reference Temperature</td>
<td>$T_r$</td>
<td>25°C</td>
</tr>
</tbody>
</table>

* **Dc-Dc Converter:**

DC-DC converters can be used as switching mode regulators to convert an unregulated dc voltage to a regulated dc output voltage. The regulation is normally achieved by PWM at a fixed frequency and the switching device is generally BJT, MOSFET or IGBT. The minimum oscillator frequency should be about 100 times longer than the transistor switching time to maximize efficiency. This limitation is due to the switching loss in the transistor. The core loss of
the inductors limits the high frequency operation. Control voltage $V_c$ is obtained by comparing the output voltage with its desired value. Then the output voltage can be compared with its desired value to obtain the control voltage $V_{cr}$. The PWM control signal for the dc converter is generated by comparing $V_{cr}$ with a saw tooth voltage $V_c$. However the boost converter is selected for the work and further discussions are concentrated towards this one. The Fig. 4 below shows the PWM boost converter. It consists of a dc input voltage source $V_g$, boost inductor $L$, controlled switch $S$, diode $D$, filter capacitor $C$, and the load resistance $R$. When the switch $S$ is in the on state, the current in the boost inductor increases linearly and the diode $D$ is off at that time. When the switch $S$ is turned off, the energy stored in the inductor is released through the diode to the output RC circuit. The inductor current for corresponding operations is shown in Fig 5.

**Fig. 4: Boost Converter**

**Steady state analysis of the boost converter:**

**Off state:**
When the switch is off, the sum total of inductor voltage and input voltage appear as the load voltage.

**On state:**

From the inductor voltage balance equation, we have

\begin{align}
V_g(DT_s) + (V_S - V_o)(1 - D)Ts &= 0 \\
V_g(DT_s) - V_g(DT_s) - V_gTs + V_oDT_s - V_oTs &= 0 \\
V_o &= V_g/(1 - D) \\
\text{Conversion ratio, } M &= V_o/V_g = \frac{1}{1-D}
\end{align}

From inductor current ripple analysis, change in inductor current,

\begin{align}
I_L &= (I_{max} - I_{min}) \\
I_L &= (Vg/L) \times (DT_s) \\
I_L &= (VgD)/(f \times L) \\
L &= VgD/(f \times \Delta I_L)
\end{align}

The boost converter operates in CCM (continuous conducting mode) for $L > L_b$ where

\begin{align}
L_b &= \frac{(1-D)^2BR}{2f}
\end{align}

When the switch is ON, the inductor is charged from the input voltage source $V_g$ and the capacitor discharges across the load. The duty cycle, $D = \frac{T_{on}}{T}$ where $T = \frac{1}{f}$.

The current supplied to the output RC circuit is discontinuous. Thus a large filter capacitor is used to limit the output voltage ripple. The filter capacitor must provide the output dc current to the load when the diode $D$ is off. The minimum value of the filter capacitance that results in the voltage ripple $V_r$ is given by

\begin{align}
C_{min} &= \frac{Dv_0}{V_r}
\end{align}
**Fuzzy Logic Controller For Mppt:**

Fuzzy logic controllers are used nowadays to track the Maximum Power Point in Standalone Photovoltaic systems. The Fuzzy controllers do not require knowledge of the exact model and exhibit robustness. The complete knowledge of the operation of Photovoltaic system is sufficient to carry out the design. Many of the researches are working in implementing fuzzy MPPT to optimize the generated power. The block diagram of fuzzy logic for MPPT is given below in Fig.6. Fuzzy logic MPPT control is categorised into three stages: Fuzzification, Rule based table look-up and Defuzzification.

![Block diagram of fuzzy logic for MPPT](image)

**Fig. 6:** Block diagram of fuzzy logic for MPPT

During the fuzzification process, control variable are converted from a numerical value to a linguistic representation like Positive Big (PB), Positive Medium (PM), Positive Small (PS), Zero Error (ZE), Negative Small (NS), Negative Medium (NM) and Negative Big (NB). The input control variables for the Fuzzification process to take place is slope of the P-V curve (S) and the change of slope (ΔE). In other words, the two FLC input variables are the error E and change of error CE.

The inputs are defined by

\[ E(k) = \frac{P(k) - P(k-1)}{V(k) - V(k-1)} \]  \hspace{1cm} (22)

\[ CE(k) = E(k) - E(k-1) \]  \hspace{1cm} (23)

P(k) is the instant power of the photovoltaic generator. The input E(k) provides information as whether the load operation point at the instant k is in the left or right of the maximum power point of the PV characteristic, whereas the input CE(k) convey the moving direction of the load operation point. To determine the control action of the duty cycle of converter based on the linguistic magnitude of the variables a look-up table is used. The control command will be in linguistic format and has to be converted to associated numerical value in the defuzzification stage. Maximum power point is attained when the input variables reach zero. The illustrations for the FLC input variables and the control action D for tracking MPP is shown in Figs. 7a, 7b and 7c.

![FLC input variables](image)

**Fig. 7a:** Error input of fuzzy logic controller
Mamdani’s method is used to obtain fuzzy inference system. Fuzzy inference system is the kernel of fuzzy logic controller. The process of formulating the mapping from a given input to an output using fuzzy logic is fuzzy inference. The mapping then provides a basis from which decisions can be made. The Mamdani-type inference system is dedicated to force the error function to zero. Two cases are considered for the purpose. If \( E \) is positive; working point is on the left of the MPP. If the change of error \( CE \) is positive, then the working point converges toward the MPP. If \( CE \) is negative, the inverse that occurs. Likewise, if \( E \) is negative; the operation point is, therefore, on the right of the MPP. In this case if \( CE \) is positive, the operation point moves away of the MPP and vice versa if \( CE \) is negative. With this consideration of two cases, the control rules are summarized as a set of a fuzzy IF-THEN rules with \( E \) and \( CE \) as inputs and \( D \) as the output. The linguistic rules of fuzzy logic controller are presented in Table. 2.

Table 2: Linguistic Rules of FLC

<table>
<thead>
<tr>
<th>E/CE</th>
<th>NB</th>
<th>NM</th>
<th>NS</th>
<th>ZE</th>
<th>PS</th>
<th>PM</th>
<th>PB</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>ZE</td>
<td>ZE</td>
<td>ZE</td>
<td>ZE</td>
<td>NB</td>
<td>NB</td>
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<tr>
<td>NM</td>
<td>ZE</td>
<td>ZE</td>
<td>ZE</td>
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<td>NM</td>
<td>NM</td>
<td>NM</td>
</tr>
<tr>
<td>NS</td>
<td>NS</td>
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<td>NS</td>
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<tr>
<td>ZE</td>
<td>NM</td>
<td>NS</td>
<td>ZE</td>
<td>ZE</td>
<td>ZE</td>
<td>PS</td>
<td>PM</td>
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<tr>
<td>PS</td>
<td>PM</td>
<td>PS</td>
<td>PS</td>
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<td>ZE</td>
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<tr>
<td>PM</td>
<td>PM</td>
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<td>PM</td>
<td>ZE</td>
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<td>ZE</td>
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<td>PB</td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
<td>ZE</td>
<td>ZE</td>
<td>ZE</td>
<td>ZE</td>
</tr>
</tbody>
</table>
The defuzzification method used in the work is the centroid method to compute the output of FLC which is the duty cycle. The crisp output of FLC is calculated using defuzzification process. The crisp output describes the mapping from a space of fuzzy logic statement, corresponding to the inferred output, into a non-fuzzy control action.

\[
D = \frac{\sum_{l=1}^{n}\mu(b_l) - d_l}{\sum_{l=1}^{n}\mu(b_l)} \tag{24}
\]

Simulation Results:

The simulation of Fuzzy logic controller with seven Membership Functions is carried out in Matlab for solar radiance of 1000 W/m\(^2\) and cell temperature of 40\(^\circ\)C. The maximum power point is calculated theoretically for the previous said conditions as follows.

\[
DT = T_c - T_{\text{ref}} = 40 - 25 = 15\,^\circ\text{C} \tag{25}
\]

\[
DI = s \left( \frac{s}{s_{\text{ref}}} - 1 \right) I_{ac} = 0.225 \tag{26}
\]

\[
DV = -\beta DT - R_s DI = -10.54 \tag{27}
\]

\[
C_2 = \frac{\frac{E_m}{V_{ac}} - 1}{\ln \left( \frac{1 - \frac{I_m}{I_{sc}}} \right)} = 0.0671 \tag{28}
\]

\[
C_1 = \left( 1 - \frac{I_m}{I_{sc}} \right) \exp \left( \frac{-V_m}{C_2V_{ac}} \right) = 3.3 \times 10^{-7} \tag{29}
\]

\[
I_m = I_{sc} \left[ 1 - C_1 \left( \exp \left( \frac{-V_m}{C_2V_{ac}} \right) - 1 \right) \right] + DI \tag{30}
\]

On substituting \(C_1, C_2, DI, DV\) in (8.13) and solving \(C_1, C_2\), we get

\[
V_m = \log \left( \frac{\frac{I_m - DI}{C_2V_{ac}} + 1}{C_1} \right) C_2V_{ac} + DV \tag{31}\]

\[
C_2 = \frac{\frac{V_m}{V_{ac}} - 1}{\ln \left( \frac{1 - \frac{I_m}{I_{sc}}} \right)} = 0.0671 \tag{32}\]

\[
C_1 = \left( 1 - \frac{I_m}{I_{sc}} \right) \exp \left( \frac{-\log \left( \frac{\frac{I_m - DI}{C_2V_{ac}} + 1}{C_2V_{ac} + DV} \right)}{C_2V_{ac}} \right) = 3.3 \times 10^{-7} \tag{33}\]

\[
V_m = 26.24; I_m = 4.95; P_m = V_m \times I_m = 130.8W \]

The Maximum Power that a PV panel has to provide at the above mentioned environmental condition is 130.8W.
Fig. 9: Simulation result of PV power with FLC based MPPT with solar irradiance of 1000 W/m² and temperature of 40°C.

Fig. 8 depicts the simulation result of PV power without utilizing MPPT controller. It is observed that boost converter stabilizes the power output with $P_{max} = 53.3$ W. Even though it stabilizes output power PV panel does not deliver the maximum power. The simulation result of PV power when fuzzy based MPPT controller is used is shown in Fig. 9. It is found that fuzzy logic based MPPT provides higher power of approximately 129.6 W with reduced steady state oscillations.

**Conclusion:**

A few control schemes that was used already showed defects and so it became necessary to find an alternative to optimize the output. The Fuzzy logic controller is found to be a better idea. In this paper, a fuzzy MPPT controller utilizing 7 MFs is proposed to extract maximum power. The standalone photovoltaic system with fuzzy MPPT controller is modeled in MATLAB/SIMULINK to examine its performance. Based on the results obtained through simulation, it can be concluded that the fuzzy controller assist PV panel in delivering maximum power. Fuzzy Maximum Power Point Tracker tracks closely the MPP in addition to the capability of reducing perturbed voltage after attaining the MPP thereby preserving a more stable power. Since, there is more flexibility exhibited by fuzzy logic controllers it can pave way to find effective solution to track MPP with lesser perturbation.

**REFERENCES**


