Design and Implementation of Intelligent MPPT Based on FPGA for PV System

Mohanad H. Mahmood*, Inaam I. Ali and Oday A. Ahmed
Electrical Engineering Department. University of Technology. Baghdad, Iraq.
*Email: 31626@student.uotechnology.edu.iq.

Abstract. This paper presents the design and implementation of intelligent maximum power point tracking (MPPT) technique for Photovoltaic (PV) systems. The proposed MPPT is based on the fuzzy logic controller (FLC). FLCs have the benefit of being very easy to design as they don't need accurate knowledge of the system and work well for the nonlinear system. The MATLAB/Simulink was used to verify the proposed method, with three scenarios of environment conditions. The DC-DC converter has been designed and simulated using PLECS simulation software, then implemented practically in order to work as impedance matching between PV source and load. The system was built based on Field Programmable Gate Array (FPGA) and connected to the PV panel and tested practically at the site for different environment conditions and compared with measurements obtained using solar analyzer device. According to the simulated and experimental results, the proposed method capable to find the maximum power point (MPP) under different climate conditions excellently with compared to perturb and observation (P&O) method. Also, it has very low oscillation about (MPP) and high response, as a result, efficiency is enhanced, providing maximum power transfer to load.

1. Introduction
Global energy attention has recently expanded significantly, due to population growth. In addition, global warming is increasing due to carbon dioxide emissions from fossil fuels. Therefore, these complex challenges must be resolved. Several studies have suggested using sustainable energies to stand up to the issue of absence of energy in the forthcoming years and to minimize the impacts of consuming fossil energizes. Solar energy has many advantages over conventional energy sources, because of its, clean, sustainable and safe energy [1]. However, the PV system is considered to be of low efficiency, due to the dependence the power of PV panel on several factors such as the intensity of radiation and the temperature, i.e. weather conditions, resulting in energy loss and lower efficiency [1,2].

To enhance the efficiency of the photoelectric system, several techniques are introduced such as sun tracker, MPPT or both [1]. MPPT is best because it’s don’t need mechanical part such that used in sun tracker, as well as the cost of implementation the MPPT is low compared to sun tracker [3].

The P&O and IncCon algorithms are common MPPT used approach, due to operational simplicity and the low number of sensors required [4-7]. The main drawback in these methods is the large oscillation about MPP and slow tracking speed during a radib change in atmospheric conditions. To overcome these drawback, intelligent techniques are introduced to enhance the MPPT performance. The author in [8] suggested an intelligent control method MPPT of the photovoltaic system under varying irradiance and temperature conditions. The fuzzy logic controller method applied to a DC-DC converter device for stand-alone DC water pumping. The author in [9] developed the MPPT controller.
based on FLC for stand-alone photovoltaic (PV) to detect the MPP. The results obtained using the proposed system based on Simulink only without practical results. In [10] the author described the hardware implementation of FLC MPPT on FPGA using Hardware Description Language (VHDL). The main disadvantage is the use of a VHDL language that requires in-depth training to implement the fuzzy controller, in addition, the practical results depend only on Modelsim simulation. A new digital MPPT control scheme for standalone photovoltaic (PV) system presented in [11], it is built upon a single input fuzzy logic (SIFLC) and based on the constant voltage algorithm. The Lyapunov method is considered for the stability analysis of the proposed control systems. The main limitation of this study is expansive of dSPACE DSP1104. The author in [12] suggested a novel adaptive neural network (ANN) for MPPT in photovoltaic (PV) systems. The proposed MPPT method can estimate the MPPs of a PV system on-line using a neural network-based system. NNs are trained by using a novel backpropagation algorithm in pre/post control phases. In [13] the ANFIS-reference model method was designed and implemented using FPGA Altera board in addition to the incremental conductance method and constant voltage method to compare the performance of each method. The main drawback is complex of implementation as well as the requires of three sensors (irradiation sensor, temperature sensor and current sensor).

In this work, the intelligent technique was used, the proposed system has been based on an adaptive technique, by considering the advantages of two algorithms to get improved results. Most of the previous literature relies on simulation results to confirm their system. in this work in addition to the results of the simulation investigation, the system was verified in practice using a practical circuit and the algorithm was constructed using a high advanced FPGA and the real-time Monitoring system worked for observing all system-related variables.

2. Equivalent circuit and mathematical model of PV cell:
The photovoltaic cell is the smallest part of the photovoltaic model that can convert sunlight into direct electricity. To form a photovoltaic model, the number of photovoltaic cells can be connected into a series; a combination of a parallel chain unit forms a PV array [3,14].

By applying Kirchhoff’s law:

\[ I = I_{PH} - I_d - I_P \]  

\[ I_{PH} \] is photocurrent, \( I_d \) is forward current of the diode, when \( R_s \) and \( R_P \) are taken into consideration; The equation (1), will be as follow:

\[ I = I_{PH} - I_o \left( \exp \left( \frac{V+IR_s}{NsaV_T} \right) - 1 \right) - \frac{V+1IR_s}{R_P} \]  

Where: \( V \) is the diode voltage in volt (V), \( I_o \) the diode reverse saturation current in ampere (A). \( V_T \) the thermal voltage in volt (V). \( a \) is ideality factor constant. \( N_s \) is a number of PV cells in series. Figure 1 represents the equivalent circuit of the PV cell.

---

**Figure 1.** Solar model equivalent circuit.
In this work, the module (MCM 90) was modelled using parameters listed in Table 1. MATLAB/Simulink was used to simulate the characteristics of this module as shown in figures 2 and 3 which represent PV module, (P-V) and (I-V) characteristics.

**Table 1: PV Panel datasheet.**

| Parameters | Values | Parameters | Values |
|------------|--------|------------|--------|
| $P_{\text{max}}$ (W) | 90.22 W | $V_{\text{oc}}$ (V) | 22.62 V |
| $V_{\text{MPP}}$ (V) | 18.19 V | $I_{\text{sc}}$ (A) | 5.38 A |
| $I_{\text{MPP}}$ (A) | 4.96 A | $N_s$ | 36 |

As shown in figure 2 The irradiance is directly proportional to the current characteristics. As the irradiance increases, the short circuit and the position of the MPP will change.

The temperature, however, is inversely related to the voltage characteristics. The open-circuit voltage ($V_{\text{oc}}$) will decrease as the temperature increases as shown in figure 3, and the location of the MPP will change.

![Figure 2. P-V and I-V characteristics under variable irradiance.](image1)

![Figure 3. P-V and I-V characteristics under variable temperature.](image2)

3. **Step-up DC-DC converter modelling:**
In this work, a step-up DC-DC converter is selected so that tracking of maximum power point achieved by means of the variable duty cycle. Figure 4 illustrates the diagram for the overall system, consisting of the PV part, the converter circuit part, the load, and the MPPT control part.
Figure 4. Schematic diagram of the PV system.

For figure 5 illustrates the DC-DC boost converter circuit. The output voltage $V_o$ is always higher than input voltage $V_i$ in steady operation. The converter includes an inductor (L), power (MOSFET) or (IGBT), the diode (D), filter capacitor (C), and load resistor ($R_L$)[15].

Figure 5. Circuit diagram during ON state and OFF state of boost converter operation [15].

The average output voltage and current are obtained by equations (3) and (4) [15]:

\[
V_o = \frac{V_i}{(1-D)} \\
I_o = (1 - D)I_{IN}
\]  

4. Maximum power point tracking algorithms

MPPT is an algorithm that produces the appropriate duty cycle ($D$) using electronic circuit and feeds it to the power adapter circuit that adapts between the PV panel and loads, to continuously track maximum power.

4.1. Conventional P&O Algorithm

The conventional P&O MPPT method is usually used, because of its simple implementation and reduced cost [16]. P&O is considered as the standard for new MPPT algorithms for comparison. The principle of P&O method depends on the change in the output power and voltage of the PV panel. If $dp/dv > 0$ the adjustment voltage perturbs in the same direction, else the voltage adjustment reversed [17], figure 6 show the flowchart of P&O method.

Figure 6. Conventional P&O Flowchart.

4.2. Proposed Adaptive Fuzzy Logic Controller Algorithm

According to technical constraints on P&O, there is an unacceptable power loss during tracking and drift issues associated with a rapid change of irradiance. Several P–V based improvements have been applied, but they are perceived to be insufficient approaches to all these issues. Accordingly, MPPT-based solutions to artificial intelligence were developed to resolve major issues with conventional MPPT processes.
Fuzzy logic is an effective technique that has been used commonly in MPPT systems. The Fuzzy Inference Systems (FIS) has three principal stages [18] as illustrated in figure 7: The Fuzzification knowledge base, Decision-making logic and Defuzzification interface.

![Figure 7. Fuzzy logic controller block diagram.](image)

It is applied to the photovoltaic system since it is robust and a favorable method that works without oscillations at the optimal point. The main disadvantages of FLC are the problem of shifting the operating point away from the peak optimum point associated with rapidly changing irradiance of more than 10 W/m\(^2\)/s as demonstrated in figure 8, and complicated implementation compared to traditional MPPT methods [19].

![Figure 8. Fast increase of irradiance level.](image)

From figure 8, due to a fast increase of solar irradiance, point MPP1 (low point), which reflects MPP at low solar irradiance, shifts to MPP2 (high point), the proper path of the vague tracker travels apart from the current MPP, according to the traditional rule base of FLC MPPT.

A modified P&O algorithm based FLC methodology was introduced in this work and designed for MPPT to combine the advantages of FLC and P&O MPPT algorithms while reducing their drawbacks. In addition, the complex engineering problems of a fuzzy system become simple and easy when the designed membership functions are few.

The proposed algorithm is consisting of two input and one output variables, the first input variable is a slope of PV power, while the second input variable is the normalized of PV current as described above. These variables were defined using the following equations:

\[
\frac{\Delta P}{\Delta V} = \frac{P_{(n)} - P_{(n-1)}}{V_{(n)} - V_{(n-1)}} \quad (5)
\]

\[
\frac{\Delta I}{I_{(n-1)}} = \frac{I_{(n)} - I_{(n-1)}}{I_{(n-1)}} \quad (6)
\]

Table (2) shows the database of the fuzzy rules designed according to the fuzzy input variables. Four terms fuzzy subset, positive big (PB), positive small (PS), negative small (NS), and negative big (NB), are defined to describe each linguistic variable. The output from the fuzzy controller was defined using the following equation:

\[
d_{(n)} = d_{(n-1)} + \Delta d \quad (7)
\]
Where $d(n)$ is the next iteration for the duty cycle, $d(n-1)$ is the previous iteration of the duty cycle, and $\Delta d$ is the output of fuzzy controller which is the incremental increase.

**Table 2.** Database of the fuzzy rule of the proposed system.

| $\Delta I/I_{(n-1)}$ | NB | NS | PS | PB |
|----------------------|----|----|----|----|
| NB                   | NB | NS | PS | PB |
| NS                   | NB | NS | PS | PB |
| PS                   | NB | NS | PS | PB |
| PB                   | PB | PS | NS | NB |

The shapes and fuzzy subset partitions of the membership function in both inputs and output are shown in figure 9.

**Figure 9.** Inputs and outputs Membership functions.

Figure 10 demonstrates the process flowchart of the fuzzy controller's calculation algorithms. By reading voltage and current signals from the PV cell, controllers would generate fuzzy input variables $dP/dV$ and $dI/I_{n-1}$ needed for FLC. To maximize power output, the fuzzy input variables would be used to calculate the duty ratio to adjust the PV Panel operating point [20].

**Figure 10.** Fuzzy logic MPPT flowchart.
5. Design and Selection of the Boost Converter Parameters

5.1. Required Duty Cycle Value

For MPPT non-linear DC-DC boost converter has been designed and modelled. Different elements of the converter are designed based on the required power rating of the PV panel which is 90W with maintaining low ripple of input current and output voltage.

The MPP resistance $R_{MPP}$ is the total resistance seen by the source as shown in figure 11. The MPP resistance, $R_{MPP}$, is determined as shown in equation (8).

$$R_{MPP} = \frac{V_{MPP}}{I_{MPP}} = \frac{V_{MPP}^2}{P_{max}}$$  (8)

![Figure 11. $R_{MPP}$ viewed from the PV source.](image)

Only in a certain condition can the MPPT boost converter produce desired system requirements. This condition occurs in the desired area of operation, as shown in figure (12). Beyond this operation area creates a greater ripple factor.

Assuming a lossless boost converter, the output power can be derived as given below:

$$\frac{V_{MPP}^2}{R_{MPP}} = \frac{V_o^2}{R_L}$$  (9)

Equation (9), can be written as:

$$\frac{V_{MPP}^2}{R_{MPP}} = \frac{V_o^2}{R_L} = \frac{(V_{IN}/(1-D))^2}{R_L}$$  (10)

By simplifying (10), equation (11) shows that the required $D$, so that operating in MPP, is depending on $R_{MPP}$ and $R_L$.

$$D = 1 - \sqrt{\frac{R_{MPP}}{R_L}}$$  (11)

![Figure 12. The change of $R_{MPP}$ during the change of irradiance.](image)
So, since the duty cycle ratio is varying between 0 to 1, hence $R_L$ must be either greater or equal $R_{MPP}$. If the above condition is not meet, the tracking of maximum power will fail. Based on the minimum irradiation value, the $R_L$ can be chosen, so that the load resistance is greater than $R_{MPP}$.

According to P-V characteristics obtained from PV data and equation (11), the table 3 illustrated the required $D$ so that operating at MPP for different irradiiances, where load resistor are chosen between (30-100 Ω), greater than $R_{MPP}$.

| Table 3. PV parameters during different irradiance level. |
|--------------------------------------------------------|
| Irrad.1 | Irrad.2 | Irrad.3 | Irrad.4 | Irrad.5 |
| 1KW/m²   | 0.8KW/m² | 0.6KW/m² | 0.4KW/m² | 0.2KW/m² |
| Maximum power ($P_{max}$) | 90.22 | 72.81 | 54.92 | 36.62 | 18.06 |
| Voltage at max. power ($V_{MPP}$) | 18.19 | 18.31 | 18.39 | 18.38 | 18.1 |
| $R_{MPP} = \frac{V_{MPP}^2}{P_{max}}$ | 3.667 | 4.60 | 6.157 | 9.255 | 18.140 |
| $D = 1 - \sqrt{\frac{R_{MPP}}{R_L}}$ @RL=30Ω | 0.65 | 0.608 | 0.546 | 0.44 | 0.22 |
| @RL=100Ω | 0.808 | 0.785 | 0.751 | 0.695 | 0.574 |

5.2 Inductor Design

The required input inductance so that the converter operates in continuous conduction mode (CCM) is given as [15]

$$L_{min} = \frac{D_{MPP,\text{max}}(1-D_{MPP,\text{max}})^2R}{2f}$$

(12)

To ensure that the converter operates in CCM mode, $L$ has been chosen equal to 3mH.

5.3. Selection of Input and Output Capacitors

$C_i$ can be determined as shown in equation (13).

$$C_i = \frac{D}{8LNT\nu_{MPP}f^2}$$

(13)

The input capacitor value selected equal to 100μF to ensure minimum output voltage ripple.

The output capacitance $C_o$ of a boost converter is calculated using equation (14).

$$C_o = \frac{D}{R(\Delta V_o/V_o)f}$$

(14)

In this work, the output capacitor value selected equal to 100μF to ensure minimum output voltage ripple.

Table 4 shows the design parameters of the used DC-DC boost converter used for the proposed MPPT system, where these parameters calculated based on the derived equations.

| Table 4. Design parameters of the boost converter. |
|--------------------------------------------------|
| Parameter | Value | Parameter | Value |
| Duty (D) % | 20%-80.85 | Ci (Farad) | 100μf |
| Frequency (Hz) | 40kHz | Co (Farad) | 100μf |
| Inductor (Henry) | 3mH | $R_L$ (Ω) | 30-100Ω |
6. Simulation and Results of the PV MPPT System:
All the discussed elements in this chapter are to be bound together to form a complete integrated PV system as seen in figure 13. This system has been studied in two MPPT methods which are
1. Perturb and observe (P&O),
2. Proposed Adaptive Fuzzy Logic Controller (AFLC).
Each method studied in different cases: which is uniform irradiation level at 1000W/m², Step change of irradiance level, and ramp change of irradiation level.

![Figure 13. Complete MPPT PV system.](image)

6.1. Case One (Uniform Irradiation Level)
First, the system is operated under a uniform irradiance level, which achieves the maximum output power at nominal operating conditions (25 °C and 1000W/m²) as shown in figure 14.

![Figure 14. Uniform irradiation level.](image)

6.1.1. Perturb and Observation Algorithm
Figure 15 shows the output PV voltage (V_{PV}), PV current (I_{PV}) and power (P_{PV}) of the PV panel for G=1000 W/m² and T=25 °C, with P&O algorithm. It can be seen that the MPPT algorithm tracking the MPP successfully. As clear from the zoomed area of figure 15 that the power has high oscillation at steady state (around MPP) about (5W), the oscillation accrued due to the perturbation step size. Also, it’s clear that the speed of convergence is fast about (0.04s).
6.1.2. Proposed AFLC algorithm

Uniform irradiation level is applied to examine the behaviour of the MPPT system with the proposed AFLC algorithm.

![Figure 16](image1.png)

**Figure 16.** Output voltage ($V_{PV}$), current ($I_{PV}$) and power ($P_{PV}$) at $G=1000\ W/m^2$ and $T=25\ ^\circ C$ using the proposed algorithm.

It can be seen in figure 16 that the proposed algorithm tracks the MPP perfectly and the oscillation at steady state are very low about (0.2W) (around MPP) in comparison to (5 W) in P&O algorithm. While it’s clear that the speed of convergence is slow about (0.4s) as compared to previous algorithms.

6.2. Case 2 (Ramp Change of Irradiation Level):

The performances of two developed MPPT algorithms were examined in this work under ramp changing irradiance, as shown in figure 17. Notice that for any MPPT algorithm, slop change in irradiance is considered as a bad disturbance even more than a step change.

![Figure 17](image2.png)

**Figure 17.** Ramp change of irradiation level.
6.2.1. Perturb and Observation Method
Figure 18 shows the output voltage ($V_{PV}$), current ($I_{PV}$), and power ($P_{PV}$) of the PV panel, for ramp changing irradiance (as described previously), with P&O algorithm. As shown, the algorithm tracking the MPP successfully. Also, it's clear that the power has high oscillation at steady state (around MPP). In addition, the P&O algorithm is may be lost when the solar irradiance changed rapidly. As a result, the latter method takes a longer time to address the phenomenon of the drift problem.

6.2.2. Proposed AFLC Technique
As shown in figure 19 the power tracking of the proposed method turned out to be fast and accurate in finding the right direction when ramp changing irradiance is applied to the MPPT system. Moreover, the proposed algorithm has low – steady-state oscillation and fast response at the change in irradiance, where the AFLC algorithm takes a short time to address the phenomenon of the drift problem.

6.3. Case 3 (Step Change of Irradiance Level)
In this case, the PV system will be examined when the system operates with solar irradiation is varied in steps between the levels from (500W/m² to 800W/m² and increased to 1000W/m² then decreased to 800W/m² and finally increased to 900W/m²) as shown in figure 20.

6.3.1. Perturb and Observation Algorithm
The output voltage ($V_{PV}$), current ($I_{PV}$), and power ($P_{PV}$) from the PV panel, for sudden changing irradiance, are illustrated in figure 21, with P&O algorithm. As shown, the algorithm tracking the MPP. As cleared from figure, the power has high oscillation at steady state, also, the P&O algorithm is
lost when the solar irradiance changed rapidly. As a result, this method takes a long time to address the phenomenon of the drift problem.

![Step change of irradiance level.](image)

**Figure 20.** Step change of irradiance level.

![Output voltage, current and power at Step change of irradiance level and T=25 °C using P&O algorithm.](image)

**Figure 21.** Output voltage ($V_{\text{PV}}$), current ($I_{\text{PV}}$) and power ($P_{\text{PV}}$) at Step change of irradiance level and $T=25$ °C using P&O algorithm.

6.3.2. **Proposed AFLC Technique**

The proposed AFLC method can overcome all the drawbacks of the other compared MPPT technique if a sudden changing irradiance is applied. The power tracking of the proposed method turned out to be fast and accurate in finding the right direction. In respect to P&O MPPT algorithm, the proposed method exhibits low steady-state oscillation and fast response at the change in irradiance and required a short time to address the phenomenon of the drift problem.

![Output voltage, current and power at Step change of irradiance level and T=25 °C using the proposed algorithm.](image)

**Figure 22.** Output voltage ($V_{\text{PV}}$), current ($I_{\text{PV}}$) and power ($P_{\text{PV}}$) at Step change of irradiance level and $T=25$ °C using the proposed algorithm.
6.4. Summary of the Simulation Results:
The results demonstrated that the proposed technique has smooth and accurate tracking compared to competing algorithms. Also, the oscillation of the proposed algorithm at steady state is very low, with comparison to conventional P&O algorithm. Inconsequent these results to be the tracking efficiency is high and more loss power can be avoided. Table 5 summarized the most important parameters of the compared MPPT techniques. Its demonstrated that the proposed technique superior the P&O MPPT methods and exhibits a good performance with very low oscillation.

Table 5 Summary of algorithms performance.

| MPPT type  | Oscillation about MPP | Transient time(s) | MPPT tracking efficiency (%) | The required time of the drift problem |
|------------|-----------------------|-------------------|-------------------------------|---------------------------------------|
| P&O        | High                  | 3.9 ms            | 96.2%                         | High                                  |
| Proposed AFLC | Very Low            | 0.45 s            | 99.7%                         | Low                                   |

7. Experimental Results:
To verify the performance of the proposed MPPT algorithm, experimental results have been carried out based on the layout shown in figure 13 which is based FPGA MyRio kit and DC-DC boost converter.

Measurements are obtained by using the digital storage oscilloscope (Twintex digital oscilloscope TSO 1102 100 MHz, 1G sa/s sampling, USB storage) and probes (Hantek 2 X 100MHz oscilloscope clip), the solar analyzer device (Solar-400) has been used to measure irradiance and PV and ambient temperature as well as, the power, voltage, current and fill factor of the PV panel.

7.1. Proposed MPPT System Results:
Experimental results are obtained based on the prototype setup illustrated in figure 23. The prototype is tested based on the parameters listed in the table 4 in section (5.3).

The measuring has been taken about 10:00 am - 12:30 pm in 13th of October 2019 and 29th of October 2019, and has been compared with data obtained using "Solar-400-solar power analyzer" device at the “Energy and Environment Research Center/Industrial Research and Development Authority/Ministry of Industry and Minerals”.

Figure 24 show the P-V characteristics and I-V characteristics of the PV panel that obtained, by connecting variable resistance to PV panel output and varying the resistance gradually to find the highest possible output power for a PV panel.
Figure 24. (a) P-V characteristics, (b) I-V Characteristics, of the PV panel obtained experimentally.

Table 6 listed the experimental results for the proposed MPPT system in comparison to the results that obtained using solar analyzer device at the same irradiance and temperature conditions at the same time. The results show an excellent matching for the proposed MPPT system compared with the actual results that obtained using measurement devices, also the output power obtained by the proposed MPPT is very close to the actual maximum power obtained using measuring equipment.

Table 6 The experimental results for the proposed MPPT system with a comparison of results obtained using solar analyzer device.

| Test | Irradiance (W/m²) | Temp. (°C) | Actual Pₚₘₚ (W) | Actual Vₘₚ (V) | Actual Iₘₚ (A) | Measured Pₚₘₚ (W) | Measured Vₘₚ (V) | Measured Iₘₚ (A) |
|------|------------------|------------|----------------|--------------|--------------|----------------|----------------|---------------|
| 1    | 543              | 44.5       | 32.6           | 15.48        | 2.103        | 32.4           | 14.4           | 2.25          |
| 2    | 613              | 51.2       | 52.2           | 15.12        | 3.45         | 52.05          | 14.3           | 3.64          |
| 3    | 731              | 48.6       | 47.8           | 15.38        | 3.111        | 47.23          | 13.81          | 3.42          |
| 4    | 764              | 49.1       | 58.6           | 15.2         | 3.902        | 58.1           | 14             | 4.15          |
| 5    | 811              | 47         | 59.5           | 15.42        | 3.859        | 59.14          | 14.22          | 4.158         |
| 6    | 846              | 57.5       | 63             | 14.77        | 4.264        | 62.78          | 14.76          | 4.253         |

Figure 25 shows the actual PV power and output (measured) power of the proposed system based on the results in a table 6, according to figure 26, the output of the proposed system is very close to actual power obtained using the solar analyzer.
Figure 25. The actual PV power and output power of the proposed system.

Figure 26 shows the actual PV voltage and output (measured) voltage of the proposed system, and the actual PV current and output (measured) current of the proposed system, based on the results in table 6.

Figure 26. (a) The actual PV voltage and output of the proposed system. (b) The actual PV current and output current of the proposed system.

From table 6, one can get the tracking efficiency as shown in figure 27, where the tracking efficiency can be calculated using the following equation

$$\eta_{T\%} = \frac{\int P_{PV} \, dt}{\int P_{PVM\text{ax}} \, dt} \quad (15)$$

Figure 27. Tracking efficiency.
Figure 28 shows the gate pulses of the MPPT controller fed to the boost converter during experimental of the proposed intelligent MPPT. The duty cycle changed according to the measured voltage and current that measured by the current sensor (ACS712) and voltage sensors (25-volt module), which is fed to the FPGA to find the appropriate duty cycle depending on the algorithm used.

![Figure 28. Gate pulses of the MPPT controller fed to the boost converter (D=1-62%, 2-65%, 3-77%, 4-79%).](image)

Figure 29 shows the results obtained using real-time monitoring using LabVIEW. As shown in these figures the system works perfectly at the real-time, and one can observe different data in the system at same time such as power, voltage, current, duty cycle and all related variable.

![Figure 29. Power at [543 W/m², 44.5°C, Ppv=32.4 W, Vpv=14.4 V,Ipv=2.25 A], [613 W/m², 51.2°C, Ppv=52.05 W, Vpv=14.3 V,Ipv=3.64 A], [731 W/m², 48.6°C, Ppv=47.23 W, Vpv=13.81 V,Ipv=3.42 A], [764 W/m², 49.1°C, Ppv=58.1 W, Vpv=14 V,Ipv=4.15 A].](image)
Figure 30 show the output maximum power for each condition environment measurement obtained from the real time-proposed system which works at the site. As mentioned earlier the results and data measured can be saved as excel or pictures, so that the data can be combined to gather for different conditions in order to analyses it. According to figure 30 the system works perfectly with different environmental conditions compared with actual results obtained using solar analyzer device.

![Figure 30. Output maximum power of a practical system.](image)

8. Conclusion:
This work has been set up to study, analysis, design, simulation and implementation the MPPT system strategies for photovoltaic systems working under uneven irradiation conditions. The main goal has been to enable the PV panel to work at optimal power points according to its respective light levels. An intelligent controller has been proposed and designed to track the MPPT by feeding the boost converter with an appropriate duty cycle so that MPP can be tracked and thus the system efficiency increased. The DC-DC converter has been achieved with 90 watts and efficiency getting between (90%-92%) at the input power range (90W). Adaptive MPPT was carried out and tested in three different cases representing the expected atmospheric changes in PV systems and a comparison was made with P&O algorithms to assess the feasibility of the proposed technique. The proposed controller was implemented on FPGA to keep the solar panel operate at the MPP. Monitoring system was building to works in real-time for data logger. Through the results and experiments, it is clear that the use of intelligent MPPT systems gives very good results compared to the traditional methods in terms of oscillation about MPP and speed of response in addition to the accuracy of the tracking. With the advancement of modern software and hardware and the associated sensors, the complexity of using intelligent MPPT systems has started to decrease very significantly, so that it is possible to build very sophisticated systems at low cost and high accuracy with the possibilities of taking measurements and analysis in real-time during the work.

References
[1] A. S. Aziz, M. F. N. Tajuddin, M. R. Adzman, A. Azmi, and M. A. M. Ramli, 2019 Optimization and sensitivity analysis of standalone hybrid energy systems for rural electrification: A case study of Iraq, Renew. Energy, pp. 775–792, doi: 10.1016/j.renene.2019.02.004.
[2] G. Dileep and S. N. Singh, 2015 Maximum power point tracking of solar photovoltaic system using modified perturbation and observation method, Renew. Sustain. Energy Rev. 50, pp. 109–129.
[3] M. E. EI-Telbany, A. Y. Mahgoub, and A. A. Zekry, 2014 An Intelligent Fuzzy Controller for
Maximum Power Point Tracking Mohamed, *IEEE Trans. Ind. Appl.* 978(1), pp. 107–111.

[4] A. Safari and S. Mekhilef, 2011 Incremental conductance MPPT method for PV systems, *Can. Conf. Electr. Comput. Eng.*, pp. 000345–7, doi: 10.1109/CCECE.2011.6030470.

[5] S. Salman, X. Ai, and Z. Wu, 2018 Design of a P-&-O algorithm based MPPT charge controller for a stand-alone 200W PV system, *Prot. Control Mod. Power Syst.* 3(1).

[6] L. Egiziano, N. Femia, D. Granazio, G. Petrone, G. Spagnuolo, and M. Vitelli, 2006 Photovoltaic inverters with perturb & observe MPPT technique and one-cycle control, *Proc. - IEEE Int. Symp. Circuits Syst.*, pp. 3718–21, doi: 10.1109/iscs.2006.1693435.

[7] M. A. M. Ramli, S. Twaha, K. Ishaque, and Y. A. Al-Turki, 2017 A review on maximum power point tracking for photovoltaic systems with and without shading conditions, *Renewable and Sustainable Energy Reviews* 67, pp. 144–159.

[8] M. M. Algazar, H. Al-Monier, H. A. El-Halim, and M. E. E. K. Salem, 2012 Maximum power point tracking using fuzzy logic control, *Int. J. Electr. Power Energy Syst.* 39(1), pp. 21–28.

[9] B. Bendib, F. Krim, H. Belmili, M. F. Almi, and S. Boulouma, 2014 Advanced fuzzy MPPT controller for a stand-alone PV system, *Energy Procedia* 50, pp. 383–392.

[10] M. Farhat, O. Barambones, and L. Sbita, 2015 Efficiency optimization of a DSP-based stand-alone MPPT controller using a stable single input fuzzy logic controller, *Renew. Sustain. Energy Rev.* 49, pp. 907–920.

[11] A. A. Aldair, A. A. Obed, and A. F. Halihal, 2017 Design and implementation of ANFIS-reference model controller based MPPT using FPGA for photovoltaic system, *Renewable and Sustainable Energy Reviews* 82, pp. 2202–17.

[12] E. M. G. Rodrigues, R. Melício, V. M. F. Mendes, and J. P. S. Catalão, 2011 Simulation of a solar cell considering single-diode equivalent circuit mode, *Renew. Energy Power Qual. J.*, no. May, pp. 369–373, doi: 10.24084/repqj09.339.

[13] M. K. Kazimierczuk, *Pulse-width Modulated DC – DC Power Converters*. Ohio: A John Wiley and Sons, Ltd, 2008.

[14] S. Saravanan and N. Ramesh Babu, 2016 Maximum power point tracking algorithms for photovoltaic system - A review, *Renewable and Sustainable Energy Reviews* 57, pp. 192–204.

[15] A. Belkaid, I. Colak, and K. Kayisli, 2017 Implementation of a modified P&O-MPPT algorithm adapted for varying solar radiation conditions, *Electr. Eng.* 99(3), pp. 839–846.

[16] H. Abbes, K. Loukil, H. Abid, M. Abid, and A. Toumi, 2016 Implementation of photovoltaic maximum power point tracking fuzzy logic controller on FPGA, *J. Inf. Assur. Secur.* 11, pp. 97–106.

[17] J. K. Shiau, Y. C. Wei, and B. C. Chen, 2015 A study on the fuzzy-logic-based solar power MPPT algorithms using different fuzzy input variables, *Algorithms* 8(2), pp. 100–127.