International Journal of Advanced Computer Research (ISSN (print): 2249-7277 ISSN (online): 2277-7970)
Volume-4 Number-2 Issue-15 June-2014

An Accurate ANFIS-based MPPT for Solar PV System

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Abstract

It has been found from the literature review that the ANFIS-based maximum power point tracking (MPPT) techniques are very fast and accurate in tracking the MPP at any weather conditions, and they have smaller power losses if trained well. Unfortunately, this is true in simulation, but in practice they do not work very well because they do not take aging of solar cells as well as the effect of dust and shading into account. In other words, the solar irradiance measured by solar irradiance sensor is not always the same irradiance that influences the PV module. The main objective of this work is to design and practically implement an MPPT system for solar PV with high speed, high efficiency, and relatively easy implementation in order to improve the efficiency of solar energy conversion. This MPPT system is based on ANFIS technique. The contribution of this research is eliminating the need of irradiance sensor while having the same adequate performance obtained by the ANFIS with irradiance sensor, both, in simulation as well as in experimental implementation. The proposed technique has been validated by comparing the practical results of the implemented setup to simulations. Experimental results have showed good agreement with simulation results.

Keywords

ANFIS, implementation, microcontroller, MPPT, photovoltaic (PV).

1. Introduction

The use of artificial intelligence (AI) based techniques such as fuzzy logic control (FLC), artificial neural networks (ANNs), and genetic algorithms (GAs) are recently increasing in MPPT applications. This increasing utilization is due to the nonlinear characteristics of PV modules. These techniques provide fast and powerful computational solution to the problem of MPPT [1].

In recent years, much research has been done on the use of adaptive neuro fuzzy inference systems (ANFIS) to track the maximum power point (MPP) of PV power generators. ANFIS systems are actually fuzzy inference systems tuned by neural networks. Thus, they combine the computation power of neural networks with the reasoning capability of fuzzy inference systems. In addition, they can automate the generation of fuzzy rules.

Various configurations of ANFIS-based MPPT controllers have been proposed in the literature [2-9]. In the ANFIS-based MPPT proposed in [2], the power and current of PV module are measured to compute the inputs of ANFIS. These inputs are similar to the inputs of hill-climbing-like fuzzy logic control (FLC) systems proposed in [10-12]. The output is the change in duty cycle of power converter. In [4], the open circuit voltage and short circuit current are fed to the ANFIS, and the output is the voltage at maximum power. Actually, these inputs mean either interrupting the power of PV module (which results in power loss) or using pilot solar cells (which increase cost). In [3, 5-7, 9], solar irradiance and cell temperature are fed to ANFIS and the output differs from reference to another. Some authors use Vmax as the output of ANFIS and others use Pmax. These MPPT systems are very fast and accurate, because they instantaneously estimate the accurate MPP, without interrupting the PV power, using trial-and-error search, or approximating the MPP. However, they have several limitations. The methods that require measuring solar irradiance and temperature can run accurately in simulation, because the value of solar irradiance applied to PV module is exactly the same value applied to ANFIS, but this is not the case in real time. The solar irradiance measured by the pyranometer (solar irradiance sensor) is not always the same irradiance that influences the PV module (strikes its surface). This is either due to shading, dust, or aging of PV cells. Furthermore, the pyranometer is rather expensive.

Manuscript received June 17, 2014.
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2. Problem Definition

The methods in the literature that avoid using a pyranometer may seem to be more practical. However, the following issues should be considered to ensure better accuracy of these methods. Figures 1 and 2 shows, respectively, the *I-V* and *P-V* curves of a PV module for different temperature values. It can be noticed from these figures that, although there is a

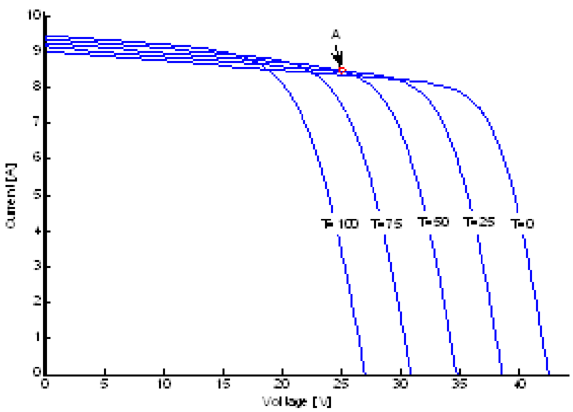

Figure 1: I-V characteristics for different temperatures showing interference between curves

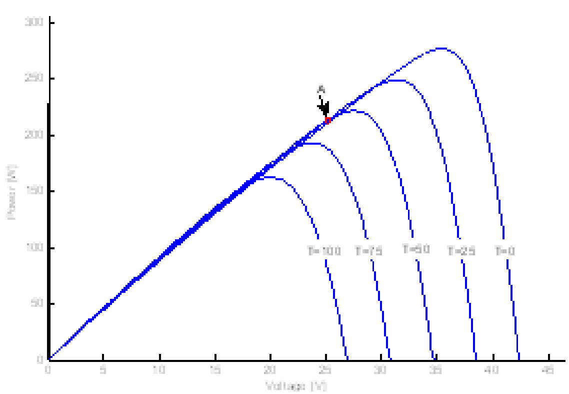

Figure 2: P-V characteristics for different temperatures showing interference between curves

distinctive characteristic curve for each temperature, some interference between these curves is exist. Assume at the startup of the system that the operating point is falling, for example, at the point **A** (for both figures). This point is falling on the curve of T = 25 ^{o}C, and in the same time it is falling on the curve of T = 50 ^{o}C. Consequently, the estimator will be confused to decide which curve this point is belonging to. The other curves also have similar interferences. This is for just five curves, and for tens or hundreds of curves the situation is more complicated. Therefore, estimating the MPP could be a confusing task and may lead to a wrong estimation. That means temperature should be measured to distinguish between the curves in order to avoid wrong estimations. In this work, a novel method is proposed, where ANFIS is used to accurately estimate the MPP. A temperature with voltage and current sensors are included to eliminate the need for solar irradiance sensor in order to solve the problems of pyranometer and the confusing points discussed above, and in the same time, to have more accurate MPP tracking.

3. The Proposed MPPT System

The proposed MPPT system (shown in Figure 3) contains two parts; an ANFIS estimator to determine the optimal reference voltage (V_{MPP}), and a closed-loop PI compensator to bring the operating point of PV module to this V_{MPP} by adjusting the duty cycle of DC-DC converter. Buck converter is used in this work. The ANFIS has three inputs; voltage (V_{pv}), current (I_{pv}) and temperature (T_{pv}) of PV module. The training data should be collected first in order to train the ANFIS. There are two possible ways to collect training data; either by collecting data from the real-time system, or from simulation by developing an accurate dynamic model for PV module. Collecting data from the real-time system was very difficult due to the fluctuating nature of weather and the inability

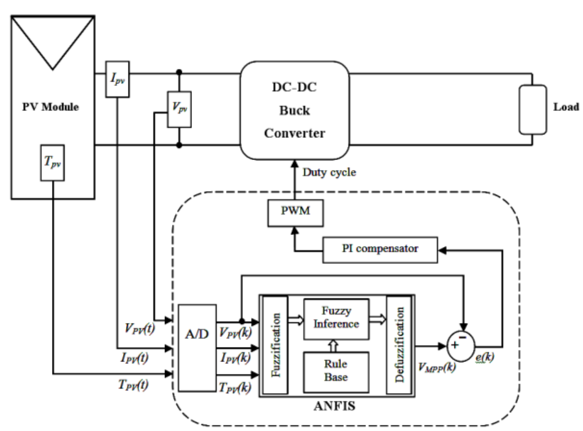

Figure 3: Block diagram of the proposed MPPT system

to the fluctuating nature of weather and the inability to control the weather conditions. Therefore, the training data were collected in this work from simulation after the development and validation of dynamic model for the utilized PV module.

The equivalent circuit of PV cell is shown in Figure 4. It includes a photo-current source, a diode, a series resistor (R_s) and a parallel resistor (R_p). The equation describing the current I produced by PV module is given by [13, 14]:

$$I = I_{ph} - I_0 [\ \exp(\ (V+R_sI)/mV_{th}\ ) - 1] - (V + R_sI)/R_p \quad (1)$$

Two parameters R_s and R_p remain unknown in (1). Some different ways have been proposed in the literature to mathematically determine these resistances. In this work, an iterative method proposed in [14] is used for adjusting R_s and R_p. The PV module used in this research is SM-250MH1. The parameters of this module obtained from its datasheet and computations are listed in Table 1.

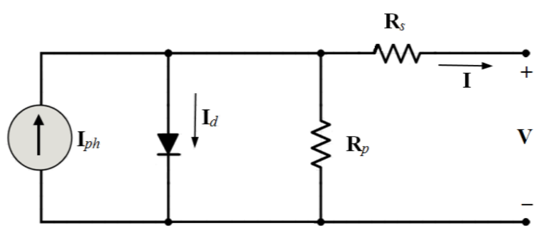

Figure 4: Equivalent circuit of practical PV solar cell

The Matlab ANFIS editor was used to create, train, and test a Sugeno type fuzzy system. The training, testing and checking data were loaded first to the editor. These data have a matrix form in order to be usable by the ANFIS editor. This matrix contains four columns. The first three columns contain the input data (V_{pv}, I_{pv}, T_{pv}) and the last column contains the output data (V_{MPP}). After that, an initial FIS model was generated. This FIS was then trained using the hybrid optimization method which combines the least squares method and back propagation gradient descent method. The generated ANFIS model structure is shown in Figure 5. The generated FIS model was imported to the Simulink fuzzy block (Figure 6) to validate it. The validation results are shown in Figure 7 where the estimated values of MPP voltages are compared to the expected ones (computed offline by simulation) at the same atmospheric conditions. To quantify the difference between the MPP voltages estimated by the ANFIS

Table1: Parameters of SM-250MH1 solar module at standard test conditions (25 °C, 1000 W/m2)

Parameter	Value
Maximum power (P_{max})	250 W
Maximum power voltage (V_{MPP})	31.6 V
Maximum power current (I_{MPP})	7.92 A
Open circuit voltage (V_{OC})	38.7 V
Short circuit current (I_{SC})	9.13 A
Temperature coefficient of V_{OC} (K_V)	-0.40% / °C
Temperature coefficient of I_{SC} (K_I)	0.05% / °C
Number of solar cells (N)	60 cells
Equivalent series resistance (R_s)	0.296 Ω
Equivalent parallel resistance (R_p)	37.363 Ω

model and the expected ones, the mean squared error (MSE) and the maximum absolute error (MAE) are calculated. For the data sample used in the validation, the MSE and MAE are 0.013998 and 0.46567, respectively.

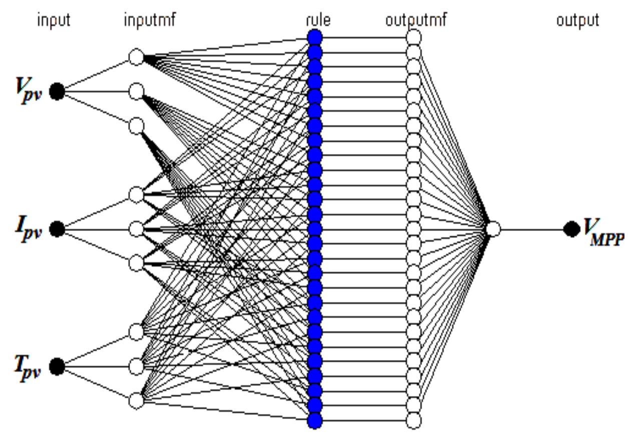

Figure 5: The proposed ANFIS model structure

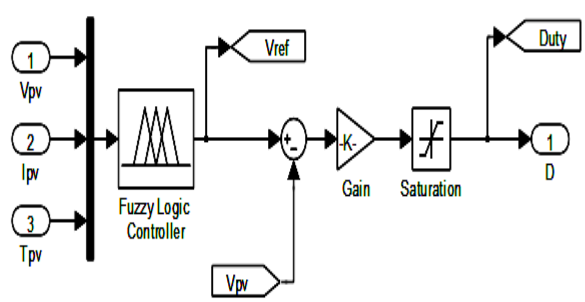

Figure 6: Simulink model of the proposed MPPT control system

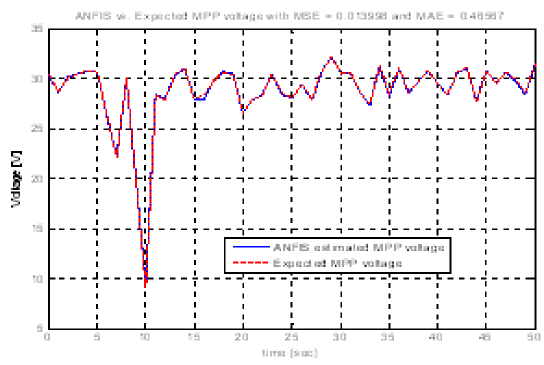

Figure 7: The ANFIS estimated vs. expected MPP voltage

4. Simulation Results

In this section the simulation results are presented and discussed. Matlab/Simulink is used to achieve these simulations. The overall Simulink setup of the PV power system is shown in Figure 8. The system is validated at different weather conditions. In Figure 9, it can be noticed that the MPPT controller closely tracks the MPP even with rapid changes in irradiance.

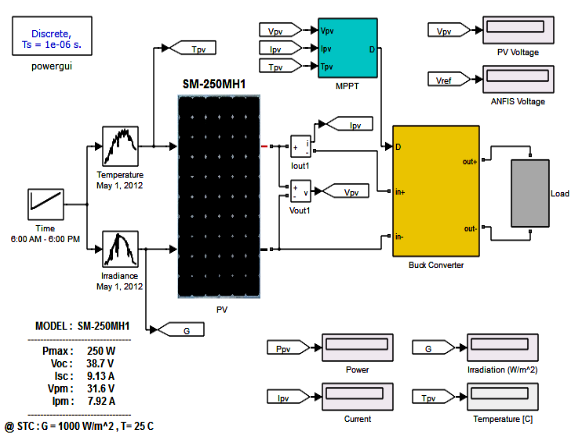

Figure 8: overall Simulink setup of the PV power system with MPPT

Since the solar irradiance waveform applied to the system (as shown in Figure 9) is linear, which is not practical, a real data of irradiance and temperature for one day (from sunrise to sunset) obtained from data logging system are used to validate the proposed system. The curves of tracked maximum power using the real data of irradiance and temperature for clear and cloudy weather days are shown in Figures 10 and 11, respectively. To investigate the proper

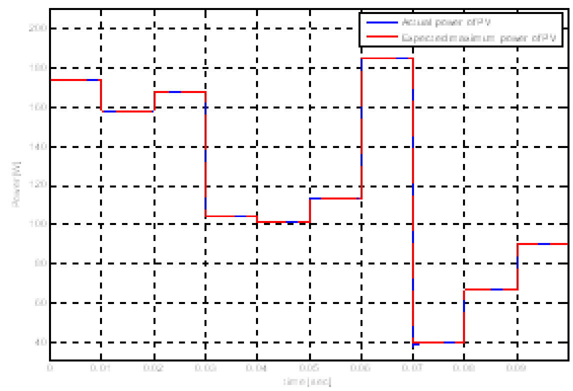

Figure 9: Simulation response of MPPT system with rapid step changes in irradiance

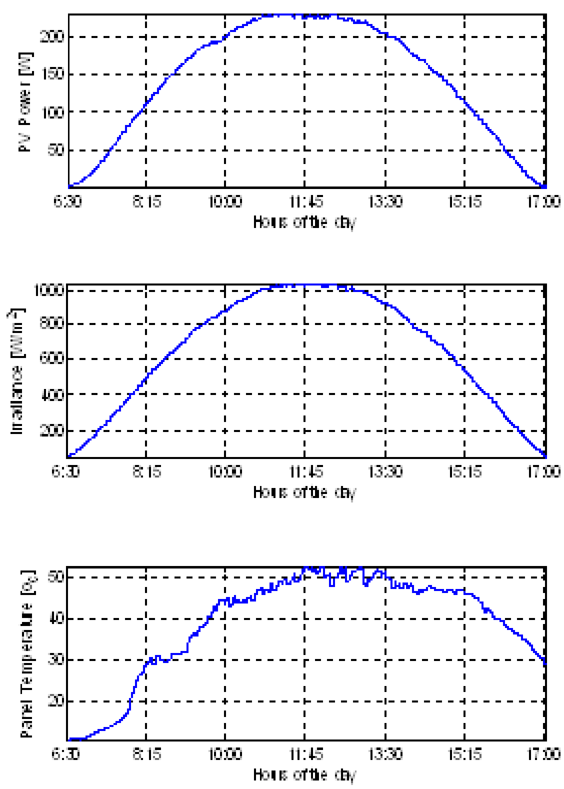

Figure 10: Simulated maximum power tracking using real data for a clear weather day from 6:30 AM to 5:00 PM

functionality of the tracking system, the tracked power is compared with the expected (computed offline by simulation) maximum power at the same weather conditions, and the results are superimposed

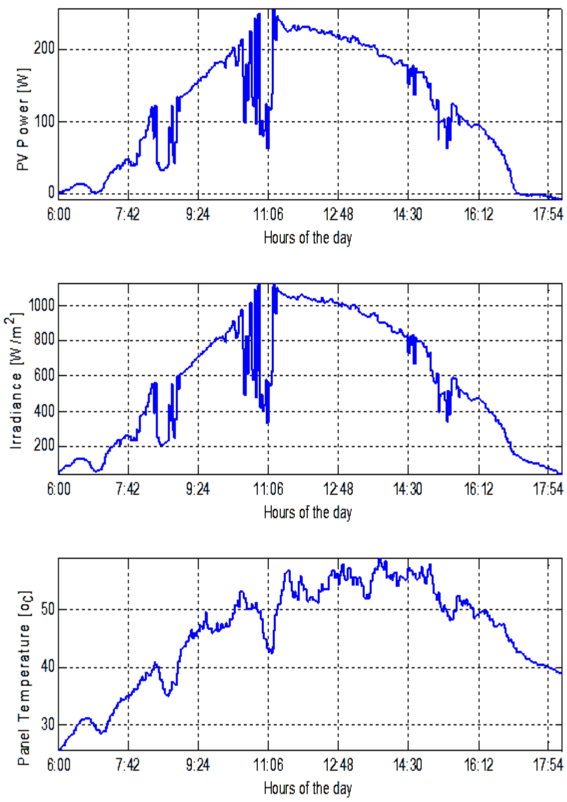

Figure 11: Simulated maximum power tracking using real data for a cloudy day from 6:00 AM to 6:00 PM

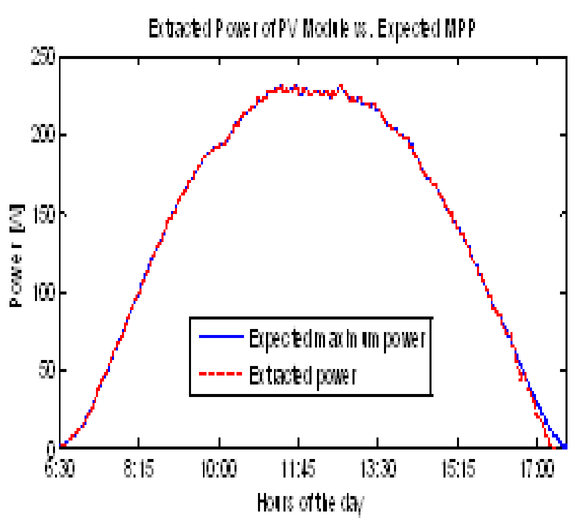

Figure 12: Validation of the simulated overall MPPT system using real data for clear weather day from 6:30 AM to 5:00 PM

in the same plot as shown in Figure 12. It can be noticed that the maximum power is extracted efficiently using the proposed MPPT algorithm.

The proposed algorithm versus P&O

The proposed method is compared with the P&O method due to its popularity. Figure 13 shows the extracted maximum power using the proposed algorithm versus the P&O algorithm. It can be noticed that the proposed algorithm has a faster response than the P&O. Moreover, there are no oscillations in the steady state of the proposed algorithm which improves the power conversion efficiency and greatly reduces the power loss that degrades the P&O and all hill-climbing based algorithms.

Efficiency of the proposed MPPT algorithm

To quantitatively measure the efficiency of the proposed MPPT system, the following equation is used [15]:

$$\textit{Efficiency of MPPT} = P_{pv} / P_{max} \qquad (2)$$

The efficiencies for some different power levels are calculated and tabulated in Table 2. It can be noticed that the efficiency is very high especially at high power levels.

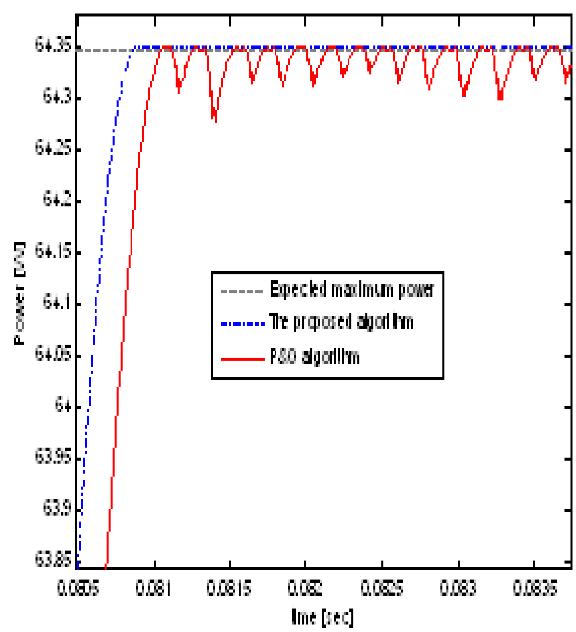

Figure 13: Comparison between the proposed algorithm and P&O

5. Experimental Implementation

Table 2: Efficiency of the proposed MPPT algorithm for different power levels

Available Power (W)	Extracted Power (W)	Efficiency (%)
231.623	231.51	99.951
213.528	213.48	99.978
195.990	195.98	99.995
100.565	100.26	99.697
75.900	73.14	96.363
30.379	29.39	96.744

The hardware implementation of the MPPT system and the experimental results are presented and discussed in this section.

Experimental Setup

The proposed algorithm is implemented using a dsPIC-6014A microcontroller from Microchip. It is a 16-bit digital signal controller. The chip has all the modules needed for MPPT implementation such as analog-to-digital converters (ADCs) to read the instantaneous signals from sensors, and pulse width modulation (PWM) module to generate the actuating signal of the DC-DC converter. Figure 14 shows the experimental setup of the project.

The built-in serial communication (RS232) is used to establish a connection between the microcontroller and the PC to log the MPPT data. A resistive load bank comprised of 13 20-watt ceramic resistors each of 33 Ω connected in parallel to obtain 2.5 Ω / 260 W (see Figure 14) is used to consume the produced power of the PV module.

Experimental Results

The experimental data were logged using a serial connection between the microcontroller and a PC using Terminal data logging software, and saved in a text file. The data were then exported into Matlab to be plotted. These data were captured on April 3, 2013 from 8:30 AM to 4:45 PM.

A cloudy day was chosen to test the robustness of the system to rapid changes in weather conditions. If the system passed the worst-case scenario test, it will absolutely pass the normal case test. Figure 15 shows the experimental results of the proposed MPPT system. These results are an evidence for the robustness and high speed of the MPPT system to track the maximum power point in a cloudy day with rapidly changing weather conditions.

To investigate the validity of the experimental results, the actual data of temperature and solar irradiance that influenced the real time system were imported into the Simulink model of the system. The system was simulated using these real input data, and

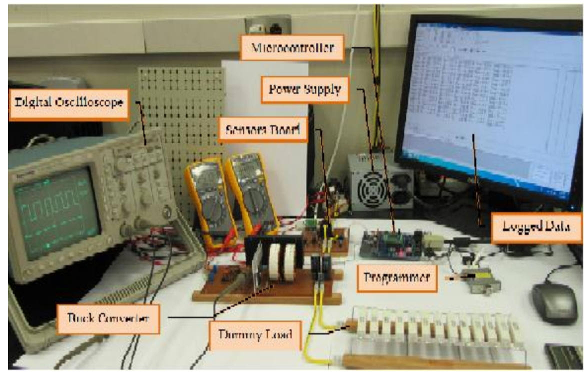

Figure 14: Experimental setup

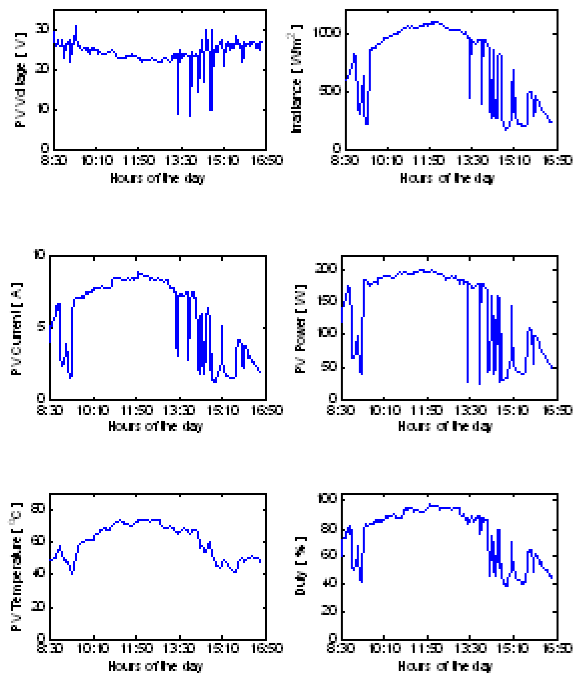

Figure 15: Experimental results for a cloudy day from 8:30 AM to 4:45 PM on Apr. 3, 2013

the simulation results were plotted. Figure 16 shows the results of simulation against the experimental results. It can be noticed that, to some extent, the results are close to each other.

The delay in the experimental results is due to the UART serial data logger delay, and the deviations between the results are due to small sensing errors. These errors can be improved by utilizing more accurate sensors. Furthermore, a solar irradiance simulator can be used to generate adequate training data for the real-time ANFIS estimator. Overall, the simulation and experimental results verify the functionality of the proposed algorithm.

6. Conclusion

In this project, a microcontroller based MPPT algorithm for PV system has been designed, simulated and experimentally implemented. The simulations have been run in Simulink environment. The response of the proposed algorithm has been analyzed under different irradiance conditions. The main contribution of this paper is increasing the accuracy of ANFIS estimations of the MPP when the solar irradiance is not included. Moreover, the hardware implementation of the proposed system has been achieved. Cell temperature sensor has been used with voltage and current sensors to avoid estimation errors that may occur in the case of temperature changes. Simulation and experimental results have been presented validating the functionality of the proposed method. Experimental results have showed good agreement with simulation results. The efficiency of the proposed system has been evaluated. It has been found that the proposed system is highly efficient with average efficiency of more than 98 %. The proposed algorithm has been compared with the P&O algorithm. The proposed algorithm has improved the transient response as well as the steady-state response of the PV power system, where it has cancelled the power oscillations at the steady state and improved the tracking speed at rapidly changing weather conditions.

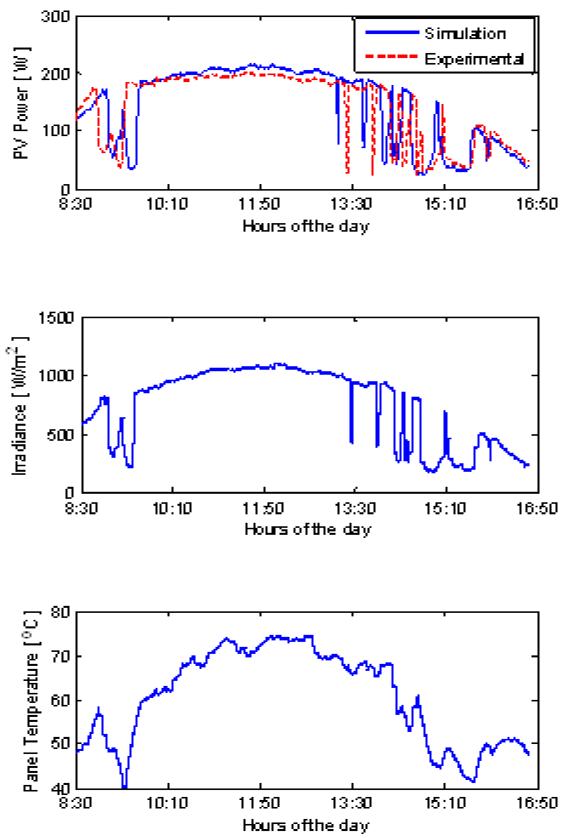

Figure 16: Validation of experimental results

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