Integrated Pyranometer For Photovoltaic Module Measurement

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***Abstract*—This paper presents the development of a handheld pyranometer which is integrated with temperature sensor modules using the application of Microcontroller PIC16F877A. The pyranometer employs a reference solar cell which is calibrated to measure the solar irradiance. Besides the pyranometer, two temperature sensor modules were introduced to measure ambient temperature and photovoltaic module temperature respectively. All measurements from the pyranometer and temperature modules were controlled by a Microprocessor PIC16F877A which provides programming strategy through basic C language. The algorithm was designed based on the calibrated solar cell and the temperature sensor modules and the measured values were displayed on an LCD display. The results show that the integrated pyranometer device has relatively similar measured values when compared to a commercial integrated pyranometer.**

Keywords-solar irradiance, pyranometer, ambient temperature, module temperature.

I. INTRODUCTION

Nowadays, there is a global need for a renewable energy sources which can provide a green energy that is safe to the environment and will last forever. One of the renewable energy is solar energy and now has been used in our daily life [1]. Solar energy actually has been harnessed by humans since ancient times which are using the technologies keep changing and evolving from time to time. This solar energy can be obtained directly from the sunlight that reaching the earth.

Solar energy usually being associated with photovoltaic (PV) system modules due to the large amount of sunlight received during the year. In order to use the solar energy power, photovoltaic (PV) systems were used to obtain the power from the solar energy. Photovoltaic (PV) system modules generally use solar panels to convert sunlight into electricity and an inverter to convert the direct current (DC) to alternating current (AC) so that it can use to supply energy to consumer [2]. The performance of photovoltaic (PV) modules is affected by several conditions such as solar irradiance, ambient temperature and module temperature [3, 4].

Recently, there are a lot of studies related to solar irradiance due to the wide applications of photovoltaic system. Solar irradiance is affected by several factors including time, latitude, cloud cover or clear sky condition, moisture in the air and temperature [5]. The measurements of solar irradiance are the important thing to estimate the power generation from the photovoltaic (PV) system and determining the correlations to the electric system loads [6]. Thus many technologies are developed to produce methods or devices that can measure the solar irradiance. In photovoltaic system, solar irradiance is the measure incident of the total amount of solar radiation transmitted to the surface of the solar cell in a given unit of time. This measurement is normally done in the units of watts per square meter (W/m^2) [7].

Solar irradiance is usually measured by pyranometers, solarimeters, or actinoraphy. Based on all the devices, pyranometer is always being used as a device in photovoltaic system application. Pyranometer is a type of device that used to measure the solar radiation flux density on a planar surface [8]. The type of solar irradiance sensor in the pyranometer should be accurate, stable and has the ability to withstand the outdoor environment.

Besides solar irradiance, the performance of photovoltaic system depends on its temperature. In general, higher temperatures will lower the performance of the photovoltaic system due to the efficiency factor [9]. Ambient temperature is one of the factors that influence on the amount of produced electric energy [10]. The module temperature will also affect the performance of the photovoltaic system. Every solar module built from many solar cells which generate electricity directly from the sunlight. The temperature will affect the I-V curve of the solar cell at the photovoltaic system. As the temperature of the solar cell increase, the open circuit voltage will decrease while the open circuit current will increase [11]. Therefore, the temperature of the solar module should be monitored and must be keep it always cool to get the maximum current output [10]. The module temperature sensor for this project can be attached at the solar module as the temperature monitoring device.

Many existing pyranometers do not integrate with the temperature measuring device. Therefore this issue had led to develop an integrated pyranometer that can measure the ambient temperature and solar module temperature.

This paper presents the development of integrated pyranometer which is used to measure solar irradiance (W/m^2), ambient temperature (^oC) and module temperature (^oC). These values would assist the user to estimate the photovoltaic (PV) module performance.

II. METHODOLOGY

There are five (5) methods that being used to develop this integrated pyranometer. The first method is the callibration of the solar cell followed by the temperature sensor selection, hardware and PIC algorithm development, and lastly the performance analysis and evaluation.

A. Calibration of Solar Cell

In this project, a polycrystalline solar cell (6V/100mA) being connected to a resistor (100Ω) is used to measure the solar irradiance. This solar cell supposed to feed the resistor by a certain current and voltage under a certain solar irradiance and ambient temperature. However, the solar cell current can be relatively measured by measuring the resistor terminal voltage as follows,

$$P_{CELL} = P_R * \eta_{WIRE} \tag{1}$$

Where P_{CELL} is the power generated from the solar cell at a specific solar irradiance, P_R is the power dissipated in the resistor and η_{WIRE} is the wire efficiency which is the losses. Assuming the loss is too small, then

$$I_{CELL} = I_R \tag{2}$$

This leads to

$$I_{CELL} = V_R * R \tag{3}$$

According to (3) the solar cell current is linearly proportional to the resistor terminal voltage and consequently the resistor terminal voltage is linearly proportional with solar irradiance. The solar irradiance is measured at the same time when the terminal voltage of the resistor which is connected to the solar cell been measured using a commercial pyranometer.

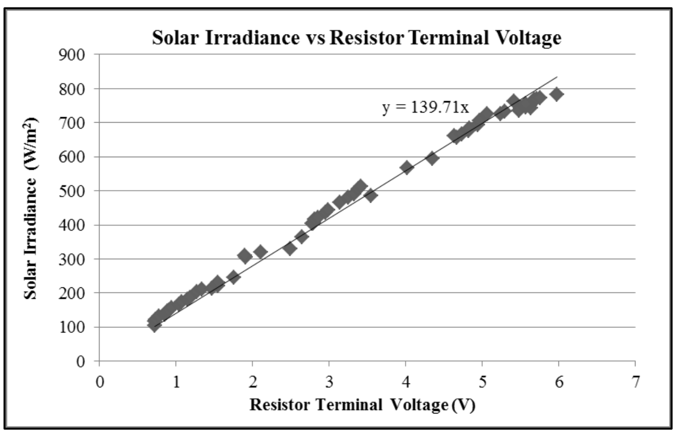

Figure 1. Relation between Solar Irradiance and Resistor Terminal Voltage

Fig. 1 shows the linear regression that suggested to fit the recorded data. From the figure, the relation between the resistor terminal voltage and the solar irradiance is linear and can be described as follows

$$G = 139.71V_R \tag{4}$$

Where G is the solar irradiance and V_R is the resistor terminal voltage.

B. Temperature Sensor Selection

The temperature sensors were selected based on the factors that affect the photovoltaic system which is involving ambient temperature and the module temperature. Thus LM35 Precision Centigrade Temperature Sensor was selected as the ambient temperature and DS18B20 Programmable Resolution 1-Wire Digital Thermometer being selected as the module temperature sensor. The LM35 sensor is a precision temperature sensor which the output voltage is linearly proportional to the Celsius (Centigrade) temperature. The DS18B20 digital thermometer provides 9-bit to 12-bit Celsius temperature measurements and it communicates over a 1-Wire bus that requires only one data line for communication with a microprocessor.

C. Hardware Development

In this project, there are five (5) main parts of hardware consisting solar cell, digital thermometer sensor, an ambient temperature sensor, Microcontroller and LCD as a display.

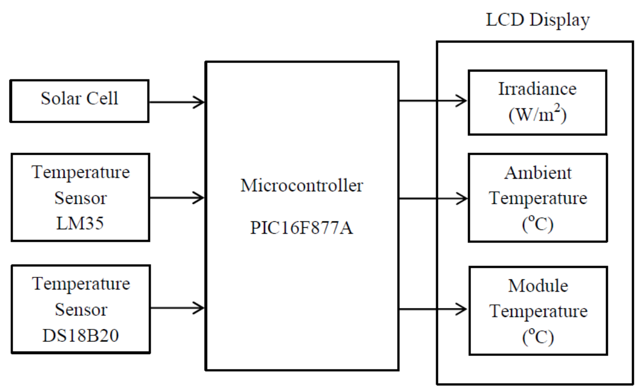

Figure 2. System Block Diagram

Fig. 2 shows the system block diagram of this integrated pyranometer project. PIC16F877A is a microcontroller operated based on program created by using MPlab software and it interfaces with a solar cell and two temperature sensors. The measurement of solar irradiance is based on the terminal voltage of the resistor which is connected to the solar cell itself. The terminal voltage of the resistor will give the analog voltage input for the analog-to-digital converter (ADC) port on the microcontroller. Analog-to-digital converter (ADC) is to read the analog voltages in the form of a digital representation. The LM35 temperature sensor which is used to measure the ambient temperature was also using analog-to-digital converter (ADC). Another temperature sensor that being used in this project is DS18B20 programmable resolution 1-wire digital thermometer. This type of sensor was connected to the digital input port on the microcontroller. All the inputs will be processed by the microcontroller and the measured output of solar irradiance, ambient temperature and module temperature will be displayed on an LCD. Fig. 3 shows the prototype of the integrated pyranometer after all the hardware has been assembled become a device.

Figure 3. Integrated Pyranometer Prototype

D. PIC Algorithm Development

All the data or results that been taken when doing the experiments of calibration of solar cell and sensors been collected and recorded in order to develop the PIC algorithm. Then the data was processed to obtain graphs, equations, and other important things that can be used in the development of PIC algorithm. PIC16F877A will be used as the microcontroller to control the input and the output of this project which can be programmed by using MPLAB software.

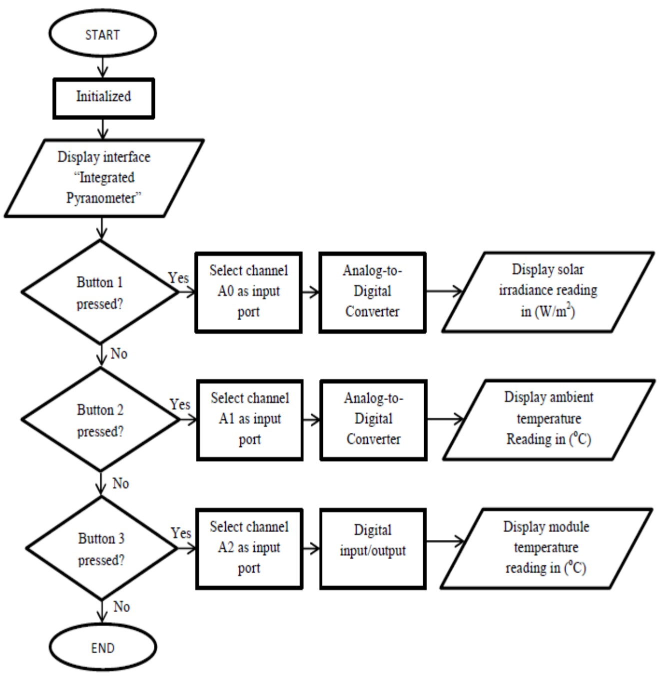

Figure 4. PIC Algorithm Flow Chart

Fig. 4 shows the flow diagram of PIC algorithm development. The program begins with the initialization of the input port for sensors and buttons, and output port for LCD. Then there will be a display interface after the initialization process. Next it will check every button if there is a button was pressed, then it will select the channel or input port before going to analog-to-digital converter or digital input/output. Finally the data of the input will be processed and being displayed.

E. Performance Analysis and Evaluation

After the prototype is prepared, it will be tested and evaluated following the objectives of this project. The problem of the prototype is determined by doing the testing and debugging process and been solved to reach the objectives of the project. A field-test for solar irradiance measurement being performed using the prototype and other commercial pyranometer. The performance analysis will be evaluated based on the reading of the solar irradiance (W/m^2), ambient temperature (^{o}C) and module temperature (^{o}C). From the result, the functionality and the accuracy of the prototype can be determined. The error of the measured values being determined by calculating the absolute error and the percent of error. The coefficient of determination was used to determine the goodness of fit of the regression which mean how good the performance of the integrated pyranometer compared to commercial pyranometer.

1) Absolute Error and Percent of Error

The difference between the measured value of a quantity x_0 and its actual value x, given by

$$\Delta x = |x_0 - x| \tag{5}$$

The percentage difference between the measured value of a quantity x_0 and its actual value x, given by

$$Percent\ of\ Error = \frac{|x_0 - x|}{x} \times 100\% \tag{6}$$

2) Coefficient of Determination

The coefficient of determination is to measure the goodness of fit of the model by calculating the proportion of measured variable values with actual variable values. Denote y_i as the observed values of the dependent variable, $\bar{y}$ as its mean, and $\hat{y}_i$ as the fitted value, then the coefficient of determination is

$$R^2 = \frac{\sum(\hat{y}_i - \bar{y})^2}{\sum(y_i - \bar{y})^2} \tag{7}$$

III. RESULTS AND DISCUSSIONS

A field test was performed to compare the reading value of the integrated pyranometer prototype with the commercial pyranometer. The first test is to determine the relation of short circuit current with the solar irradiance of this integrated pyranometer as shown in Fig. 5. The value of the solar irradiance is determined from the value of open circuit current. Thus the relation of short circuit current with the solar irradiance should be in linear regression. The figure also shows the coefficient of determination of the linear regression and it is good because the value is near to unity value which is 1.

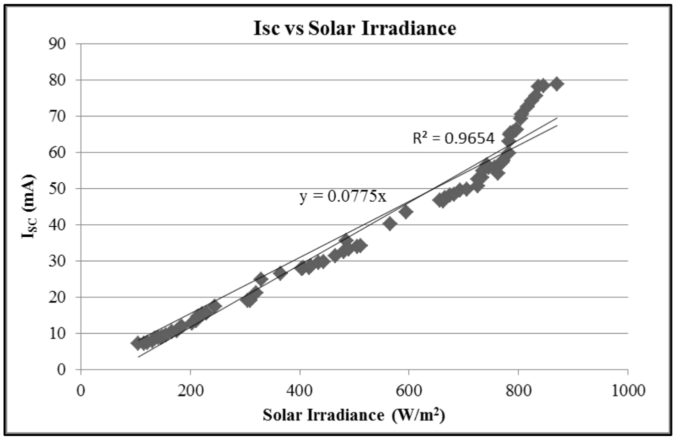

Figure 5. Relation between Isc and Solar Irradiance

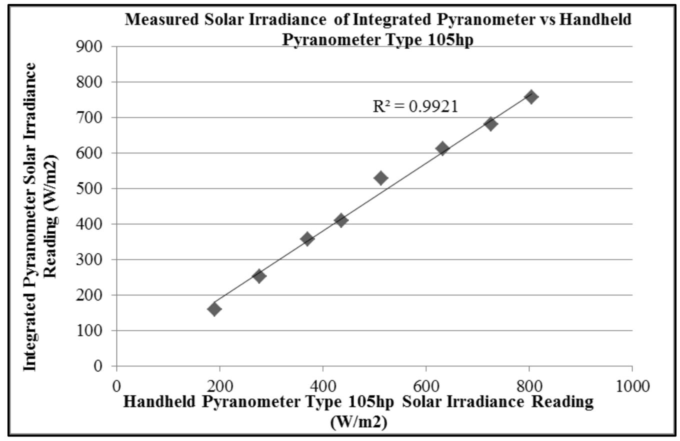

Figure 6. Comparison of Solar Irradiance Measured by Integrated Pyranometer and Handheld Pyranometer Type 105hp (SolData Instruments)

Table I shows the comparison of solar irradiance reading between the integrated pyranometer and Handheld Pyranometer Type 105hp (SolData Instruments). There are also the percentages of error between the two (2) readings and the highest percentage of error is at lowest solar irradiance reading. The percentage of error shows that the integrated pyranometer gives a relative difference in solar irradiance reading compare with the commercial pyranometer.

TABLE I. COMPARISON OF SOLAR IRRADIANCE READING BETWEEN INTEGRATED PYRANOMETER AND HANDHELD PYRANOMETER TYPE 105HP (SOLDATA INSTRUMENTS)

Type of Pyranometer	Integrated Pyranometer	Handheld Pyranometer Type 105hp (SolData Instruments)	|Error (%)|
Solar Irradiance (W/m^2)	159	190	16.32
	252	277	9.03
	358	370	3.24
	410	436	5.96
	528	513	2.92
	612	633	3.32
	682	725	5.93
	758	805	5.84

A typical calibration graph which shows the comparison of the measured values between the Integrated Pyranometer and Handheld Pyranometer Type 105hp (SolData Instruments) is shown in Fig. 6. In order to examine the goodness of fit between the integrated pyranometer and the Handheld Pyranometer Type 105hp (SolData Instruments), the solar irradiance readings were compared. There are very close readings between the two (2) devices which are shown by the coefficient of determination of the linear regression. The coefficient of determination of the linear regression is 0.9921 which is near to the unity value or 1. The better performance if the value of the coefficient of determination is near to unity value or 1.

Table II shows the result of the ambient and module temperature reading of the integrated pyranometer and the Handheld Pyranometer Type 105hp (SolData Instruments). There is a slight difference between the ambient temperature reading between the integrated pyranometer and the Handheld Pyranometer Type 105hp (SolData Instruments). Only integrated pyranometer has the reading of module temperature while the Handheld Pyranometer Type 105hp (SolData Instruments) did not have the module temperature reading because it was not equipped with the temperature sensor.

TABLE II. AMBIENT AND MODULE TEMPERATURE READING

	Irradiance Reading During Temperature Reading (W/m^2)	Integrated Pyranometer	Handheld Pyranometer Type 105hp (SolData Instruments)
Ambient Temperature (°C)	159	34	34
	252	34	34
	358	34	35
	410	35	35
	528	35	36
	612	36	37
	682	37	37
	758	38	37
Module Temperature (°C)	159	35	
	252	37	
	358	38	
	410	39	
	528	42	
	612	45	
	682	47	
	758	49	

IV. CONCLUSION

An integrated pyranometer has been designed, developed and applied to the photovoltaic system. It has been successfully to give the reading of solar irradiance, ambient temperature, and module temperature and display it on an LCD. Field test and comparison against the commercial pyranometer have shown fairly good accuracy in its irradiance reading. There are small errors due to the solar cell that's been used in this project but it is acceptable in a lot of photovoltaic applications.

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