Design and simulation of a low-cost solar irradiance meter for PV applications

Mohammed Rhiat1,2*, Mohammed Karrouchi1, Anas Hassari1,2, Mustapha Melhaoui3, Ilias Atmani1,2, Hanae Azzaoui2, Mostafa El Ouariachi1, Jamal Bouchnai1, Pascal Schmitz4 and Kamal Hirech1,2

1Higher School of Technology - LGEM Laboratory, Mohammed First University, Oujda, Morocco
2Higher School of Education and Training - ASPIL Laboratory, Mohammed First University, Oujda, Morocco
3Faculty of Sciences & Technics - LSEET Laboratory, Cadi Ayyad University, Marrakech, Morocco
4Solar-Institut Jülich, Aachen University of Applied Sciences, Jülich, Germany

Abstract. This work presents the design and simulation of a low-cost solar irradiance meter based on a PV cell that offers a cheap alternative to existing expensive solar irradiance instruments like pyranometers. Our proposed theoretical framework establishes a direct correlation between solar irradiance and the short circuit current of the photovoltaic (PV) cell. Through sophisticated simulations, we have demonstrated that solar irradiance levels can be accurately determined by measuring the voltage drop across the shunt resistor connected to the PV cell. This voltage differential is subsequently amplified and captured by the analog to digital converter of a microcontroller. The real-time results are then displayed on a Liquid Crystal Display (LCD), providing immediate feedback. The proposed system can be used to measure direct solar irradiance in solar applications to estimate the energy generated by PV panels.

1 Introduction

In recent years, the world has been witnessing a significant shift towards renewable energy sources as a sustainable solution to address the global energy challenge. Among these renewable resources, solar energy stands out as one of the most promising and abundant sources of clean power [1-3].

Understanding solar energy and its potential relies on precise measurement and monitoring of solar irradiance. Solar irradiance refers to the amount of solar radiation received per unit area over a given period. This crucial parameter directly influences the amount of energy that can be harvested from solar panels, making it essential for both research and practical applications in the field of solar energy [4,5]. Irradiance sensors can also help to identify any issues with the system, allowing the homeowner to take action before it becomes a bigger problem. Measuring solar irradiance provides knowledge to make important decisions on future energy yield, efficiency, performance, and maintenance [6].

* Corresponding author: mohammed.rhiat@ump.ac.ma
To measure solar irradiance, a variety of instruments are employed, such as pyranometers and pyrheliometers, which help quantify different components of solar radiation, including direct, diffuse, and global radiation. These instruments play a pivotal role in maintaining the accuracy and reliability of solar energy data. However, they are expensive and require special circuitry [7,8]. Hence, the importance of creating a cheap alternative data acquisition system for measuring solar irradiation.

This paper presents the design and simulation of a low-cost solar irradiation meter using a photovoltaic cell and amplifying circuit based on operational amplifier. This meter could be a good option in direct solar irradiance measurement.

2 Design and specification

The simplest model of a solar cell is the one-diode model illustrated in Figure 1, which is composed of a photovoltaic current generator $I_{PV}$, parasitic diode $D$, shunt resistor $R_{sh}$ and series resistor $R_s$ [9].

![Fig. 1. One diode model of a PV solar cell](image)

The relation between the voltage and current of such a cell is given by Eq. (1):

$$I_{cell} = I_{PV} - I_D - I_{R_{sh}} = I_{PV} - I_{sat}\left(\frac{V_{cell} + l_{cell}R_s}{\eta V_T} - 1\right) - \frac{V_{cell} + I_{cell}R_s}{R_{sh}}$$

(1)

Where $I_{sat}$, $\eta$ and $V_T$ are called the diode’s saturation current, diode ideality factor, and thermal voltage, respectively.

When the PV cell is short circuited ($I_{cell} = I_{sc}$, $V_{cell} = 0$), the expression of (1) become:

$$I_{cell} = I_{sc} = I_{PV} - I_{sat}\left(\frac{R_s l_{sc}}{e \eta V_T} - 1\right) - \frac{I_{sc}R_s}{R_{sh}}$$

(2)

If we take in consideration that $R_s \ll 1\Omega \ll R_{sh}$, the above expression is simplified further:

$$I_{cell} = I_{sc} = I_{PV}$$

(3)

The PV current $I_{PV}$ has a linear dependency with solar irradiance received by the PV cell with little influence from temperature. So, we can estimate the solar irradiance by connecting a shunt resistor of fairly low value to the PV cell and measure the voltage drop across that resistor. The microcontroller can’t directly measure the voltage difference, for that an amplifier circuit is also needed to make the signal large enough to be sampled by the Analog to Digital converter of the microcontroller, after that the calculated irradiance is displayed on
an LCD for easy monitoring. Figure 2 represents the block diagram of the data acquisition system.

![Block Diagram](image)

**Fig. 2.** Block diagram of the proposed solar irradiation meter

### 3 Simulation and results

Using the proposition mentioned earlier, we will try to simulate a circuit formed by a model of a solar cell connected to a shunt resistor and then amplify the voltage difference with a non-inverting amplifier. Unfortunately, manufacturers don’t include the values of parameters that form a solar cell \((R_s, R_{sh}, \ldots)\), they only provide certain points like short circuit current \(I_{sc}\), open circuit voltage \(V_{oc}\) and maximum power point voltage/current \((V_{MPP}/I_{MPP})\).

Despite that, we have managed to create a one-diode model that approximately simulates a PV cell using LTspice which is represented in Figure 3 from the following data at the standard test conditions (irradiance of 1000 W/m² and temperature of 25°C):

- Short circuit current \(I_{sc} = 300 mA\)
- Open circuit voltage \(V_{oc} = 750 mV\)
- Maximum power point current \(I_{MPP} = 270 mA\)
- Maximum power point voltage \(V_{MPP} = 0.63 V\)

![Diode Model](image)

**Fig. 3.** One diode model of a solar cell in LTspice

The simulated current-voltage (I/V) and power-voltage (P/V) characteristics of the PV cell for different irradiance values at 25°C are detailed in Figure 4. As we can see from current characteristics, the current of the PV cell \(I_{cell}\) is equal to short circuit current \(I_{sc}\) when \(V_{cell}\) is lower than 0.5V. This means that the value of shunt resistor \(R_1\) doesn’t need to be too small, in our case we chose \(R_1 = 0.1 \Omega\).
However, the voltage drop $V_{R_1}$ can’t be directly measured by a microcontroller since the majority of Analog to Digital (A/D) converters have low resolution and maximum input voltage of 5V, to fix that we’ve also added a non-inverting amplifier with a gain of:

$$G = 1 + \frac{R_3}{R_2} \quad (4)$$

At the standard test conditions ($Le = 1000W/m^2$ and $T = 25°C$), we can expect a current value of 0.3A that will create a voltage drop of 30mV, we’ve selected $R_2$ and $R_3$ so that $V_{out}$ will be 151 times greater than $V_{R1}$ without affecting the measurement thanks to the large input impedance of the OP Amp. The overall schematic of circuit in illustrated in Figure 5 below:

Figure 6 represents the simulation of the voltage drop $V_{R1}$ and the output of the amplifier $V_{out}$ as a function of time for difference values of solar irradiances. We observe that voltage is constant with respect to time for all solar irradiance values. At $1000W/m^2$, the voltage...
Drop $V_{R_1}$ is equal $30mV$ in the simulation, this is verified by theory mentioned before. We also see that $V_{out}$ is 151 times the value of $V_{R_1}$ for all solar irradiance values.

![Graph showing variation of $V_{R_1}$ and $V_{out}$ with respect to time for different solar irradiances.]

**Fig. 6.** Variation of $V_{R_1}$ and $V_{out}$ with respect to time for different solar irradiances

The following Figure represent the voltage drop $V_{R_1}$ and the output of the amplifier $V_{out}$ as a function of solar irradiance from $200W/m^2$ up to $1000W/m^2$. We observe that both voltages have linear dependency with solar irradiance.

![Graph showing variation of $V_{R_1}$ and $V_{out}$ with respect to solar irradiance.]

**Fig 7.** Variation of $V_{R_1}$ and $V_{out}$ with respect to solar irradiance.

As the output of the amplifier is connected to the input of Analog to Digital converter of the microcontroller, we can calculate solar irradiance by measuring the $V_{out}$ and inject it into
the line equation that relay solar irradiance with $V_{out}$. Using linear regression on the second graph of Figure 7 we obtain the following equation:

$$\text{Solar Irradiance (} W/m^2) = 221.53 \cdot V_{out} (V)$$ (5)

A small margin of 0.5V was left intentionally because solar irradiance can exceed 1000W/m$^2$ in some events.

4 Conclusion

In this article, we have detailed the design and simulation of a low-cost solar irradiance meter, presenting it as a viable alternative to its more expensive industrial counterparts. Through our extensive simulations using LTspice, we have demonstrated the feasibility of constructing a solar irradiance sensor using a low-cost solar cell, coupled to a simple amplifier circuit. The results demonstrate a linear correlation between the output voltage of the operational amplifier (OP Amp) and the incoming solar irradiance. This meter can be used for precise measurements of direct solar irradiation, facilitating accurate estimates of the total energy harnessed by a photovoltaic (PV) application, as illustrated in our study.

References