Nigerian Journal of Solar Energy, Vol. 25, 2014.

Comparative Study of the Performance of Silicon Solar Cell and Light-Dependent Resistor as Transducer Elements in Radiant Flux Measurement

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Abstract *- The study was undertaken to compare the performance of a light dependent resistor (LDR) to that of silicon solar cell in terms of their potentials as transducers for solar irradiance flux measurement. To achieve this, a solar panel and an LDR were exposed to solar radiation for a period of three days. For the LDR, the variation in its resistance in relation to the amount of solar radiation falling on it was studied while in the case of the solar cell; its incident solar irradiation is measured against its short circuit current on one hand and open circuit voltage on the other. The values obtained were modelled into appropriate transfer functions and there accuracy tested using R^2. The study found that the LDR has a near perfect exponential transfer function with R^2 of 0.99. This underlies its suitability as transducer for measuring solar flux. In the case of the solar cell, it was found that a good linear relationship also exist between the incident solar irradiance and the short circuit current with R^2 of almost unity. This is an indication that the solar cell is a good current transducer usable in measuring solar irradiance. The last finding showed that the solar cell has a good polynomial input/output relationship as a voltage transducer. Comparatively, due to the linear nature of the solar cell transfer function characteristics, it is to be preferred over the others.*

Keywords - transducer, solar irradiance, light dependent resistor, solar cell, transfer function

1. INTRODUCTION

The level of advancement in the field of electronics today can, to some extent, be attributed to the availability of quality transducers that enable the transformation of energy from one form to another. Radio communication, computer engineering, instrumentation and control, measurements to mention just a few, involve one or more forms of energy transducers. Energy once converted into electrical quantity can be manipulated, stored and transferred from one place to another. Most electronics measurements involve the conversion of a physical quantity into a quantifiable electrical signal. Few of such measurements include temperature, light level, magnetic field strength, strain and sound intensity. In all these measurements a suitable sensor is used to transform such physical quantity into a corresponding electrical quantity in form of current, voltage, resistance or power. The output can be measured easily and it is calibrated against the input, thus enabling the measurement of the value of the input. The performance of these sensors can be assessed based on accuracy, span, linearity, calibration, updatability etc. (Khemani and Stonecypher, 2009).

LDRs or Light Dependent Resistors are devices whose resistance changes according to the light intensity falling on it (Seymour, 1981; Theraja and Theraja 2002). This property of the LDR is as a result of the light energy creating free electrons from the semiconductor device leading to increase in its conductivity (Seymour, 1981). Normally the resistance of an LDR is very high, but when it is illuminated with light, resistance drops dramatically (Ryan, 2002). The photo resistor or light dependent resistor is very useful in many circuits such as photographic meters, flame or smoke detectors, burglar alarms, card readers, controls for street lighting and many others. A solar cell which is also known as photovoltaic cell is used to convert solar energy into electrical energy. Solar cells are basic elements of a solar module (also known as a solar panel). Silicon is by far the commonest of a variety of semi-conductor material from which solar cells are made (Seymour, 1981). Though, the two elements are popular transducers, there is no record of their use to measure radiant solar flux. The general aim of this paper is to carry out a comparative study of two elements that may be used in the measurement of solar flux by exploring and comparing the suitability of light dependent resistor (LDR) and solar cell as transducer elements for measuring radiant flux.

2. METHODOLOGY

The experiment is segmented into two parts; the first part investigates the relationship between the variations of the resistance of an LDR to that of solar radiation falling on it while the second experiment investigates

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the relationship of incident solar radiation on silicon solar cell and the corresponding short circuit current and open circuit voltage of the solar cell. The two experiments were performed concurrently at the premises of the Energy Research Centre of the Usmanu Danfodiyo University, Sokoto from the 15th to 17th of October, 2012.

2.1 LDR Measurement

The LDR is more or less a passive component and the study was restricted to its variation in resistance as a result of incidence solar radiation. For the purpose of this experiment the major component used was the LDR device (LDR 55).

The components are the following:

1. LDR
2. Irradiance meter (Meteon serial number: 0708163: Made in Netherland) with a sensitivity of 18.63 μV/W/m^2
3. Ohmmeter
4. Connecting wines

The set-up of the experiment is as shown in Figure 1

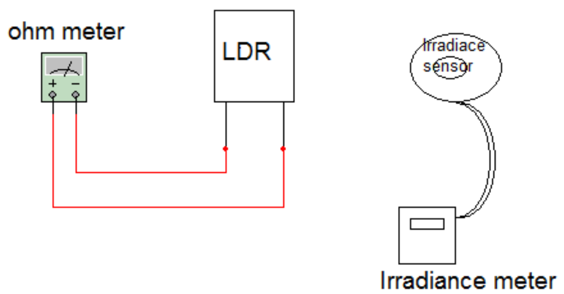

Fig. 1: LDR Experimental Set-up

The values of the solar radiation were taken at random intervals against the corresponding resistances of the LDR. The values were recorded and tabulated as the raw data.

2.2 Solar Cell Experiment

The aim of this second experiment was to, on one hand; compare the amount of solar radiation falling on a solar cell with the corresponding value of the short circuit current generated by the cell. This is the basic form of a light meter as indicated in (Gibilisco, 2002). Here, however we are interested in determining the open circuit voltage and short circuit current.

Consequently, for the second part of the experiments, the changing values of solar radiation falling on the solar cell were recorded against the open circuit voltage developed across the cell. The reason for taking the short circuit currents and open circuit voltages are that, these are the maximum values obtainable Christiana and Stuart (2014). The components used are:

1. Irradiance meter (Meteon serial number: 0708163: Made in Netherland) with a sensitivity of 18.63 μV/W/m^2
2. Digital multimeter
3. Connecting wires

The set-up for the experiment is shown in Figure 2 below.

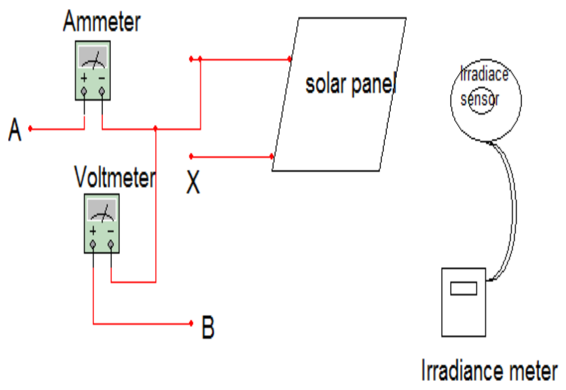

Fig. 2: Solar Cell Experimental Set-up

The irradiance meter sensor was placed at the same height and close to the solar cell so that they were exposed to the same amount of solar radiation. The digital voltmeters were connected as shown (Fig. 2) with one of the terminals not connected. The digital multimeters were labelled as A and B with A set to measure the open circuit voltage while B measured the short circuit current. When measuring voltages terminal A was briefly connected to terminal X and since the voltmeter has very high resistance the values obtained is mainly an open circuit one. During the measurement of the short circuit current the digital multimeter B was set to measure current range and was connected to point X of the solar panel. As the current meter has very low resistance it measured short circuit current. As a precautionary measure, the current meter was never allowed to be connected for more than 4 seconds as the wires were noticed to heat up due to the large short circuit current passing through. The values of the solar radiation as measured by the irradiance meter, open circuit voltages as measured by digital voltmeter and short circuit current as measured by the digital ammeter were recorded and tabulated from 6a.m to 8p.m for three days. The readings were taken randomly.

3. RESULTS AND DISCUSSION

The results obtained for the solar cell test and LDR test taken over three days were recorded and tabulated. The first set of results were those of the solar radiation against the corresponding values of the LDR resistances in ohms while the second set of values are those of solar radiation as measured by irradiance meter in watts/meter square (W/m^2) against the solar cell corresponding values of short circuit currents in amperes and open circuit voltages in volts.

To enable the values to be plotted using the Microsoft Excel package, the results were first arranged in ascending order of the solar radiation. The modified result was used to plot graphs of solar radiation against open circuit voltages and of solar radiation against short circuit currents. The third graph was that of the incidence solar radiation against the variation in LDR resistance. All the graphs were first plotted using scatter diagrams then lines of fit were tested using the Microsoft Excel to find the best. At each stance the modelled equations and R^2 values were compared. The results obtained were tabulated. The trend lines considered were linear, exponential, logarithmic, polynomial, and power.

The graph of the LDR resistance against the solar radiation falling on it is shown in Figure 3. A table showing the complete equations and R^2 values for all the lines of fit is shown in Table 1.

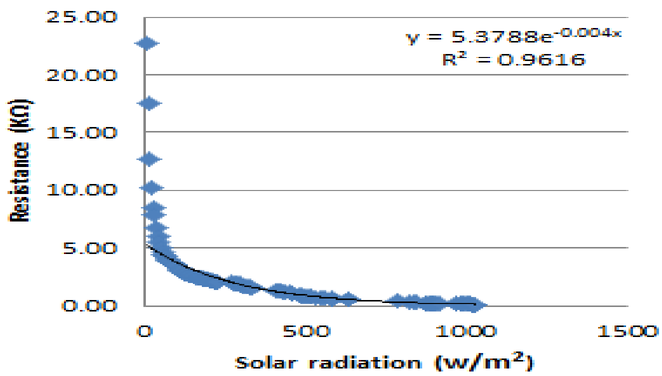

Fig. 3: Graph Of LDR Incident Solar Radiation against Its Resistance m^2

Table 1: Summary of the LDR trendline results

Trendline options	Equations	R^2 values
Linear	$Y = 0.0053x + 4.4991$	0.3559
Exponential	$y = 5.3788e^{-0.004x}$	0.9616
Logarithmic	$Y = 2.411lin(x) + 15.764$	0.7856
Polynomial	$Y = 2E - 15x^6 - 7E - 12x^5 + E - 8x^4 - 6E - 6x^3 + 0.0019x^2 - 0.27x + 16.443$	0.8934
Power	$y = 398.83x^{-0.014}$	0.8712

3.1 Solar cell (solar radiation vs current)

The graph of solar radiation incident on the solar cell against the generated short circuit currents is shown in Figure 4. The transfer function equation and R^2 value yielding the equation are tabulated in Table 2.

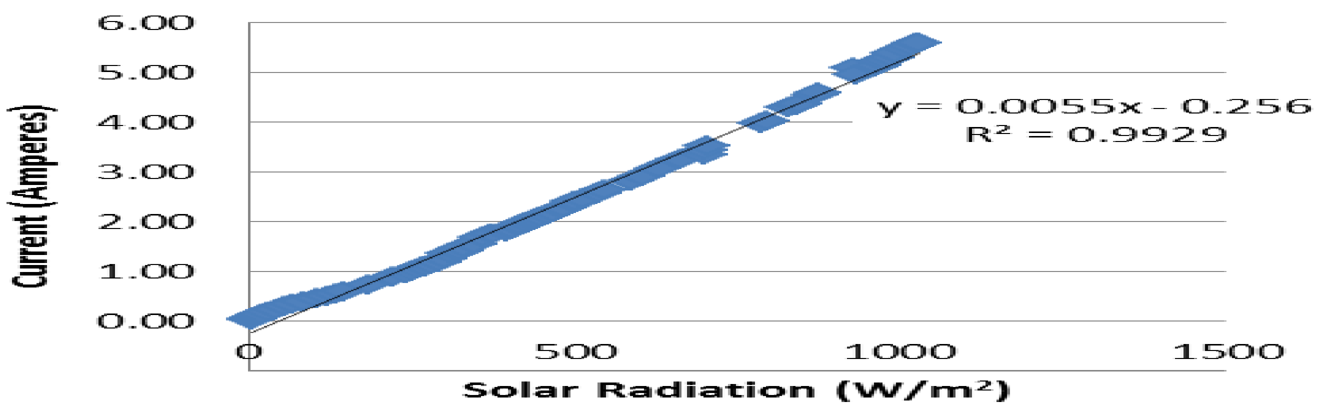

Fig. 4: Graph of Solar Cell Short Circuit Current Test

Table 2: Summary of the solar cell current trendline results

Trendline	Equations	R^2 values
Linear	$Y = 0.0055x - 0.256$	0.9929
Exponential	$Y = 0.3334e^{0.0032x}$	0.8068
Logarithmic	$Y = 1.1915\ lin\ (x) - 4.4752$	0.6447
Polynomial	$y = -8E - 17x^6 + 2E - 13x^5 - 3E - 10x^4 + E - 7x^3 - 3E - 5x^2 + 0.0061x + 0.0174$	0.9995
Power	$y = 0.0064x^{0.9515}$	0.6068

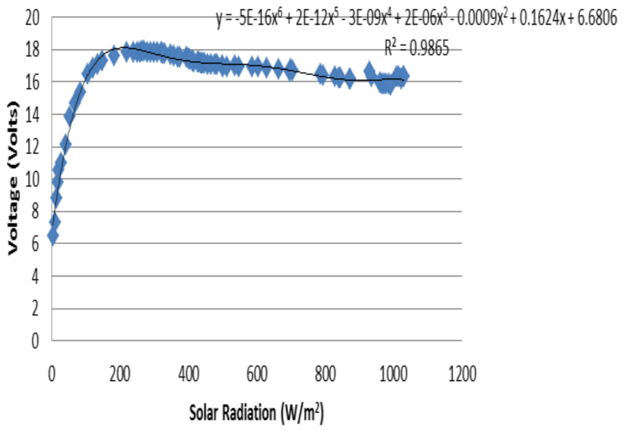

Fig. 5: Graph of solar cell incident radiation against voltage

Table 3: Best line of fit for solar radiation against voltage test

Trendline option	Equations	R^2 values
Linear	$Y = 0.0023x + 15.097$	0.0944
Exponential	$Y = 14.439e^{0.002x}$	0.1175
Logarithmic	$Y = 1.51lin(x) + 7.44$	0.5741
Polynomial	$Y = -5E - 16x^6 + 2E - 12x^5 - 3E - 0.9x^4 + 2E - 0.6x^3 - 0.0009x^2 + 0.1624x + 0.6806$	0.9865
Power	$Y = 1.56814x^{0.1264}$	0.6068

3.2 Span of the transducers

The solar cell and LDR result shows that the lowest values of solar radiation was zero which was recorded in the mornings and evenings and corresponds to dark period when sunlight was virtually absent while the highest solar radiation was recorded at around mid-day with a value of 1030 watts per square meter. These upper and lower limit values indicate the span of the possible transducer which is the dynamic range of the input quantity which, in this case, is the solar radiation. This range of the full scale input is the same for both the solar cell and that of LDR.

3.3 Full Scale Output

For the measurement of the full scale output swing of the LDR and solar cell it could be seen that the LDR has a value of 110Ω - 22700Ω. These values correspond to the algebraic difference between the electrical output signals measured with maximum input stimulus and the lowest input stimulus applied. While 22.7kΩ was the value of the resistance obtained at the lowest value of solar radiation, 110Ω corresponds to the value obtained with the maximum input solar flux which is 1030W/m^2. In the case of the solar cell, it is seen that the value of the full scale output is from 0.04A-5.59A for current while that of voltage is from 5.7V-16.29V. The implication of these full scale values is that during circuit design they must be taken into consideration. They may however be scaled down or up using appropriate circuit.

3.4 Transfer Function and Accuracy

The transfer function establishes the dependence between the electrical signal produced by the sensor and the stimulus (Bajpai and Gupta, 1986). For this purpose the results from the table were plotted and equations modelled from the corresponding lines of best fit.

LDR:-From the shape obtained for the LDR result as plotted in Figure 3 the highest value of R^2 with the best fit trend line is exponential with R^2 value of 0.99616 and an equation of $Y = 5.3788e^{-0.004x}$. This value of R^2 is almost 1 which is a measure of its accuracy with very little deviation. The LDR can therefore be said to be suitable as a sensor for detecting variation in solar flux and consequently usable as transducer for solar flux measurement. This value was followed by power trend line with modelled equation of $y = 398.83x^{-0.0041}$ and value of $R^2 = 0.8712$. Other values are even lower showing that if these equations are used the measured flux may have high error.

3.5 Solar cell as current transducer

From Table 2 it is seen that the best line of fit corresponds to a linear function (Boylestad and Nashelsky, 2002) with a modelled equation of $y = 0.0055x - 0.256$. It has an R^2 value of 0.9929. The high R^2 value obtained is an indication that it could be used as current transducer. The value of 0.9929 is reliable enough for high accuracy measurement. The power equation of $y = 0.0064x^{0.9515}$ with R^2 score of 0.9789 is also not too bad. But it is easier to use electronic component to design a circuit with linear function than the power function. Other values of R^2 are however too low to be considered as good transfer function of a reliable transducer.

3.6 Solar cell as voltage transducer

On the graph of Figure **5** it is seen that the line of best fit with the highest R^2 was the polynomial trendline with a transfer function of;

$$Y = -5E - 16x^6 + 2E - 12x^5 - 3 - 0.9x^4 + 2E - 0.6x^3 - 0.0009x^2 + 0.1624x + 0.6806$$

The R^2 value of 0.9865 is an indication that it could be used to accurately measure solar flux. The main problem with this; however, is that due to high powers in the equation; there could be different values of voltages for a particular solar radiation which might be confusing. Another factor that does not favour the use of solar cell as solar flux voltage transducer is that, as could be seen from Figure 5, the voltage was, at certain instances, decreasing when the solar radiation was increasing. This trend could be as a result of increase in temperature (Aminu *et. al*., 2013). The complexity in the circuit to realise the above function is another drawback for this type of sensor

3.7 Comparative Analysis of the Transducers

Table 4 summarizes the performances of the transducers under span, full-scale output, transfer function and the R^2 values for the chosen lines of best fit.

Table 4: Summary result of the performance of the transducers

Transducer	Span (W/m^2)	Output full-scale	Transfer function	R^2
LDR	0-1030	110Ω-22.7kΩ	$Y = 5.3788e^{-0.004x}$	0.9616
Solar Cell as current transducer	0-1030	0.04A-5.59A	$Y = 0.0055x - 256$	0.9929
Solar Cell as voltage transducer	0-1030	5.7V-16.29V	$Y = 5E - 16x^6 + 2E - 12x^5 - 3E - 0.9x^4 + 2E - 0.6x^3 - 0.0009x^2 + 0.1624x + 0.6806$	0.9865

In comparison, both the LDR and solar cell have the same range of input span of 0-1030Watts/m^2. In terms of the output full-scale range, the LDR has a resistance range of 110Ω to 22700Ω. This resistance may be converted to current or voltage for analogue deflection or digitized and displayed.The solar cell output voltage and current are also large with values of 5.7V-16.29V and 0.04A-5.59A respectively.

In terms of the transfer function, the LDR has an exponential relationship of $Y = 5.3788e^{-0.004x}$ between the input quantity (solar radiation x) and the resistance Y. The relationship between incident solar radiation and the developed short circuit current is a linear one ($y = 0.0055x - 0.256$). It is easier to develop a linear circuit as compared to other functions and on this base the solar cell circuit when used as a current transducer will be less complex. For a nonlinear transfer function, the sensitivity is not a fixed number as for the linear relationship Boylestad . and Nashelsky (2002). The solar cell when used as a voltage transducer has a transfer function that is polynomial:

$$Y = 5E - 16x^6 + 2E - 12x^5 - 3E - 0.9x^4 + 2E - 0.6x^3 - 0.0009x^2 + 0.1624x + 0.6806$$

It is obvious that the circuit to realize the above function would be very complex. In terms of accuracy, the solar cell when used as voltage sensor has the highest value but due to the complex nature of its circuit a great deal of error is expected to result from its circuit design. Meanwhile all the three cases considered have very good R^2 values an indication of their suitability for accurate solar flux measurement.

4. CONCLUSION

The study has found that both LDR and Solar cell could be used as transducer element for radiant flux measurement. The LDR was found to be a good resistance transducer while Solar cell could serve as either current or voltage transducer. The transfer function with the best correlation coefficient for the LDR was exponential in shape with the R^2 close to unity. In the case of the solar cell as current transducer the transfer function with the best R^2 was a linear one with R^2 value of almost one indicating that most of the points passed through the line of fit. In the last consideration with solar cell as voltage transducer it was found that the transfer function with the best line of fit is a polynomial type. The relationship though with very high R^2 value may not be too suitable in terms of circuit requirement.

RECOMMENDATION

Based on the outcome of this research work, it is recommended that further studies be carried out to determine the effect of other parameters, such as temperature, on the performance of the two components when used as transducers.

The results obtained may also be used to design circuits either practically or employing software simulation to ascertain their workability.

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