A simple resistive load I-V curve tracer for monitoring photovoltaic module characteristics

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***Abstract* - Current-Voltage (I-V) curve tracers are useful implements for solar Photovoltaic (PV) research and manufacturing, particularly when wishing to ascertain module yield viz-a-viz solar irradiation falling on the module in different climatic conditions. This paper presents a simple affordable and easy to fabricate instrument for tracing I-V characteristics of a PV module. It comprises of rapidly varying resistive loads centred on power resistors connected to relays and controlled by an electronic circuitry. The circuit consists of a 555 astable oscillator that is used to send clock pulses to the clock terminal of a 4017 decade counter which in turn produces a sequence of pulses. Each progression of pulse advances by one bit to sequentially turn on individual relays via driver transistors. The speed of the count is made variable from the frequency determining network of the 555 oscillator. The I-V characteristics of the module are thus measured by the sequential selection of the relays which are each connected to a selected load resistor to determine the operating point on the I-V curve. The currents and voltages are then recorded simultaneously with irradiance from a pyranometer, by a datalogger to which the instruments are connected. The circuit was tested on two monocrystalline modules to compare the effect of Harmattan dust on PV output yield.**

Keywords - Photovoltaic, current-voltage, resistive load, irradiance, module yield.

I. INTRODUCTION

The utility supply in Nigeria is usually epileptic due to the failure of the utility corporation to catch up with the growing electrical energy demands, inability to modernise existing and failing infrastructure as well as economic reasons. On how best to improve power supply and discard fossil fuel based energy supply, as well as mitigate climate change by reducing carbon emissions, discourse and efforts are on implementing renewable energy systems. One of the several areas in which Nigeria is endowed with renewables is solar energy. Awareness of the benefits of PV systems is growing albeit at a slow pace. As such the industry growth rate is sluggish in comparison to the advanced countries. Several reasons account for this. There is skepticism about the viability of the PV system because in some private installations, clients have been disappointed by its presumed unsatisfactory performance. This is due in large part to miscalculation or under sizing of the system by so called amateur contractors, who are either ignorant of, or may not have taken into account required knowledge of pertinent parameters such as accurate energy demand, daily and seasonal variation of irradiation, climate and weather patterns at a site, or even PV module yield characteristics. For example, in the town of Ota, (Long. 6.67˚N, Lat 3.16˚E), near Lagos in southwest Nigeria, the weather is mostly cloudy because of its proximity to the gulf of Guinea and the southwesterly tropical maritime (mT) monsoon airmass which transports moisture, cloudy and overcast weather conditions to the region during the rainy season months from April to October. During this period, almost all of the solar irradiance is diffuse radiation that affects the clearness index, K_T, a parameter used to determine the degree of clearness of the sky. The closeness of Ota to the coast situates it under the influx of sea salt and other types of aerosols sprayed from the Atlantic Ocean. The effect of dust is a particularly worrisome issue. During the dry Harmattan season from December to March, the

978-1-4799-2195-9/14/$31.00©2014 IEEE

southwest region lies in the path of the dry continental (cT) North East Trade winds which blow desert dust from the Sahara down south. Much of the dust accumulates and settles on PV modules. Ota is a municipal town that abounds with very inefficient vehicles spouting exhaust carbon monoxide fumes and smoke particles that contribute to urban haze. Also, there are many manufacturing factories within the area that emit carbon monoxide into the atmosphere. These observable meteorological and man-made occurrences of water vapour, aerosols and dust increase the turbidity of the atmosphere as well as attenuate most of the solar irradiance falling on solar PVs, consequently diminishing PV output yields [1]. Several research works have investigated the effect of dust on PVs. A correlation between thickness of dust collected on a PV module and its efficiency was determined [2] in India, while the impact of dust on the electrical parameters of monocrystalline and polycrystalline silicon modules was investigated in the sahelian region of Senegal [3]. There is a dearth of research work in this area in southwest Nigeria. Moreover, most modules imported into the country are second-hand used types that have degraded over time. It has been discovered that some modules, even when subjected to high clear sky radiation do not reflect the electrical characteristics on the labeling on the back panel.

II. OBJECTIVE

Covenant University, Ota, Nigeria, is considering investing in the renewable energy sector and for a start wish to utilize bioenergy and solar energy. It is about embarking on installing stand alone solar home systems for some individual residences. To inject money into the project, study of key parameters for sizing solar systems, especially the number of PV modules in relation to energy demands and clear sky conditions must be investigated. Importantly, the PV array size (peak wattage), W_{PV}, required for a stand-alone system at a site may be obtained from the peak current which is a function of peak sunshine hours [4], i.e.

$$W_{PV} = \frac{E}{G * \eta_{SYS}} (W_{PK}) \qquad (1)$$

where E is the daily energy demand in watt-hours, G, the average daily number of peak sun hours and η_{SYS}, the total system efficiency expressed as a factor (1 is 100%).

It then becomes necessary to develop efficiency models that allow the calculation of effectiveness of different modules under various climatic conditions at the campus of the university and in general, the southwest region of the country. Continuous measurements and collection of performance data is being carried out. The monitoring of these parameters is to create an informative database of performance indicators for module output yield for different seasons and weather conditions. It is therefore the ambition of the Department of Physics of the University to have a robust weather station with affordable measurement instruments. The Department had a Davis Wireless Vantage Pro2 weather station installed on its rooftop in April 2012. The weather station contains among others a suite of sensors for temperature, global solar radiation, relative humidity, rainfall, wind speed and direction, all combined in one package called Integrated Sensor Suite (ISS). A sensor interface module (SIM) collects outside data from the ISS and transmits the data to a Vantage Pro console via low power radio. The console incorporates a weatherlink software and USB datalogger that connects directly to a computer, continuously saved data record. At present, data from the station is logged at 1 minute intervals. It is on this premise that the department is seeking to augment the weather equipment with a simple design of an I-V tracer that is easily produced, to catch Harmattan data between December and March. In order to avoid the inconvenience of climbing to the roof top to turn a mechanical rheostat for measurements, the option of an electronic circuitry that logs data at regular intervals from about 10 a.m. to 5 p.m. is preferred. For testing the circuit, two monocrystalline modules in horizontal positions were used, one regularly cleaned and the other left to gather dust, in order to observe the effect of accumulation of Harmattan dust on the output yield.

III. MEASUREMENT OF CURRENT–VOLTAGE CHARACTERISTICS

Manufacturers of solar PV modules specify their I-V characteristics for the purpose of estimating power conversion yield for either solar home or grid tied systems or for some other research investigation. These characteristics are obtained in the laboratory under simulated and controlled Standard Test Conditions (STC) of light intensity (G =1000 W/m^2), temperature (t = 25˚C) and airmass (AM = 1.5) [5, 6]. But the conditions under which these values are achieved are usually different and difficult to reproduce from those obtained under varying natural atmospheric conditions [7] in which the module will function.

The testing and determination of true I-V module characteristics in field environments are usually obtained using I-V curve tracers. Several sophisticated brands are commercially available on the market but are very expensive. For example, the Daystar DS100-C product uses a capacitive load to vary the impedance connected to the output terminals of the PV array under test. Currents and voltages are sampled as the capacitors in the DS-100C are charged from 0 V to V_{OC}. Data sets are then transferred to a control computer for display, analysis, and storage using a Windows-based IVPC software that displays the PV parameters. Due to the exorbitantly high costs of these instruments, the Department of Physics decided to start off with building a simpler circuit with cheap and available components with the ultimate aim of improving the circuit. Different designs of low cost tracers have been reported in literature to monitor I-V characteristics. A method for the monitoring and control of the performances of the photovoltaic systems was proposed [8]. A Labview program was developed to sequentially activate Mosfets connected in series with load resistors to obtain I-V plots. A power Mosfet operating in its linear and active region as a fast varying dc load was employed [9, 5, 6] to trace PV module I-V and P-V characteristics. A Mosfet can operate as an electronically controlled load that moves the operating point of the PV module over the whole range of I-V curve [10]. The circuit thus provides the values of the I_{SC}, V_{OC}, and P_{MP}. The inclusion of electronic circuitry [11, 5, 6, 8] to measure currents, voltages and power using op amps improves the accuracy of the measurements.

The cheapest and easiest tracer to build is the resistive load type. With future upgrades using the [7, 11] design in mind, this paper presents the resistive load type which consists of several power resistors with values ranging from 0.1 Ω to about 100 Ω (Fig. 1) that are sequentially switched in rapid succession and in short duration to cover the range of I-Vs developed by the module. Each value of resistor then accounts for one operating point on the I-V curve.

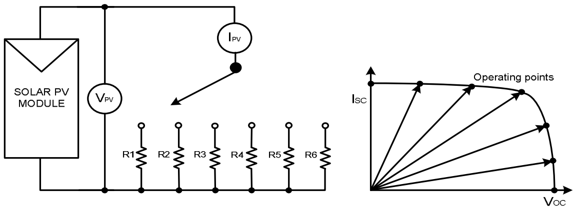

Fig. 1. Resistive load I-V curve measurement

IV. CIRCUIT DESCRIPTION

The block diagram of the circuit is shown below in Fig. 2. Figs. 3 and 4 illustrate the circuit schematics. It is intended that measurements be made every ten minutes, hence the adjustable interval timer for conducting sweeping cycles at desired time periods. The timer and the astable multivibrator are each derived from 555 timer ics but use is made of the 556 timer ic which houses two 555s in one package (Fig. 3). IC1A functions as the interval timer. RV1 determines the time for which the multivibrator, IC1B, remains on, while RV2 establishes the off time of the timer.

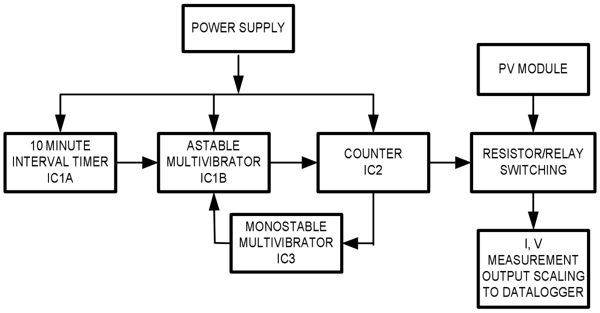

Fig. 2. Block diagram of the I-V curve tracer

At switch on, pulse sequences are initiated and sweep through the transistors, turning on the relays one after the other and connecting individual load resistors to the module. At the end of the final pulse, the astable is disabled by a monostable represented by IC3A, B, C until the timer goes off. More on this further on. At the end of the 10 minute intermission, the timer output pin 5 (IC1A) goes high toggling on the astable multivibrator (IC1B) via Q1 and Q2. LED1 should light up as a result indicating the on state of the timer. The high output at pin 5 is used also to first switch on the relay (LED 2 on) by means of Q5 to connect the PV module to the circuit, although no power resistor is connected as no load relay has been energised. This measures the open circuit voltage V_{OC} ($I_{SC} = 0$). This first pulse first appears at pin 3 of the 4017 but is not used, since it coincides with the logic high from pin 5 of IC1A. The square wave oscillations produced at pin 9 of IC1B are sent as clock pulses to the clock terminal of IC2, a 4017 decade counter ic. LED3 can be seen flashing, the flash rate and hence the speed of the count is determined by the frequency determining network R8, RV3 and C2 of IC1B oscillator. The sequence of pulses generated advance the 4017 outputs by a single bit one after the other and in this manner sequentially turn on individual relays via driver transistors. Since only six load resistors are used, then six output pins in sequence: 2, 4, 7, 10, 1, and 5 of the 4017 are utilized. As each relay energises, its contacts connect the module to a load resistor that is in series with the current sensing resistor, *r*. A rapid switching of the relays via transistors is essential to quickly take measurements because of the varying weather conditions, e.g. cloud movement. The set of relays shown in Fig. 4 is replicated for a second module such that each driver transistor powers two relays. As each load is selected and connected, current and voltage are generated. The I-V characteristics of the module are then measured. After the last pulse from pin 5 of the 4017, the next pulse appears at its pin 6. This pulse is used to switch on the monostable circuit formed by IC 3A, B and C via Q4. Once Q3 is switched on, its collector goes to ground thereby disabling the multivibrator and hence the counter from starting the sequence all over again and to hold them in the off state until the timer goes off. The moment the timer goes off, the PV module is disconnected from the circuit. The monostable circuit also prevents the count from ending up at any one of the switches.

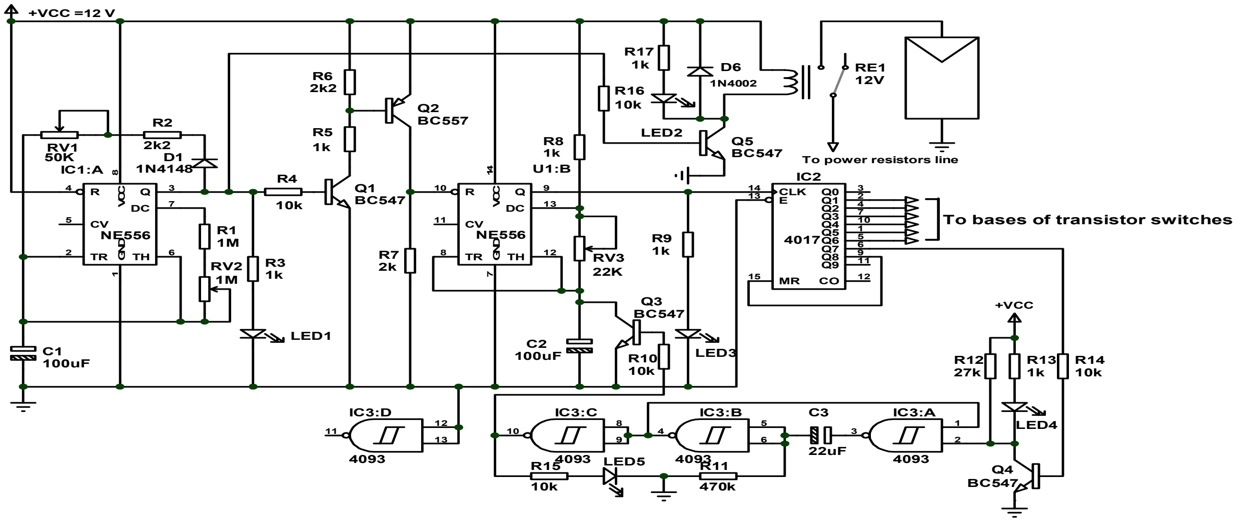

Fig. 3. Circuit diagram of the interval timer, astable and monostable multivibrators

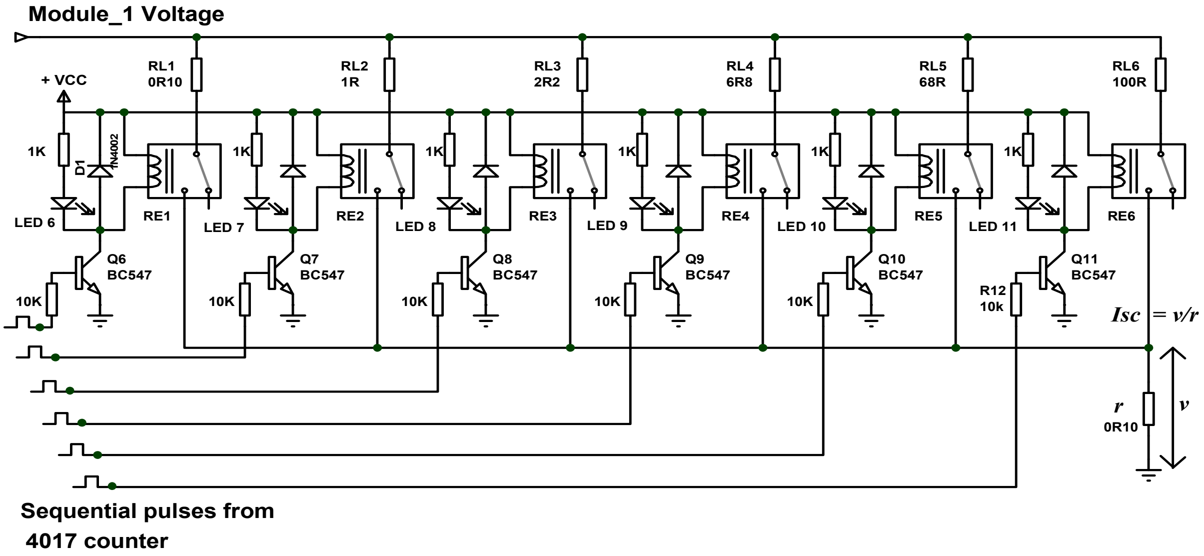

Fig. 4. Circuit diagram of switching driver transistors and load switching relays

V. EXPERIMENTAL RESULTS

The performances of two modules with similar standard electrical parameters, shown in Table 1 were evaluated with a prototype of the tracer. Fig. 5 shows the photo of the circuit board. The board was designed to accommodate two modules. Plots of I-V and P-V data retrieved from a Pace XR5 datalogger for 20th January 2014 are shown in Figs. 6,7 & 8. Six load resistors were switched in the circuit but from the I-V plots, extra points were observed on the curve. This observation may be attributable to the on time of each pulse or contact bounce of the relay contacts in relation to the sampling rate of the logger. In Fig. 4, the PV current passes through both the load (RL) and the current sensing resistor, r (= 0.1Ω). The current is then deduced by noting that

Fig. 5. Photo of the I-V curve tracer

$$I_{SC} = \frac{v}{r} \qquad (2)$$

where v is the voltage measured across the current sensing resistor, r. As the output voltage from the PV is higher than the permitted input to the datalogger, it is scaled down using a potential divider and then retrieved thereafter by multiplying with the calculated scale factor. The performance indicator of a PV module may be expressed by the following equations:

$$FF = \frac{I_{MPP} * V_{MPP}}{I_{SC} * V_{OC}} \qquad (3)$$

$$\eta = \frac{P_{OUT}}{P_{IN}} = \frac{I_{MPP} * V_{MPP}}{G * A} \qquad (4)$$

where *FF* is the fill factor, I_{MPP} and V_{MPP} are the current and voltage at maximum power respectively, η is the efficiency, G is the irradiance in W/m^2, the module dimensions being 840*541*35 mm ($A = 0.454\ m^2$). As shown in Table1, at 860 W/m^2, 16% and 14% reductions were observed in the short circuit current and maximum power respectively due to dust accumulation in a period of seven weeks between December 2013 and mid January 2014.

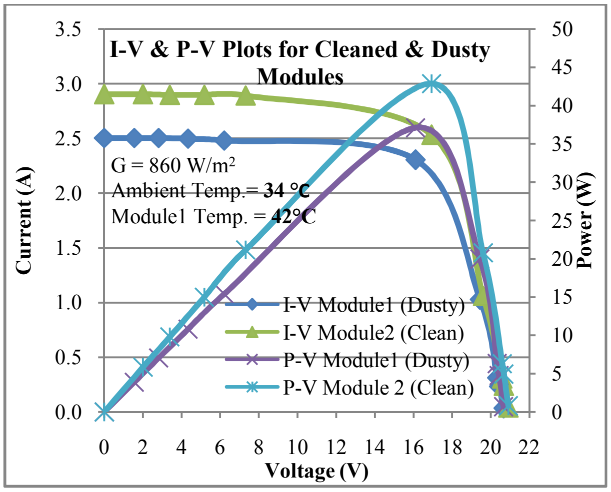

Fig. 6. I-V & P-V characteristics of the clean and dusty modules.

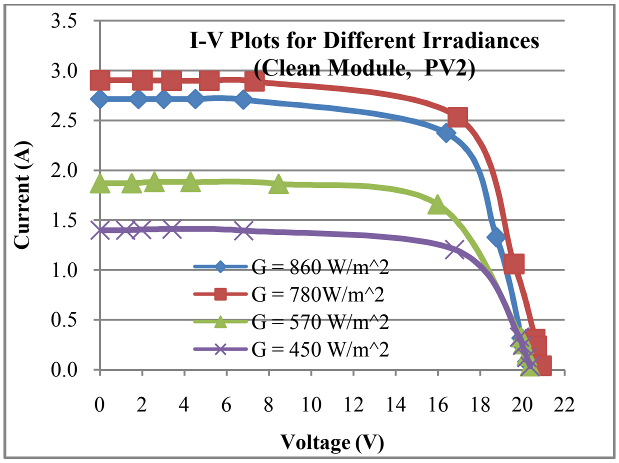

Fig. 7. I-V characteristics for different irradiances, G for clean module, PV2.

TABLE 1. Module rating & performance indicators

Module Rating Label, G = 1000 W/m^2					
	V_{OC} (V)	I_{SC} (A)	V_{MPP} (V)	I_{MPP} (A)	W_P (W)
PV1	22	4.8	18	4.45	80
PV2	22	4.8	18	4.45	80

Experimental, G = 860 W/m^2, Ave. PV Temp.= 42°C							
	V_{OC} (V)	I_{SC} (A)	V_{MPP} (V)	I_{MPP} (A)	P_{MPP} (W)	FF	η (%)
PV 1	20.6	2.5	16.1	2.3	37.0	0.7	9
PV 2	20.9	2.9	16.9	2.5	42.3	0.7	11

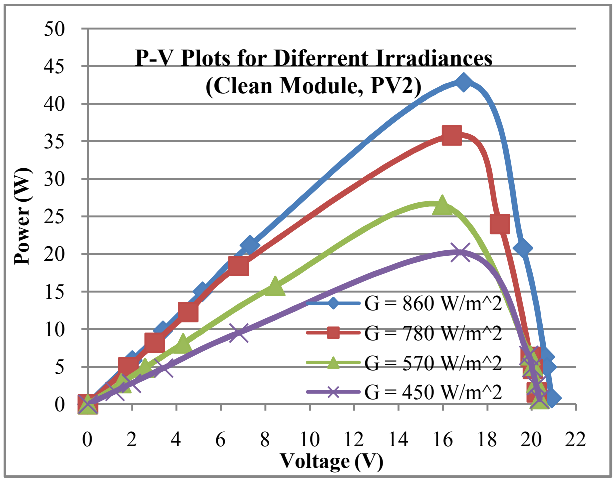

Fig. 8. P-V characteristics for different irradiances, G (clean module).

VI. CONCLUSION

The main objective of the paper was to present a simple design of an I-V curve tracer to meet the immediate needs of the Department of Physics in taking measurements of output characteristics of PV modules. I-V characteristics of two PV modules were measured and the power curve deduced. A few more load resistors may be added to the circuit to obtain more operating points with the aim of achieving a smoother curve. Improved upgrades will be made to incorporate a software interface. The improved designs will then be used to continuously monitor PV parameters and performance for different seasons in the region.

FUTURE WORK ON DESIGN

As a follow up, the authors are working on utilizing a single PIC microcontroller to execute the functions of the timer, astable multivibrator and the sequencer. The switching relay contacts are prone to bouncing and will be replaced by Mosfets with low R_{DS}. I_{PV} and V_{PV} measurements will be implemented by differential amplifiers and their outputs will be multiplied using the AD633 analog multiplier to obtain the output power, W_{PV} of the module.

ACKNOWLEDGEMENTS

The authors are grateful to the Covenant University Centre for Research and Development (CUCERD) for the provision of grants to purchase the equipment to facilitate the research. Special thanks also go to Williams Ayara of the Physics Department laboratory for his contributions towards the fabrication of the circuit board.

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