Simple and Accurate I-V Measuring Circuit for Photovoltaic Applications

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***Abstract*—Photovoltaic systems are recongnized as an important alternative among the renewable energy sources that will secure the availability of energy in future. The characteristics of any photovoltaic module can be drawn from its current – voltage curve. Since the module characteristic curve mainly affected by natural conditions such as solar radiation level and module surface temperature, it must be measured as fast as possible with acceptable accuracy at different operating conditions. The present paper presents an implement of a simple and accurate current – voltage measuring circuit for various types of photovoltaic modules based on an electronic load. The proposed circuit used a MOSFET transistor driven by a control signal to drive its gate to track the photovoltaic module current – voltage curve. The control signal generated by the analoge output of the data aqusition system and sweeps the gate – source voltages of the MOSFET to scan the module voltages from open circuit to short circuit values. The measured data as solar radiation, module temperature, module current and module voltage taken via a data acquisition system. The results showed the advantages of the proposed circuit in terms of accuracy, simplicity and reliability.**

Keywords—photovoltaic module characteristics; current – voltage measurement; MOSFET driving circuit; data acquisition system; isolation circuits.

I. INTRODUCTION

Rising oil prices, global warming, threat of terrorist attacks on oil industry, tense political environments in oil producing countries, and severe weather conditions have compelled many nations to look for alternative sources to reduce reliance on fossil based fuels. Solar energy is one of the most promising renewable sources that is currently being used worldwide to contribute for meeting rising demands of electric power [1]. It has been reported that solar photovoltaic (PV) is the fastest growing power-generation technology in the world, with an annual average increase of 60% between 2004 and 2009 [1]. A PV cell is defined as the semiconductor device that converts sunlight into electricity. A PV module refers to a number of cells connected in series and in a PV array, modules are connected in series and in parallel [2].

Power of a PV module depends on light intensity, module temperature, orientation of the panel and atmospheric conditions. The light intensity primarily affects the amount of produced current, and the module temperature controls the module voltage [3]. Even though the most important electrical characteristics of PV panels are evaluated and published under the standard test condition (STC, solar radiation of 1000 w/m^2, surface temperature of 25 ^{o}C), under real operation conditions (i.e., varying light intensities as well as large temperature excursions) most panels do not behave as given in the data-sheets [4].

I–V characteristics of a PV cell, module or array is the important key for identifying its quality and performance as a function of varying environmental parameters such as solar radiation and ambient temperature [5]. The curve indicates the characteristic parameters of the PV generator represented in short circuit current, open circuit voltage and the point of maximum power at which the generator would work at its peak efficiency. These parameters are indispensable for designing any small or large PV power system. Moreover, the curve renders determining the equivalent circuit components of the PV generator represented in the series resistance and shunt resistance, which are disclosure parameters for classifying the quality of the generator substrate material. Therefore, it is of prime importance to measure the I–V characteristics with high accuracy under natural environmental conditions [6].

The monitoring process of the PV devices involves mainly the recording of the I-V characteristics as a function of time. Indoor testing of the PV cells performed under STC leads to an overestimation of its electrical output. More important, the accelerated indoors tests sometimes do not reveal problems which come out during the operation under field conditions [7]. Therefore, the testing procedure of the PV modules under field conditions provides very useful information on the real performance and on the possible degradation effects of the devices. The PV module has to be tested under real conditions

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in different places corresponding to different climatic conditions with varying solar radiation and ambient temperatures.

There are many researches deal with the measurement of the I-V curve of the PV cells or modules under different operating conditions with a variety of methods. The easiest and most simple method is to use variable resistor as a load to the PV generator and measure the stepwise voltage and current. Fig. 1shows a schematic circuit for measuring the I–V curves of a PV generator using a rheostat. In this method, the value of the resistance R_L will be varied in steps from 0 to infinity to measure the points of the I–V curve from short circuit to open circuit [8].

A low cost measuring system was designed by [9] for measuring the I-V characteristic of seven modules. A set of mechanical relays are used to select a parallel combination of resistors to act as resistive load and another set of mechanical relays are used for PV module selection.

The I–V curve obtained by the above method in ref [8,9] is deficient in accuracy, uniformity and smoothness, since it is susceptible to varying solar radiation and thermal conditions during the measurement due to manual change of the load resistor and slowness of the measuring process [10,11].

The second measuring method is to load the PV generator by a capacitor and to charge it fully from short circuit to open circuit, and to record the respective voltage and current by X–Y recorder or a computerized data acquisition system. Fig. 2 shows a circuit for measuring the I–V characteristics by capacitor charging and data acquisition system [6]. Reference [6], as shown in fig. 2, used the switchable capacitor bank allows switching the proper capacitor value (C) while the load resistor (R_L) is used for discharging the capacitor via S_3. The switches S_1, S_2 and S_3 can be either manual switched or are automatic switches (controlled transistor—relay switches).

The I–V curve obtained by this method is much more accurate and uniform with respect to the previous method since it is measured in a very short time. In addition, it surpasses the first method by enabling the measurement of the I–V curve of PV generators of higher power with reasonable capacitor values.

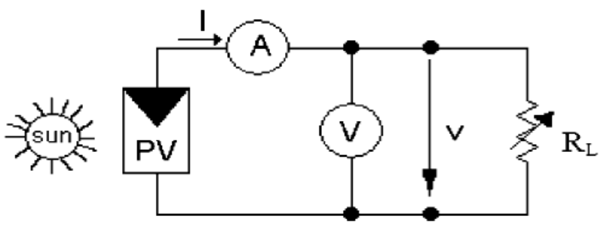

Fig. 1. A schematic circuit for measuring the I–V curve of a PV generator using a rheostat.

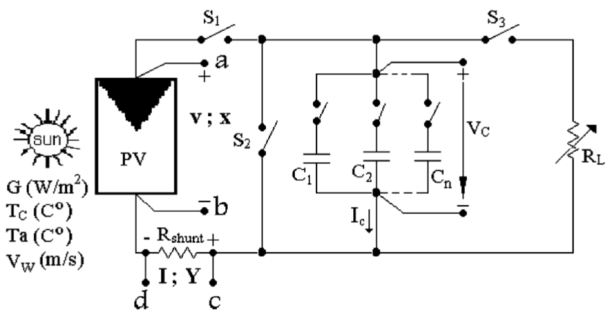

Fig. 2. A circuit for measuring the I–V characteristics by capacitor charging and data acquisition system.

The third measuring method is to test the photovoltaic modules using electronic dc loads, which can vary the resistance (load) over the entire range in a very short time [12]. However, the ones available on the market are often expensive. Anyway, by using quite simple and much cheaper circuits, it is also possible to build an electronic dc load taking advantage of a suitable operation of a power Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET). In fact, a power MOSFET operating in its active region and mounted on a heat sink to dissipate the power, if necessary, can be used as an electronic load to test PV modules [13]. Some simple and/or low cost electronic circuits have been being developed along this decade. Reference [14] is a simple electronic circuits that facilitate the data acquisition of I-V characteristics of PV cells.

The proposed circuit for the electronic I-V tracker in the above method is suitable to be used for analyzing the influence of field conditions like temperature, irradiance and partial shadowing on the PV module performance, as well as in identifying degradation and malfunction conditions [15].

Another way is considered in studying the PV effect by modeling and simulation the I-V characteristics of the PV module. Reference [16] presented an integrated thermal and electric simulation model for the operation of PV modules and strings. The electric model is based on the well-known one-diode model and a method is introduced to derive the unknown parameters from the manufacturer's information datasheet. Another I–V modeling approach for photovoltaic arrays based on time warp invariant echo state network [17]. It concluded that I–V characteristic model of a PV array is not only nonlinear and implicit, but also strictly dependent on material types, manufacturing process, ageing and environmental influence. Reference [18] discussed the five main parametric models for PV systems available in the literatures. The current–voltage characteristics of a photovoltaic module can be reproduced modeling the PV panel as an equivalent electrical circuit made of linear and non-linear components. The parameters describing such components are directly related to the performance characteristics of the specific PV panel, which are generally available in a graphic form with respect to standard values of temperature and incident irradiance.

In this paper an improved simple and accurate measuring electronic circuit is presented to outdoor test PV modules by tracing their I-V characteristics at different operating conditions and for a variety of modules power. It is based on a power MOSFET as an electronic load. The electronic load at PV module terminal can be controlled by a varying DC control signal applied at the Gate-Source terminal of the MOSFET (V_{GS}). Moreover the scanning voltage (V_{GS}) is achieved in a simple and smooth innovative way in order to improve the I-V tracing via an output of the digital to analog card (DA) of a data acquisition system depending on the applied software parameters. Furthermore, galvanic isolation is introduced for the scanning signal as well as the current and voltage measurements. This is important to prevent damage of data acquisition system and mainly to enable the circuit to be used in tests with PV strings and not only with modules. In this case, the protection of the equipment and operators is mandatory. In spite of this improved characteristics, the developed electronic circuit, as a fast varying dc load, keeps the quite simple design and low cost advantages with higher accuracy.

II. THEORY OF OPERATION

Measuring I-V curves for PV cell, module and array depends mainly on scanning the voltage at the terminal of the PV module from short circuit (minimum value) to open circuit (maximum value), that corresponding to change of the module current from maximum value (short circuit current) to minimum value (zero current). A power MOSFET was used as an electronic fast varying load controlled by means of a variable gate-source voltage (V_{GS}). Fig. 3 shows the basic idea of the circuit for testing a PV module using a MOSFET as an electronic load.

Thus, the operating point corresponds to the intersection of the PV module characteristic with the MOSFET one for a given voltage V_{GS}. Fig. 4 shows a characteristics of the PV module with that of the MOSFET. By sweeping V_{GS} with a suitable signal the operating point of the MOSFET sweeps the I-V characteristic between module open circuit voltage and short circuit current. While V_{GS} is less than the threshold voltage (V_{th}) the MOSFET will be OFF. When V_{GS} is increased above V_{th}, the device will operate in its active region where the drain current (I_D) rises approximately in a linear way with V_{GS}.

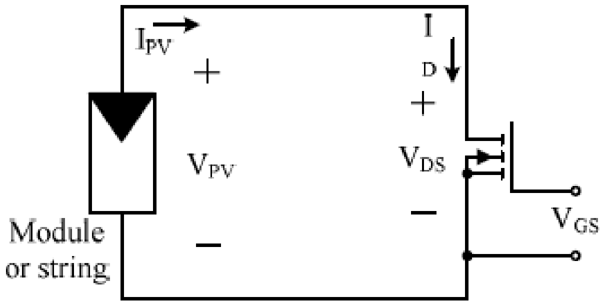

Fig. 3. Basic circuit for testing PV modules using a MOSFET as an electronic load.

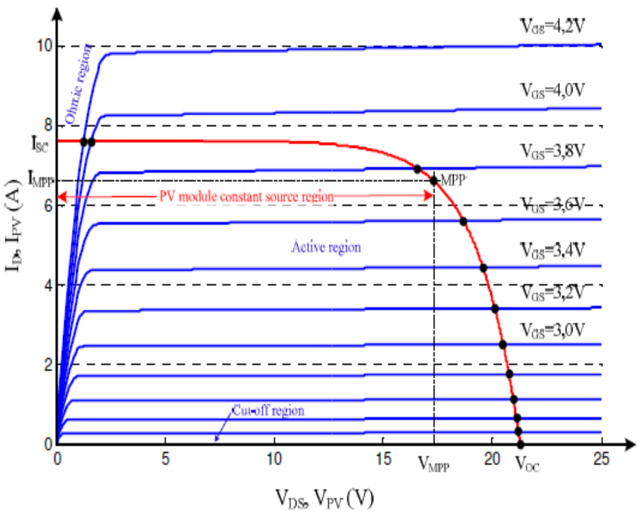

Fig. 4. Characteristic of a PV module and characteristics of a MOSFET.

As far as the PV module is concerned, for voltage higher than the voltage at the maximum power point (V_{MPP}), the characteristic will be similar to a voltage source one. At voltages below V_{MPP} the PV module will behave as a current source. In this flat region, indicated in Fig. 4, the module voltage (V_{PV}) is sensitive to small variations in module current (I_{PV}) and hence to small variations in V_{GS}. Because of this high sensitivity, the operating point will move too fast in this flat region unless a suitable sweeping signal is created to generate the voltage V_{GS}.

III. HARDWARE IMPLEMENTATION

The block diagram of the electronic circuit developed to measure the I-V characteristics of PV modules is shown in Fig. 5. From the figure, the hardware components of the measuring circuit are; MOSFET as electronic load with a heat sink to dissipate the power, gate (control) signal for sweeping V_{GS}, measuring tools, isolation tools and data acquisition system. The next sections describe in detail each component of the I-V measuring circuit.

A. MOSFET Transistor

The used MOSFET is N-channel enhanced mode high voltage power MOSFET (APT5010JN) with rated parameters (at 25 °C) as follows;

- Drain – source voltage (V_{DS}) is 500 V.
- Continuous drain current (I_D) is 48 A.
- Gate – source voltage (V_{GS}) is ± 30 V.
- Total power dissipation (P_D) is 520 Watt.
- Operating junction temperature range is -55 to 150 °C.

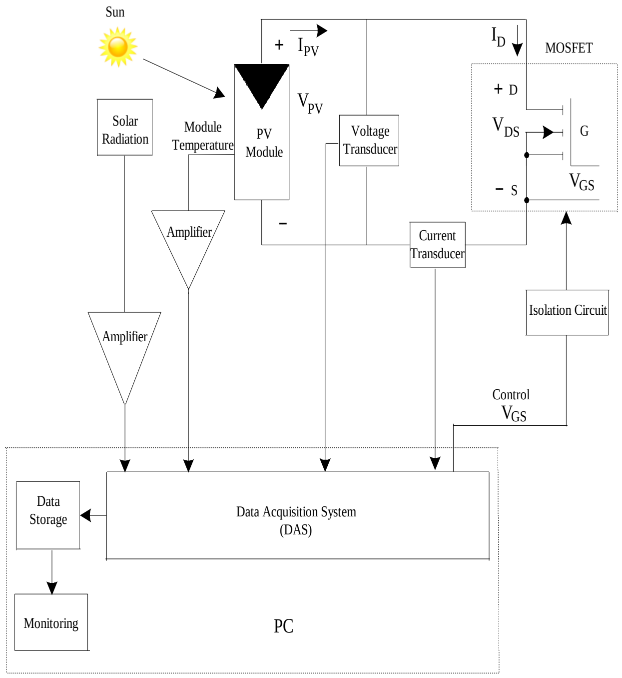

Fig. 5. The block diagram of the electronic circuit developed to measure the I-V characteristics of PV modules.

B. *Measuring Tools*

For tracing the I-V curves of the PV modules, the following parameters must be measured; the module voltage, module current, module surface temperature and solar radiation level as shown in Fig. 5. These parameters can be measured as follows [19];

- PV module voltage measurement: the PV module voltage can be measured accurately by using an appropriate voltage transducer. The used voltage transducer is a bipolar LV 25-P voltage transducer, with galvanic isolation between the primary circuit (high voltage) and the secondary circuit (low voltage). An excellent accuracy, very good linearity, low thermal drift, low response time, and high immunity to external interface voltage transducer is used to get a voltage signal (from 0 to 5 V) corresponding to the measured value. The measured voltage signal is passed to the Analog to digital (AD) card of the data acquisition system (DAS).
- PV module current measurement: a multi-range current transducer LA 25-NP is used to measure the load current. It has an excellent accuracy, very good linearity, low temperature drift, and current overload capability. The current transducer is used to convert the module current into a voltage signal (from 0 to 5 V) to be suitable for reading by the AD card of DAS.
- Solar radiation measurement: a thermopile pyranometer of type Kipp & Zonen (model CM5-774035) is used to measure the solar radiation intensity. The pyranometer is mounted parallel to the PV module. Since the pyranometer output voltage is in the range of millivolts corresponding to the measured radiation, the output voltage signal must be amplified to be suitable for the AD card of DAS.
- PV module surface temperature measurement: since the temperature is important parameter on the PV module performance, it must be measured accurately to get the correct response of the PV system. A type K thermocouple is used to measure the PV module surface temperature. The thermocouple converts the module temperature to a very small voltage signal (about 1 mV for each 25 ^{o}C). A suitable amplification circuit is used to amplify this signal to be suitable for the AD card of DAS.

C. *Data Acquisition System*

The data acquisition system (DAS) is used to record the signals from the different sensors and measuring tools described above that are used for measuring the different physical parameters of the PV system. These parameters can be measured and recorded via a PC driven by AD card [19].

- Analog to digital conversion (AD): the main part in the data acquisition system is the AD574 analog to digital module, which receives the voltage analog signals from the measuring devices and converts theses signals into digital signals to be processed by the PC. The AD card has 8 input analog channels each with 12-bit resolution with multi input voltage ranges with 25 μsec conversion time.

D. *Control Signal*

The control signal is used to sweep the value of V_{GS} voltage to scan the voltage and currents of the PV module from minimum values to its maximum values as shown in fig. 4 and Fig. 5. The PM7548GP digital to analog (DA) converter module is used to send the control signal required, depending on the software program. The DA module has 12 bits resolution and sends the DC control signal from 0 to 10 V with settling time of 30 μsec. The control signal is applied at Gate-Source terminals of the MOSFET as V_{GS} required tracing the PV module I-V characteristics. It must be noticed that the control signal in not require additional circuit, since it depends only on the DA port of the DAS. This simplifies the measuring circuit and accurately controlling V_{GS} values especially near to the short circuit current.

E. *Isolation Circuits*

The electronic measuring circuit includes galvanic isolation to avoid damage of data acquisition systems and improve safety for operators, mainly in case of high voltage module or array tests. As shown in fig. 5, the DA supply the control signal that directly applied to V_{GS} of the MOSFET via a galvanic isolation by using a voltage transducer circuit with a unity gain with galvanic isolation between its primary and secondary circuits. Also the measured signals are isolated by the galvanic isolation of the used transducers as shown in section B.

As described above, the used hardware for the electronic measuring circuit depends mainly on simple, widely used and low cost components either for measuring the module parameters or for controlling the MOSFET gate signals, since it depends mainly on a data acquisition card without needing any special driving circuits for the MOSFET or control signals.

IV. EXPERIMENTAL RESULTS

The experimental work based on measurement the characteristics of a single stand alone PV module and two modules connected in series to test it under different operating conditions with the electronic measuring circuit shown in fig. 5. Table 1 describes the characteristics of the PV modules used to be tested by the measuring circuit at STC. The experimental data are; I-V and P-V curves for a single PV module at different operating conditions and a small array of two modules connected in series.

TABLE I. CHARATERISTICS OF THE PV MODULE USED TO BE TESTED BY THE MEASURING CIRCUIT.

Parameter	**Specifications (STC)**
Rated power	22 W
Open circuit voltage	20.2 V
Short circuit current	1.72 A
Volatge of maximum power point (V_{MP})	15.2 V
Current of maximum power point (I_{MP})	1.45 A
Module fill factor (FF)	0.63
Module weight	3.85

Fig 6 and Fig. 7 show the I-V and P-V curves of the PV module at 950 W/m^2 solar radiation and surface temperature of 51 ^{o}C. From the figures it is clear that the measuring circuit tracing the PV module characteristic with higher accuracy and the measured curves are smoothly sweep the voltages and currents from minimum to maximum values. The suitable sweeping voltages (V_{GS}) to control the MOSFET that is applied at the MOSFET gate-source terminals can vary approximately between 0 and 4 V, for different solar radiation levels, where the PV module behaves as a current source and the voltage V is sensitive to small variations in V_{GS}. This voltage can vary quite quickly from V_{th} until the value that produces the voltage V_{MPP} at the output of the PV module. After that, V_{GS} should vary more slowly in order to increase the number of operating points captured in that flat region. As a result, the measured I-V characteristics become more uniform and persistent. It must be noted that the true value of the short circuit current (I_{SC}) is not exactly achieved since the PV module is not completely short circuited because of the internal resistance of the MOSFET.

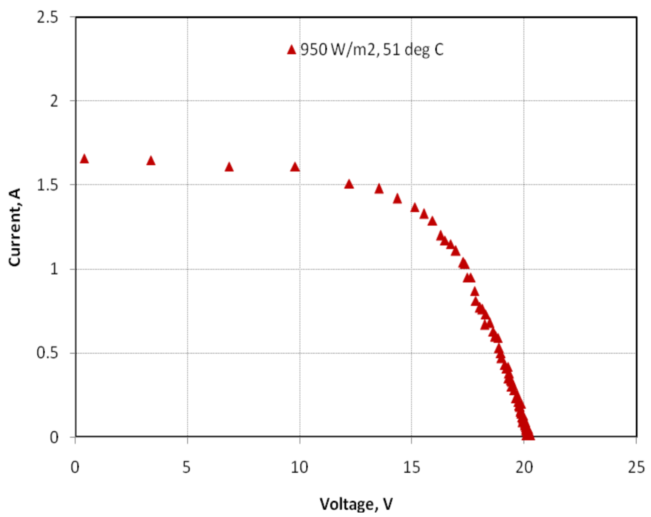

Fig. 6. Measured I-V curve of the PV module.

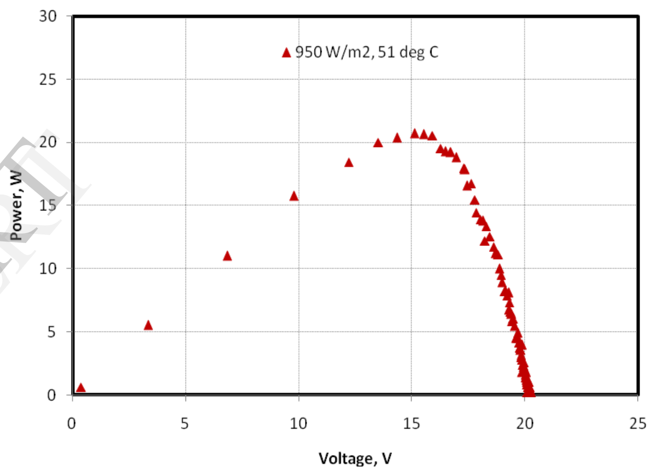

Fig. 7. Measured P-V curve of the PV module.

Fig. 8 and fig. 9 show the measured I-V and P-V curves for the PV module at different operating conditions, while fig. 10 shows the measured PV module short circuit current and maximum power at different solar radiation levels. The trend of increasing the short circuit current and the module maximum power linearly with the radiation levels ensure the accuracy of the measuring circuit in tracing the I-V characteristics of the PV module at various solar radiation levels.

Fig. 11 and Fig. 12 show the measured I-V and P-V curves of two PV modules connected in series as a small PV array (at 650 W/m^2 of solar radiation and 46 ^{o}C of surface temperature). Since connecting the PV modules in series in an array increases the array voltages, the measured curves show the ability of the measuring circuit in tracing higher voltages and currents PV arrays.

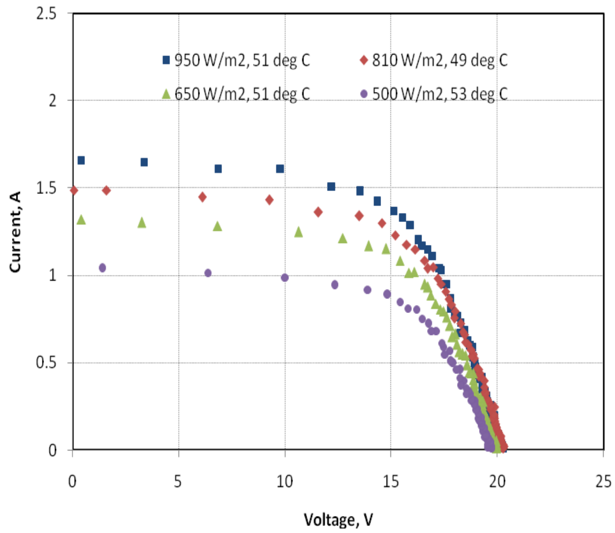

Fig. 8. Measured I-V curves of the PV module at different operating conditions.

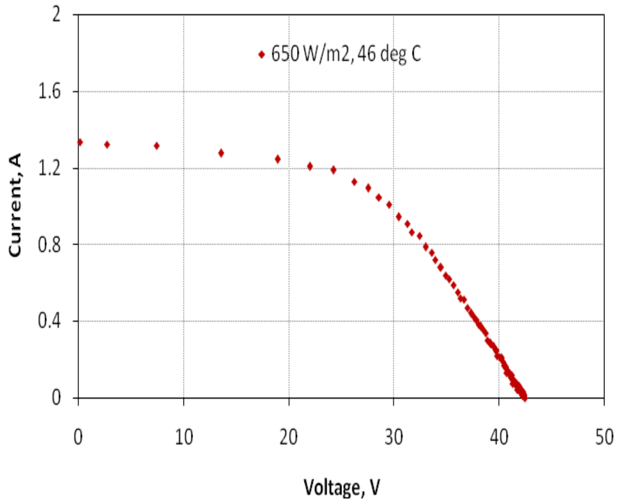

Fig. 11. Measured I-V curve for two PV modules connected in series.

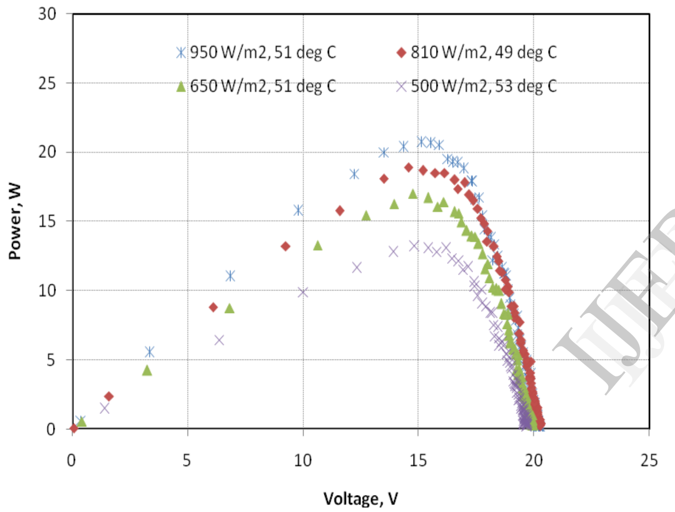

Fig. 9. Measured P-V curves of the PV module at different operating conditions.

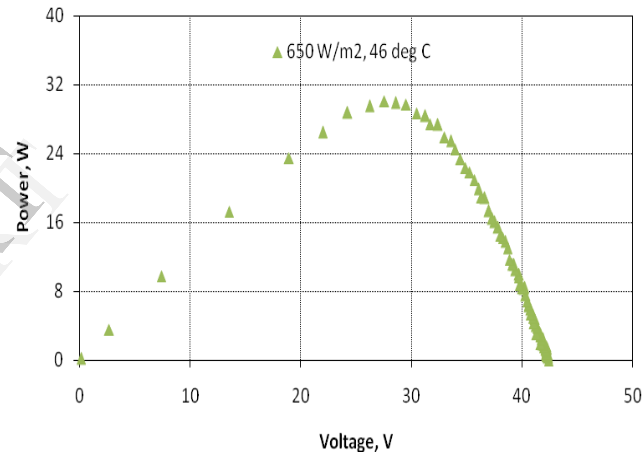

Fig. 12. Measured P-V curve for two PV modules connected in series.

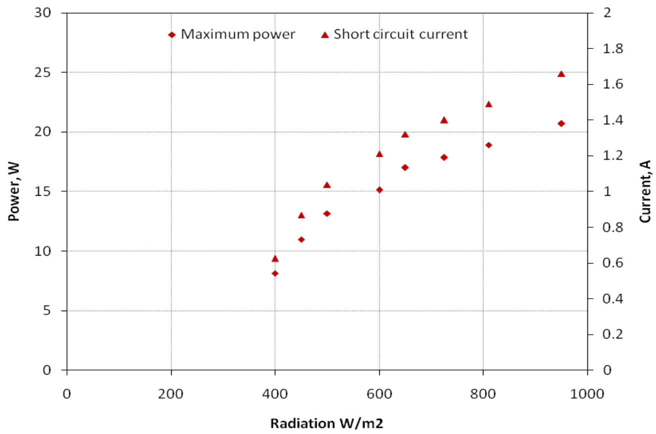

Fig. 10. Measured PV module short circuit current and maximum power at different solar radiation levels.

V. CONCLUSIONS

This paper presents a simple and accurate measuring electronic circuit for tracing the I-V characteristics of the photovoltaic modules to be used at different operating conditions. The circuit used an electronic load based on MOSFET. The MOSFET is controlled by sweeping the gate-source voltage through a DC control signal resulting from analog to digital port of the data acquisition system controlled by software via a galvanic isolation circuit. The measured parameters such as module currents and voltages as well as solar radiation levels and module surface temperatures are measured by a simple and accurate data acquisition system. Since the control signals driven by the data acquisition system, no additional circuits are required, that ensures the simplicity of the measuring circuit, lower cost and higher tracing frequency with higher accuracy.

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