Solar Cell Emulator and Solar Cell Characteristics Measurements In Dark and Illuminated Conditions

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Abstract - This paper describes a novel data acquisition system designed and implemented with facilities for measuring and monitoring the characteristics of a PV solar cell, module and/or system. The functioning of the equipment is based on the so-called virtual instrumentation. This is a non-conventional concept, however it does not have the many limitations in other systems. Additionally, the whole equipment can be implemented at significantly lower cost than the commercial one. The dark characteristics test facility, based on LabVIEW software to design an easy handling Graphical User Interface (GUI) and use a single chip microcontroller with a serial interface. The system is used to acquire the measured data from the cell under test and transfer it to a supervisory computer for monitoring and other signal processing. The preliminary test we have made indicates that the equipment we propose here is highly reliable, which allows measuring and monitoring variety of solar cell characteristics with a good accuracy.

Key Words: LabVIEW, AVR Microcontroller, Solar Cells & Solar Array, I-V Curve Measurements, Solar Cell Emulator.

1. Introduction

In the photovoltaic field, manufacturers provide ratings for PV modules for conditions referred to as standard test conditions (STC). However, these conditions rarely occur outdoors, so the usefulness and applicability of the indoors' characterization in standard test conditions of PV modules are a controversial issue. Therefore, to carry out photovoltaic engineering well, a suitable characterization of PV module electrical behavior (V–I curves) is necessary [1].

Since solar cells convert light to electricity it might seem odd to measure the photovoltaic cells in the dark. However, dark I-V measurements are in valuable in examining the cell properties. Under illumination, small fluctuations in the light intensity add considerable amounts of noise to the system making it difficult to measure. Dark I-V measurements use injects carriers into the circuit with electrical means rather than with light generated carriers. In most cases the two are equivalent and the Dark I-V measurements give extra information about the cell for diagnostic purposes. Even in the absence of noise there is a wealth of information in comparing the illuminated and dark I-V curves [2].

The solar cell characteristics are handled in many references [3-10]. Alternatively, the static parameters and characteristics of solar cells are normally determined from their illuminated current-voltage characteristics under standard solar simulators, based on flash lamps or distributed light sources, or outdoor conditions. They are used in assessing solar cell efficiency and fill factors. On the other hand, dynamic parameters are required in designing circuits containing solar cells and switching devices as well as providing important diagnostic tools.

2. Survey of Previous Work

Daniel KOSTER et. al, have reported in [11] that, as commonly known the most significant method to describe the performance characteristic of PV modules is the measurement of I-V curves under real operating conditions. Although there is no need to reinvent the wheel since all recognized PV test-facilities and a number of manufacturers of PV modules are using their specific equipment.

Yan-Fang Li, et. al, have reported in [12] that, Basic Stamp 2 (BS2) is a popular microcontroller used both in hobby and industrial projects. Similar to other microcontrollers, BS2 programming environment lacks graphical user interface (GUI) capability. In there paper, they present an approach to endow the BS2 microcontroller with GUI capabilities by interfacing it with Matlab and by exploiting Matlab’s abundant GUI tools. The proposed Matlab-based GUI environment for BS2 relies on the use of serial communication between the BS2 and a personal computer.

Also, in space application, the spacecraft photovoltaic arrays (PVA's) must be carefully handled during ground integration processing and transportation to the launch site. Care is exercised to avoid damage that could degrade on-orbit electrical performance. Because of this damage risk, however, PVA's are typically deployed and illuminated with a light source so performance characteristics can be measured prior to launch. Another alternative is dark forward electrical testing. This testing is performed while the array stowed, obviating the need for deployment and illumination test support equipment. Dark test support equipment is inexpensive, it is easily portable to launch site facilities, and testing can be accomplished with only one or two test engineers [13].

Giorgos Ristas has reported in [14] that he used in the PV I-V measurement a general purpose and low cost data acquisition card (NI-DAQ 6024E) by National Instruments. It is installed in PCI slot of the system computer, which samples and digitizes the sensor signals in order to process the collected data and display the measured time series via the appropriate software. The computer system, that has installed in its PCI bus the DAQ card and is running LabVIEW software that controls the acquisition process, analyzes and displays the collected data. He declared that the LabVIEW software was selected because it provides powerful tools for distributed monitoring systems. It is designed especially for engineers and scientists that can take full advantage of its measurement-specific user interface design tools. It has a great collection of built-in functions designed specifically for extracting useful information from any set of acquired data and for analyzing measurements and processing signals through underlying sophisticated algorithms. The open LabVIEW environment provides superior connectivity to third-party software, having simple transitioning and coexisting and thus can be easily integrated and upgraded to a powerful software package. The whole system is designed and integrated in order to meet the laboratory’s energy needs and will be used by students as an experimental exercise. Thus, for educational and research purposes, carefully selected current and voltage sensors are used in order to provide the necessary measurements to monitor the system. Voltage sensors have a range of 0-1.8V. Current sensors have a range of 0-100mA. Both types of sensors are connected to the DAQ card via RC low pass filters. The sensors signals are connected to a DAQ card in a PCI slot of PC that is running the LabVIEW software in order to store and process the measured data.

Dezso Sera et.al, have reported in [15], The objective of this study is to clarify the impact of shading on a solar panel performance in relatively simple terms that can be followed by a power engineer or PV system designer without difficulty. First, the circuit model of a PV cell and its I-V curve are reviewed. This is followed by the impact of partial shading on the I-V and P-V curves of a circuit containing two cells with and without bypass diodes. The concept is extended to the circuits with series and parallel sub-modules. Finally, the impact of shading is illustrated by measurements on a commercial PV panel and a large PV array.

Authors of [16, 17] developed a work for measuring and analyzing the characteristic curves of the current-voltage (I-V) and power-voltage (P-V) of the PV module, and boost converter circuit is designed and implemented. The components of the boost converter have been selected so as to enhance its performance. The controller is developed by integrating the boost converter with the microcontroller.

The emulator allows the user to obtain reliable results for PV system at any weather analogous to that can be obtained from the real PV system regardless of the actual weather conditions. A further benefit is that the SCE can be used as a platform to compare the various approaches to maximum power point tracking for PV stand alone, grid-connected, or hybrid power system.

A wide range of array simulators or emulators based in power converters have been proposed and developed during last year’s. Some of them without galvanic isolation, some based on structures with low frequency transformer, and some based on HF transformers; some using Pulse Width Modulation (PWM) principle, and some using linear converters to avoid EMC-measurements. Trying to emulate the PV current-voltage curve (I-V curve) some converters amplified the curve of a reference solar cell, and some obtained the I-V curve from a discrete table stored in a memory and then interpolated the points, but most of them used mathematical models of panel’s I-V curve and calculated it from array‘s parameters, making possible to modify and simulate the PV curve under different situations easily [18].

3. Solar Cell Characteristics

In the characterization of PV modules several types of methods can be differentiated. Those are able to obtain the PV module behavior in STC. The methods obtain the characterization of the PV module in STC from outdoor measures. In these cases, a process in two stages is necessary:

- 1st, the experimental measurement of I-V characteristic along with the predominant conditions of operation, and
- 2nd, the extrapolation of the measures to STC.

In this work, the I-V characteristics of the solar cell is provided in the dark mode as a diode characteristics, then data extrapolation is made to normalize the test result curves to STC.

3.1. I-V Curve Measurements of Solar Cells

A solar cell is usually represented by an equivalent one-diode model. The model contains a current source I_{ph} and series resistance R_s, which represents the resistance inside each cell and in the connection between the cells as shown in Figure 1. The net current is the difference between the photocurrent I_{ph} and the normal diode current I_D:

$$I = I_{ph} - I_D = I_{ph} - I_0\left(\exp\frac{e(V + IR_S)}{mKT_{ab}} - 1\right) \quad \text{Eq. 1}$$

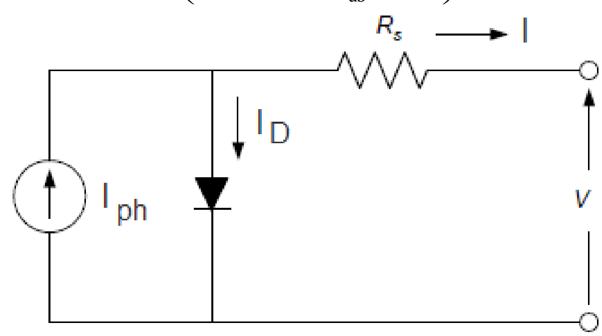

Figure 1, Solar cell model.

Where:

m is the idealizing factor,
K is the Boltzmann’s constant,
T_{ab} the absolute temperature of the cell,
e electronic charge and
V is the cell voltage.
I_0 is the saturation current, which depends strongly on the cell temperature.

3.2. System objective

The system was developed for measuring and monitoring a PV solar cell, module and/or system. It provides facilities to get the test through three kinds of measurements:

- Environmental and system variables (ambient temperature, solar radiation, current, voltage, energy, power, etc.).
- The dark I-V characteristics for the cell, module and/or system. (open circuit voltage, V_{oc}; short circuit current, I_{sc}; fill factor, FF; efficiency, □ and maximum power, P_{max})..
- Forecast the I-V and P-V curves of the PV cell, , module and/or system in STC or any condition as well as determination of its electric cell parameters.

The user can display in a computer screen the instantaneous values of any of the above parameters and graphs of the I-Vs. V and P vs. V curves.

3.3. System Setup Circuit

The proposed mentioned data acquisition system is using the microcontrollers as a data logger for measuring and acquiring the signals and transmitting it to a PC through serial port RS-232.

The experimental setup circuit for cell in both dark and illumination characteristics is shown in Figure 2.

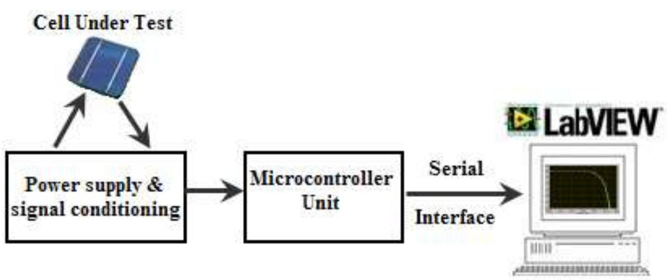

Figure 2, Dark and illumination cell measurements setup circuit.

Usually, the data transmission through the serial port is limited when data acquisition at high sampling rates is required [19]. In our work we acquiring the data and saving it in the microcontroller S-RAM, after test is completed the data are transmitted to the PC via the serial port. Also this limitation does not occur when the data acquisition is performed using I/O modular devices. Another limitation we have identified in conventional data acquisition systems is the difficulty of making any modification to the test programs. This limitation is absent where the programs are developed using LabVIEW, where the user can modify and process the collected data to minister his own objectives. Additionally, the high cost of commercial automatic data acquisition systems that are capable of monitoring and operational control of PV solar plants is the main limiting factor for the development of PV system projects in developing countries.

4. Measurement System Description

The dark test equipment consists of AC power supply with DC offset adjustment facility, signal conditioning circuit, AVR microcontroller and a personal computer (PC), as shown in the schematic diagram.

Under dark condition, an AC signal from power supply is imposed on the cell under test, and then the resulting current and voltage signals are collected. Several current-voltage data points are obtained to generate the dark cell characteristic curve. The data are stored in the microcontroller S-RAM. The PC then collects the data from the microcontroller via the RS-232 serial port. The data can be stored in a data file for documentation purpose, and in a table and in X-Y graph for mentoring on the PC screen. Those data can be manipulated to obtain the corresponding illuminated electrical performance for the solar cell, module and/or system at any environmental condition.

In illuminated mode test, the cell is imposed to the outdoor normal sun light or to indoor sun simulator light to trace the corresponding characteristics also.

4.1. Solar Cell I-V Test LabVIEW Program

Unlike [11], [12], LabVIEW based GUI program (vi) is developed to configure the computer as supervisory monitoring system and interfaced with AVR microcontroller via RS232 serial communication. The program controls the microcontroller by ordering it to start solar cell testing, and to collect the measured data. The PC LabVIEW receives the data from the microcontroller, save it in a file, then viewing the measured points in a table, processing the received data and controlling the result graphs. The graph preview area shows the collected data points after a sweep. The voltage, current and power data are recorded in a table specified by the user. The program allows the user to configure and modify the method of data processing.

4.2. LabVIEW Program Block Diagram

The solar cell I-V & P-V test setup block diagram is shown in Figure 3. The block diagram can be divided into two main sections; the first section is the initialization of serial VISA interface while the second section is responsible for measured data processing.

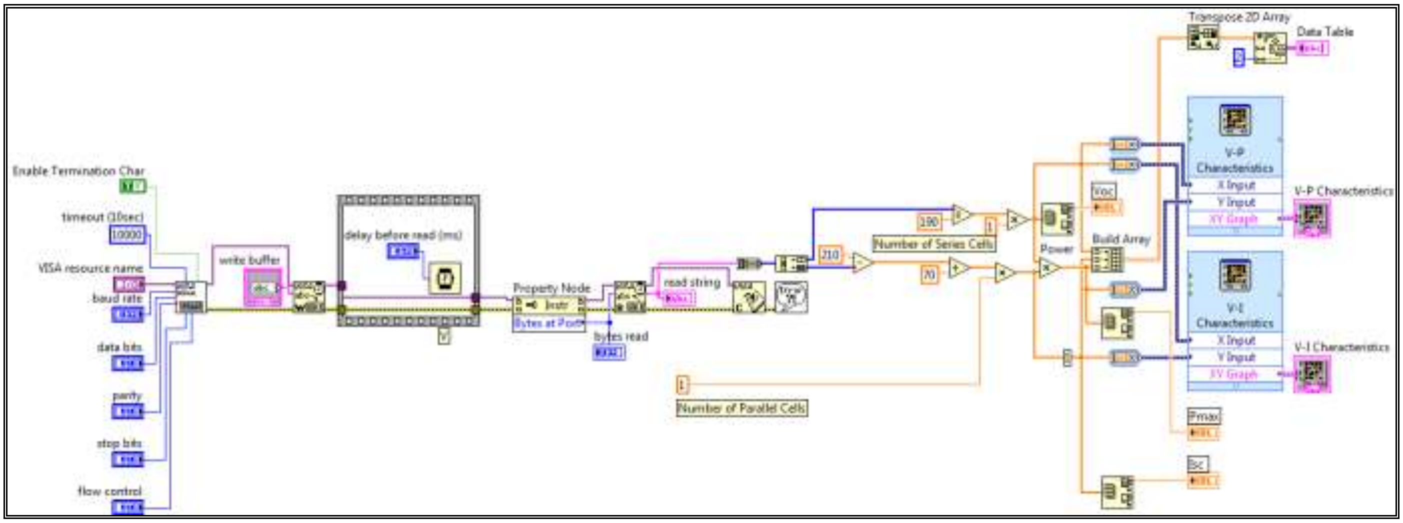

Figure 3, LabVIEW Serial Interface and I-V Curve Measurement Block Diagram

4.3. LabVIEW Program Front Panel (GUI)

The front panel of the developed LabVIEW Program is shown in Figure 4. The measured data is presented in the front panel of LabVIEW program in two forms, table with four columns; numbers of measured points, voltage, current and power. The other form is the X-Y graph for I-V and P-V. Also the other important points as I_{SC} , V_{OC}, and P_{max} are presented. The initialization parameters of the serial VISA are presented also in the front panel allowing the user to input the relevant data for his application. The output buffer (write) orders the microcontroller to start testing process then transferring data to PC. The measured data are back to input buffer (read) that is included also in the front panel. The solar cell I-V & P-V diagrams are shown in Figure 4.

4.4. AVR ATmega16 Microcontroller

The AVR ATmega16 microcontroller that is used in the proposed work is a low-power CMOS 8-bit microcontroller. It has powerful instructions in a single clock cycle, the ATmega16A approaching 1 MIPS (million instruction per second) per MHz allowing the system designer to optimize power consumption versus processing speed.

The AVR ATmega16 microcontroller has the following important features:

- 0 - 16 MHz
- 32 Programmable I/O Lines
- Byte-oriented Two-wire Serial Interface
- 8-channel, 10-bit ADC
- 16KB of Self-programmable Flash program memory
- 512 Bytes EEPROM
- 1K Byte Internal SRAM

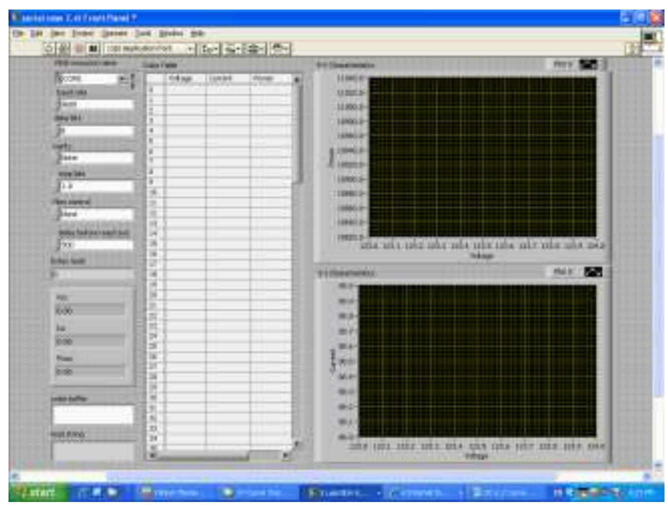

Figure 4, LabVIEW Graphical User Interface Menu.

The following sections illustrate the control circuit hardware and the microcontroller control program flow chart.

4.5. Microcontroller Control Circuit with Serial Interface

The microcontroller control circuit is shown in Figure 5.

The circuit consists of the ATmega16 microcontroller with the reset circuit. A serial interface circuit based on the MAX232ACSE device is implemented and attached to the microcontroller to interface the microcontroller with the PC which acts as supervisory controller and monitoring panel. Port C is used to out the control word for the I-V testing circuit. The digital signal is directly converted to analog one via the DAC0808 device. An operational amplifier with its rated designed accessories is attached to the circuit as shown in figure 5.

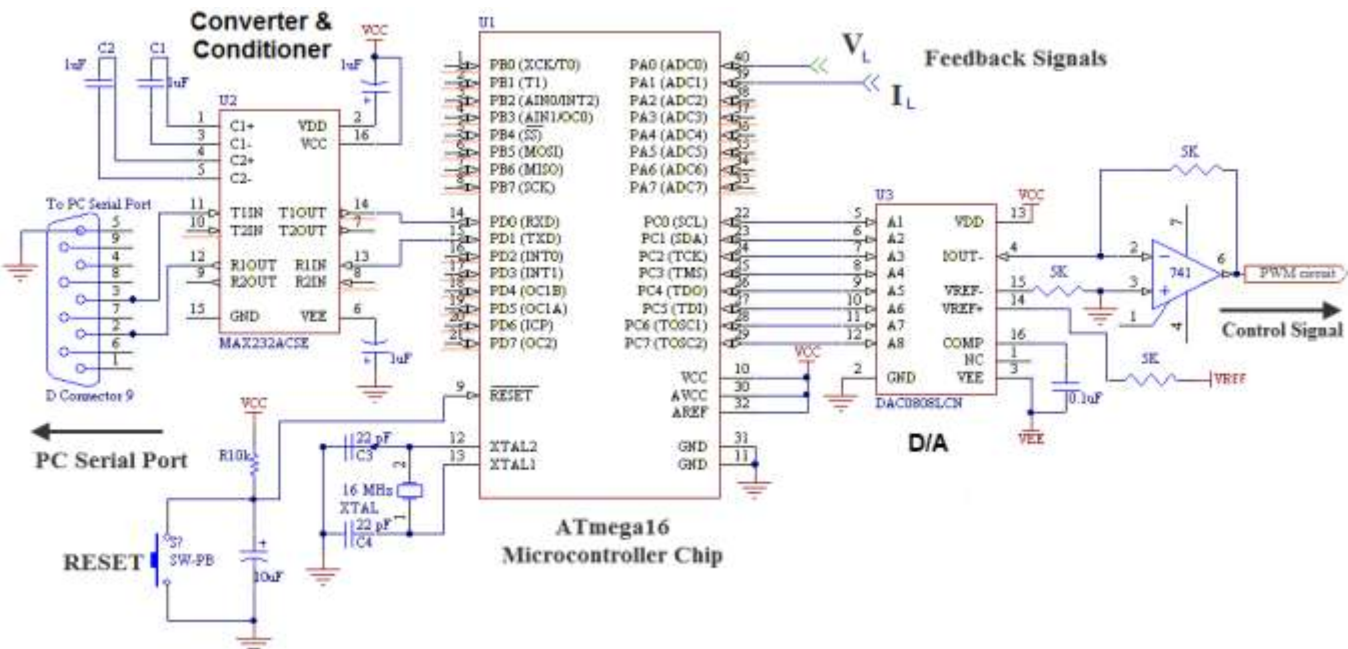

Figure 5, The microcontroller interfacing and measurement control circuit.

Serial interface is used to communicate with PC where the Graphical User Interface software is developed using the LabVIEW Software package. The converter and conditioner device MAX232 chip is used to interface the microcontroller serial terminals and the PC RS232 via standard serial cable. The required power supplies, reset and crystal circuits for microcontroller operation are developed also. The microcontroller is configured where one port (port C) is interfaced with D/A device to generate the analog control signal that controls the power switch of solar array testing in illuminated mode. Port A is used as A/D converter; channel 0 and channel 1 are used to measure the solar array current and voltage. Serial Interface is used to communicate with PC where the Graphical User Interface Software is developed using the LabVIEW Software package.

4.6. Microcontroller Program Flow Chart

The microcontroller program flow chart is shown in Figure 6. The microcontroller measurements control program starts with initialization of all microcontroller peripherals as parallel and serial ports, ADC channels, etc.

The program is divided into two main phases; data measuring phase, and data transmitting phase. This technique is used to override the serial port speed limitations.

5. The Dark Test Circuit

The dark measurements of a single solar cell or a complete photovoltaic module or system are a trustworthy in the photovoltaic world as well as the outdoor measurements.

The proposed dark test circuit of the single solar cell is illustrated in Figure 7. As the microcontroller A/D device is a unipolar device, so it can't measure negative signal. So, DC offset signal is added to the AC signal of power supply (AC PS). A signal conditioning circuit is built to read the two measured signals (V&I) with one common ground. In the dark mode the photo-generated dc current from the cell equals zero, so the cell characterizes as a series diode in the circuit. 1-ohm resistor current represents the current flow in the circuit, and the voltage difference across the cell as the measured voltage.

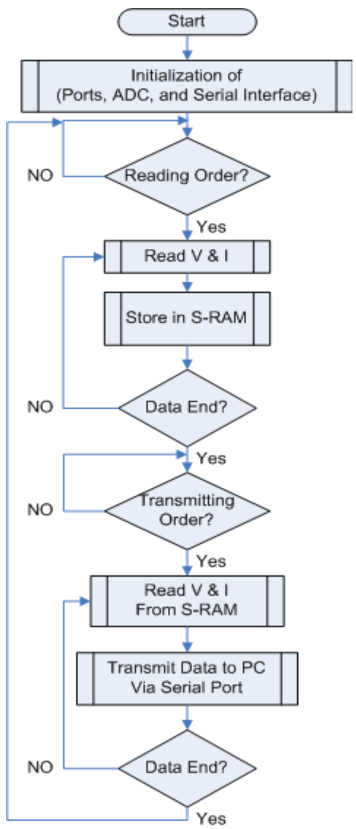

Figure 6, Microcontroller program flow chart.

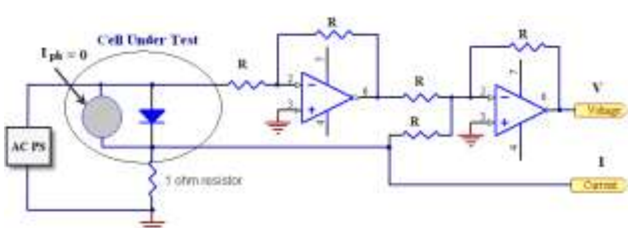

Figure 7, Single solar cell dark test, and signal conditioning circuit.

6. The Illuminated Mode

In illuminated mode of cell test, the cell is illuminated with outer illumination source, as the sun or sun simulator. The current and voltage data were recorded at various solar radiation levels and module temperatures [20, 21].

6.1. The illumination Test Circuit

The illuminated or outdoor characteristics test is another but costly way for PV system characteristics measurements. This method may be outdoor i.e. in the working field, so the illumination is come from the sun and can't be controlled. Or it may be in the laboratory and the illumination comes from a sun simulator works with controlled halogen lamps, in this case the illumination can be controlled at a desired test conditions. The power circuit of the solar array module or subsystem testing in illumination mode is illustrated in Figure 8. It consists of the following components:

The solar module or solar array under test,

- A voltage transducer LV25-P type to measure the solar array terminal voltage,
- A power MOSFET that represents an electronic load to change the solar array output current from zero to short circuit value, or to the change the solar array terminal voltage from open circuit to zero value,
- A signal conditioning circuit used to isolate the control signal from microcontroller and to control the operation of the power electronic switch (MOSFET) which operated in the linear (active) region,
- A current transducer LA25-NP type to measure the solar array output current,

The two output analog signals; voltage and current (V & I) are wired to the input two analog channels in the AVR microcontroller.

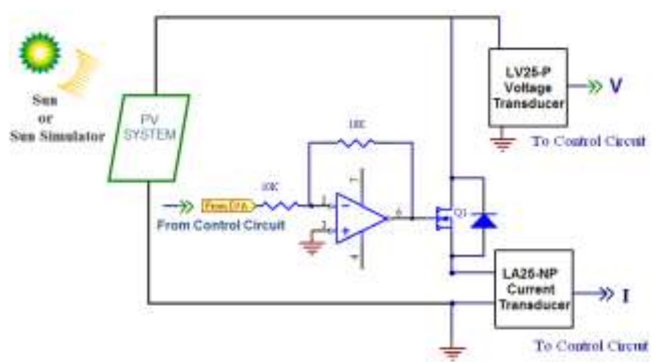

Figure 8, Illumination test circuit.

7. Solar Cell Emulator (SCE)

7.1. Emulator Importance

Distributed generation poses new problems to the control of the electric utility, and needs new solutions and technologies to face a massive penetration of PV-generators without renouncing to power quality [18]. Photovoltaic inverters are required to know their efficiencies for PV power inversion and transformation, the quality of the energy injected in the utility under different climatic conditions, and specially the performance of the different anti-islanding methods in solar inverters under large penetration of PV. Therefore, becomes vital to have appropriate test equipments for manufacturers and laboratories dedicated to PV inverter's R&D. Therefore manufacturers and researchers in the photovoltaic field need to have appropriate test equipments for PV system.

In this work, the design and construction of a solar cell emulator (SCE) is presented. The proposed system is a power electronics system able to behave the PV system characteristics without depending on the weather conditions and capable to emulate PV systems. SCE possible to perform different PV energy production systems tests under many environmental conditions and without depending on weather conditions or much more expensive systems. The development of a SCE based on a Buck converter based on amplified the curve of a reference solar cell, is presented. The I-V curve of a single solar cell at STC is stored in the memory of system controller, the applied weather parameters is estimated as set points input data, the developed program adapt the required parameters and generate the solar cell I-V new curve that will be the main set points values for the solar module emulator.

The proposed system consists of controlled power converter, and microcontroller as a monitoring and control system. Figure 5 shows the proposed circuit of SCE. The analog control signal is generated from the control circuit via D/A device as shown in Figure 5 and connected to reference input of the PWM generator as shown in Figure 9. The PWM generator is the TL494 that has the ability to generate a two output PWM signals which could be push-polled or single ended forms. In our case, a push-poll topology is applied to reduce the rms value of the implemented switches and increase its reliability. Two auxiliary FETs were used to power the two main MOSFETs switches.

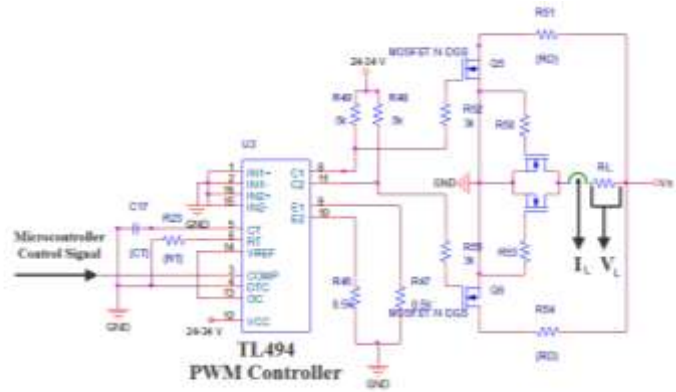

Figure 9, Power circuit of solar emulator

7.2. Current controlled Circuit

The power converter is a controlled-current voltage source inverter (CCVSI). The I-V curve characteristics of the PV system are stored in the microcontroller RAM as a look up table for different insolation levels. At certain defined insolation level, open circuit voltage (V_{OC}) of the system is read from the microcontroller, then applied to the power converter control circuit that responsible of outs the same voltage at the similar insolation level from the power converter. The voltage is applied to the load and the produced current are read again and compared to the reference value. If there is a difference between them, the voltage must be modified to match the corresponding current in the same I-V curve of the system. Many iterations are imposed till the output current and voltage matches the PV system curve and the load curve intersection point.

Figure 9 shows the current controlled voltage source inverter circuit. There are a reference and feedback current signals that compared to adjust the circuit voltage to minimize the error to zero. Then the output current must be equals the reference current. The error must drive the control circuit to adjust the output voltage to produce current equals the required reference current.

8. Experimental Results

The implemented proposed system is shown in Figure 10. The system composes the following components; solar cell under test, conditioning circuit, power supply, microcontroller board and the measuring tools oscilloscope and supervisory control (Laptop Computer) with the developed LabVIEW software program. The solar cell tests are executed in two stages. In the first stage, the system is used to measure the diode characteristics of the solar cell under test. The solar cell is a Si mono-crystalline cell with 10x10 Cm^2. The I-V curves are measured and the results are shown on an Oscilloscope monitor as well as on the front panel of implemented LabVIEW GUI software.

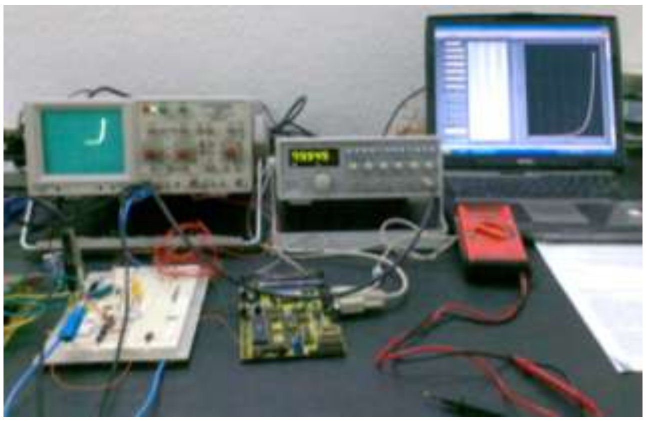

Figure 10, Hardware setup showing I-V on Oscilloscope and on the Laptop monitor using LabVIEW GUI Software**.**

The test results are shown in the following graphs.

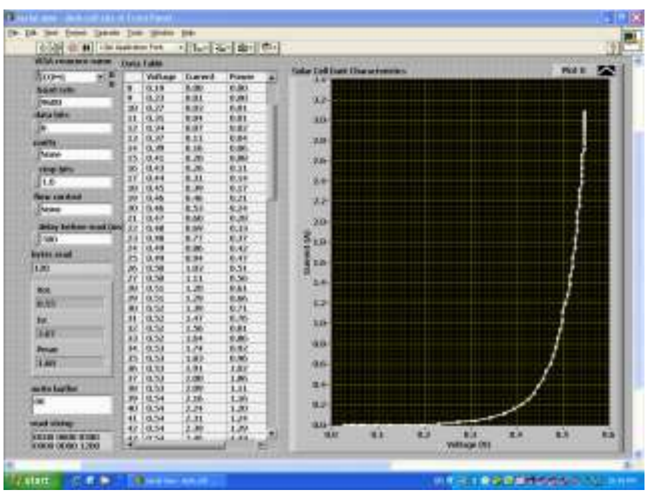

Figure 11, the I-V Curve of diode characteristics of the solar Cell under test using the developed LabVIEW test program.

Comparing the two I-V curves, it seems that they are identical by means that, the data processing in the developed LabVIEW test program is valid. In the second stage, a data processing module were added to developed LabVIEW program block diagram to present the I-V in the first quarter as usual form. Also, the power curve (P-V) is deduced from the measured data. Both I-V and P-V curves are presented in the GUI front panel window. The results are shown in Figure 13.

Figure 12, 10x10 Cm2 Solar Cell I-V Test Results, X-axis: 0.2V/div, Y-axis 1A/div

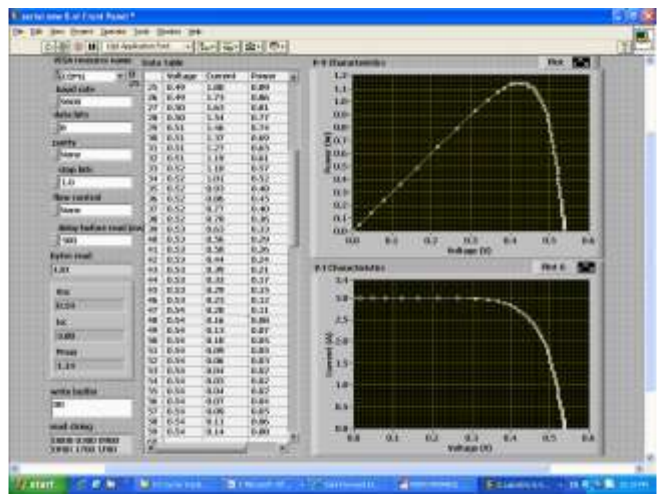

Figure 13, LabVIEW GUI of 10x10 Cm^2 Solar Cell Test Results; I-V & P-V

9. Conclusions

A developed technique for presenting the methodology of solar cell characteristics is presented in this paper. The hardware setup of the proposed technique is illustrated in details in this paper. The AVR ATmega16 is applied and the wiring diagram of the microcontroller and all the necessary conditioning circuits are given. The flow chart of the developed microcontroller software program is given also. The power circuit of measuring the solar cell (or solar array) characteristics in both dark and illumination modes are implemented and illustrated. Also a proposed solar cell emulator is designed and implemented in this work.

The LabVIEW software is applied in this work to pack and draw the collected data of solar cell characteristics from microcontroller subsystem. The complete block diagram is shown in details in this paper. A graphical user interface (front panel) is designed in the developed LabVIEW solar cell testing program. It is used to present the measured solar cell testing data, the packed data and the plotted I-V and P-V curves. A mono-crystalline solar with 10x10Cm^2 is used and the test results before and after the normalization process are given.

An intelligent module is added in the block diagram to normalize the measured solar cell characteristics data in dark mode to be presented in the usual form. An examination of the implemented LabVIEW model is applied and the results shows a compatibility between the test results presented directly on Oscilloscope monitor with other presented on the developed LabVIEW model front panel.

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