CHAPTER 4

PV MODULE CHARACTERIZATION SYSTEM

4.1 INTRODUCTION

The ever-increasing world energy demand and the fast depletion of fossil fuels have prompted the world to look for abundant alternative renewable energy sources. Solar energy is the most favoured source of energy since it is environmentally friendly, readily available and is everywhere. Globally there is active research going on in the photovoltaic (PV) industry, but the high cost of the characterization systems (Current-Voltage testers) currently in the market has been the major setback. Many previously disadvantaged institutes and young and upcoming researchers cannot afford to purchase these expensive systems thereby limiting research capabilities.

The aim of this study was to design a low cost photovoltaic module characterization system capable of measuring the current-voltage (I-V) characteristics of PV modules, at any site. The system capability was to accommodate eight PV modules of different technologies. This chapter presents the design of a current-voltage tester employing a variable power supply unit as active load. The components used in this system as well as the data acquisition system are discussed in detail. The methodology behind the I-V system's operation is also presented.

4.2 SYSTEM DESCRIPTION

The continuous changes in meteorological conditions cause PV modules' I-V characteristics to vary greatly when deployed outdoors. The outdoor characteristics at the user site are also very different from the rated characteristics under Standard Test Conditions (STC) (1000 W/m², ambient temperature 25°C, and Air mass 1.5 global spectrum) and different module technologies respond differently to specific outdoor conditions. It is therefore imperative for both system designers and users to know and understand PV module performance under outdoor conditions. The system used in this study was designed and built at the University of Fort Hare (UFH). Figure 4.1 shows a block diagram of the I-V tester. The main components of this system are:

(i) Data Acquisition System (DAS), which comprises an A/D computer card, temperature card, electromechanical relays, current and voltage transducers, aluminum housed resistors and power MOSFETS.

(ii) Programmable variable Power Supply Unit (PSU) with a voltage range of 0 - 30 V and a current range of 0 - 20 A.

(iii) Signal isolator.

(iv) Eight PV modules either of the same or of different technologies.

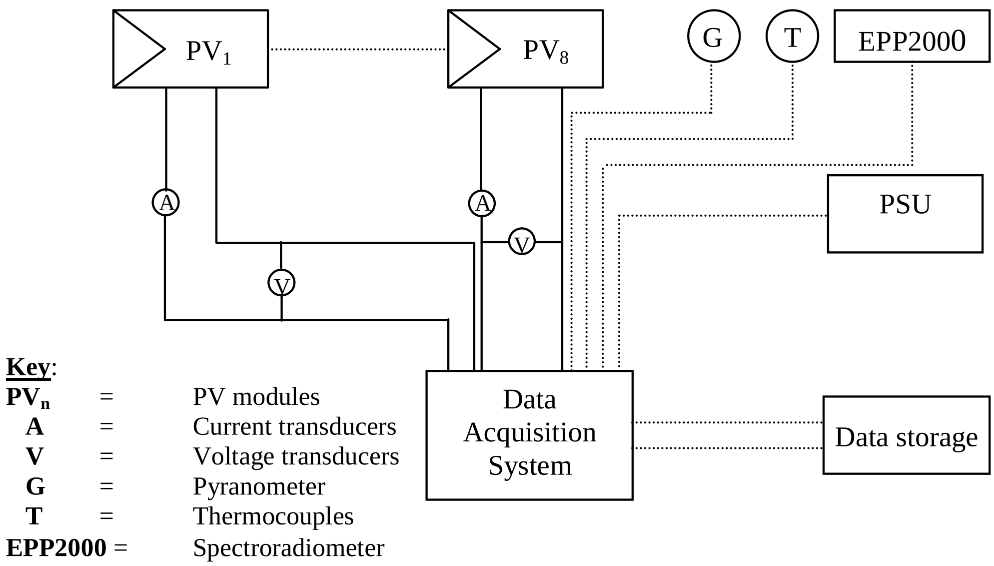

Figure 4.1: *Block diagram of the I-V curve tracer.*

This low cost I-V tester is fast, accurate, portable and above all reliable. The system employs a programmable variable PSU as load that enables the I-V curve to be swept from I_{sc} to V_{oc} in an average time of 2 seconds. Apart from I-V data points, the DAS also acquires meteorological parameters, i.e. irradiance, ambient temperature and solar spectral content. Back of module temperature is also measured. A detailed description of how the performance and meteorological parameters were obtained is given in subsequent sections.

4.3 SYSTEM COMPONENTS AND OPERATION

4.3.1 Data Acquisition System

The measurement of the current-voltage data, using this tester was facilitated by a data-acquisition system comprising two plug-in-cards, the high precision PCI- 6228 A/D card from National Instruments (NI) and the PCI 4351 temperature card. Analog signals from the current and voltage transducers and pyranometer were measured with the A/D card. This card was also used to output digital signals to control relays and output analog signal from 0-10 V in differential mode. All temperature signals were read using the temperature card. Figure 4.2 illustrates the electronic components used in the build up of the system.

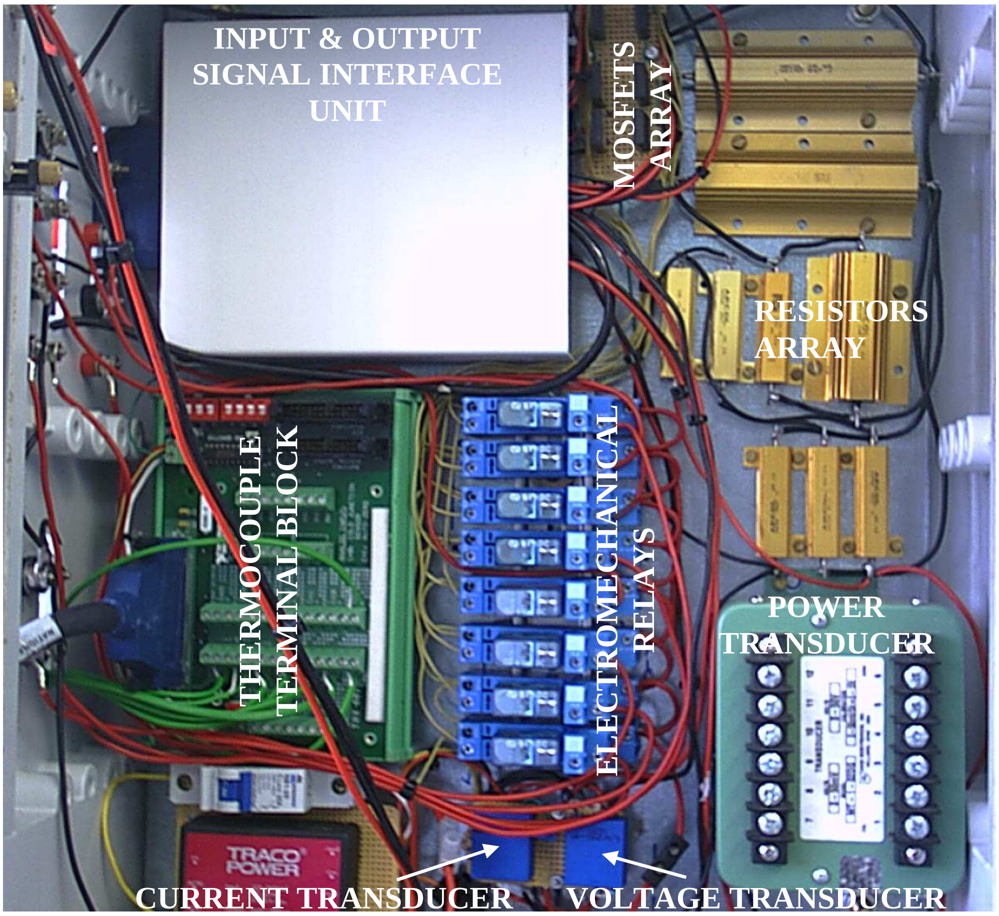

Figure 4.2: *Electronic Components used in the build up of the system.*

4.3.2 Programmable Power Supply Unit

The corner stone of this project was the use of a power supply unit employed as the electronic load. This means that a highly, reliable and accurate power supply was needed for this project. The one used is model 30/20 Elteknix Universal Power Supply from Elteknix Electronics Corporations.

The main specifications of this PSU are:

(i) High stability/low ripple.

(ii) Forced air-cooling.

(iii) Output voltage range of 0 to 30 V continuously adjusted automatically in steps 0.5 V through labview programme.

(iv) Current rating of 0 to 20 A. The PSU have the capacity to sustain short circuit current indefinitely.

(v) Low noise and can be operated in an environment with humidity close to 70%.

These specifications were of major importance in choosing the power supply for this study [Elteknix manual, 2005]. Since the 0-10 V DC control voltage is supplied by the same PCI-card that reads the PSU output voltage, there is bound to be some interference. To compensate for this, a dual isolation amplifier is used. This isolator has two input channels of a voltage range between 0-10 V DC and an output voltage range of 0-10 V DC. The isolation amplifier has an input to output isolation of 500V DC. These specifications are of crucial importance for the overall device performance.

4.3.3 Current Measurement and Calibration

The LA 55-TP model transducer is a closed loop current sensor consisting of a Hall generator mounted in a gap of a magnetic core, a coil wound around the core and a current amplifier. Figure 4.3 illustrates the internal circuit of this device.

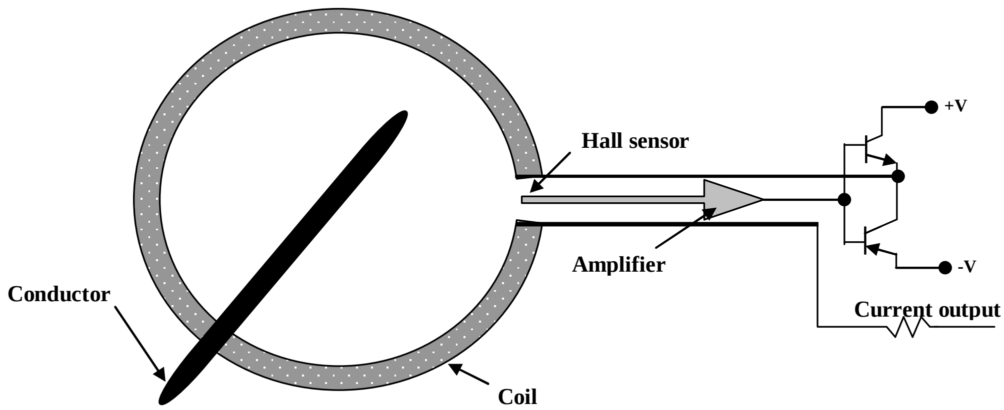

Figure 4.3: *Internal diagram of the closed loop Hall-Effect current-transducer.*

The current carrying conductor which is placed through the aperture of the sensor produces a magnetic field proportional to the current flowing. This magnetic field induces a current in the coil with an associated potential difference called the Hall voltage. This is measured by the Hall sensor, amplified and fed to the PCI-card as a 0-5 V signal. The current through the coil produces an opposing field to that provided by the current through the aperture leading to the flux in the core to be driven to zero. The output is a current proportional to the aperture current multiplied by the number of turns on the coil. The output current is converted to a voltage by a shunt resistor. This output voltage is scaled using the resistor [www.chenyang-gmbh.com]. The correlation between the input signal (PSU) and the output signal (Labview) which is read by the PCI-card is linear relationship illustrated in figure 4.4.

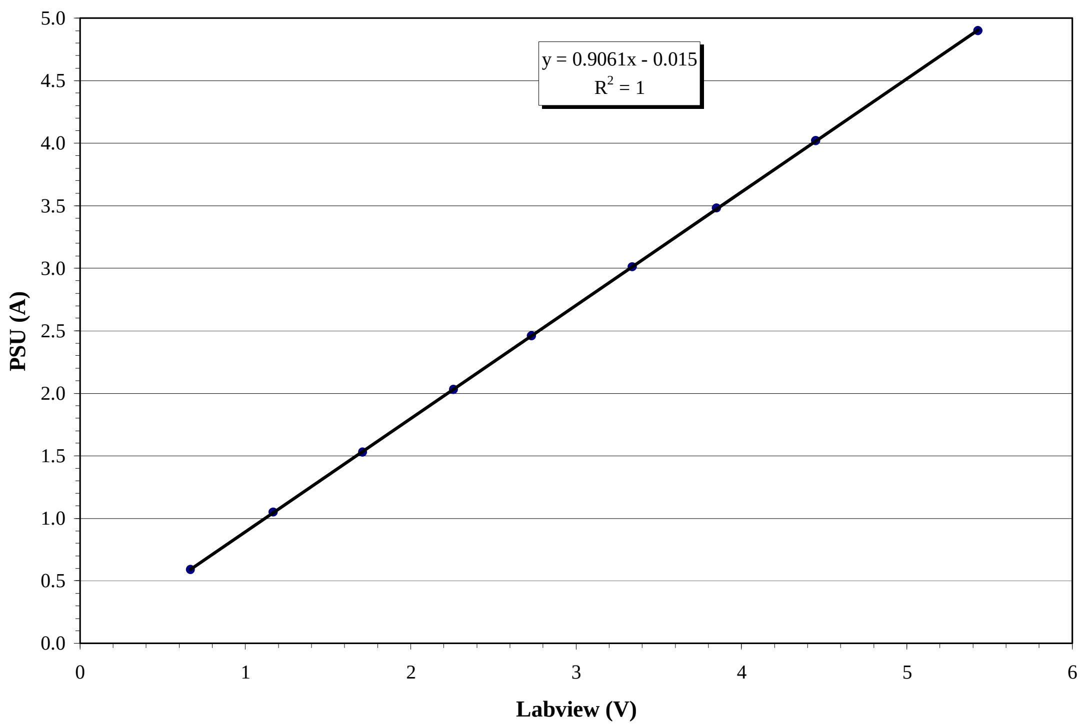

Figure 4.4: *Calibration curve for the Hall-Effect current-transducer.*

The graph as illustrated represents the entire range of the device. The procedure used for calibration of the current sensor was based on using an external power supply as a current source. The current of the power supply was manually increased in steps of 1 A and the corresponding voltage output was read by a calibration programme using Labview language. This procedure was repeated until the output voltage signal was 5 V which is the maximum signal that can be sustained by the PCI-card.

The equation obtained is used to calculate the equivalent current output in the programme. The coefficient of correlation R^2 is equal to 0.9999, which means that 99.99% of all points not lying on the line are being represented by the linear fit.

4.3.4 Voltage Calibration

Voltage measurement was done with an LV 25 P-voltage transducer. This device is a Hall Effect voltage sensor based on the magnetic compensation principle. Figure 4.5 illustrates the schematic diagram of this device.

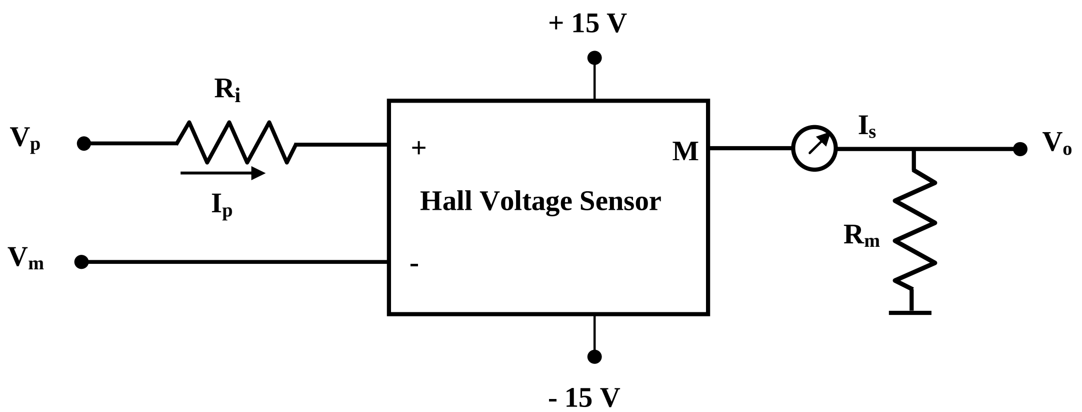

Figure 4.5: *Schematic diagram of LEM voltage transducer illustrating the connection principle [www.lem.com, 2004].*

For DC voltage measurements, a magnetic field is firstly generated by current I_p when a voltage ($V_p - V_m$) is applied on the input terminals of the sensor through the primary resistor R_i. The generated magnetic field is compensated with the reverse magnetic field caused by the current in the secondary coil. The field compensation is detected with a Hall Effect element. When the magnetic flux is zero, equation 4.1 is obtained

$$N_p I_p = N_s I_s \qquad \text{...........4.1}$$

where:	I_p	=	primary current
	I_s	=	secondary current
	N_p	=	primary turns
	N_s	=	secondary turns

The I_s is the output current of the sensor and therefore the (V_p - V_m) is easily measured using the resistor R_m. Although this device can measure a voltage range of 10 - 2500 V, the primary resistor R_i should be selected in a way so as to obtain optimal accuracy for the measurement range. Also, selecting a proper measuring range prevents overheating of the device, thereby guaranteeing high electric isolation.

Although a suitable measuring range can be selected, the relationship of the input signal and the output signal is not accurately linear. Therefore, a conversion relationship had to be established. To establish an accurate linear relationship between the input voltage signal and an output signal, the following methodology was adopted since the device in this case was used to measure low voltages. A voltage signal from the external power supply was used to supply a constant signal to the device input terminals. Each time the applied voltage signal was increased in steps of 1 V, the consequent voltage value was read using Labview. The procedure was done until the maximum voltage value read from the card was 5 V. A typical operational range of 0-25 V input signal from each module was achieved as is clearly represented by figure 4.6.

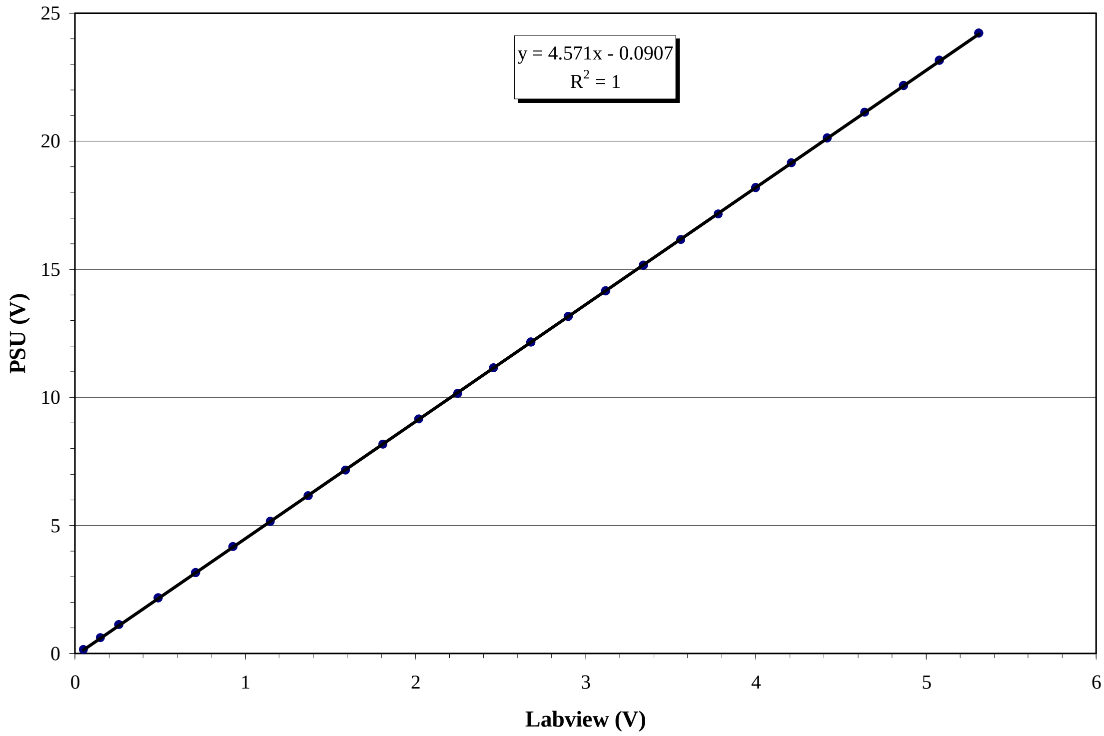

Figure 4.6: *Calibration curve for voltage transducer showing the relationship between applied voltage (PSU) and Labview values.*

The equation obtained was fitted into a formula in Labview programme in order to have the actual voltage values. The reading obtained using this method was found to be equally similar to the actual value as can be noticed by the coefficient of correlation R^2, equal to 1. This means that the calibration value is 100% accurate.

4.3.5 Operational Principle of the I-V tester

The I-V tester measures the current and voltage of the eight PV modules separately. Transducers, as described in previous sections, measure all the electrical performance parameters. The circuit diagram of the I-V tester is shown in figure 4.7.

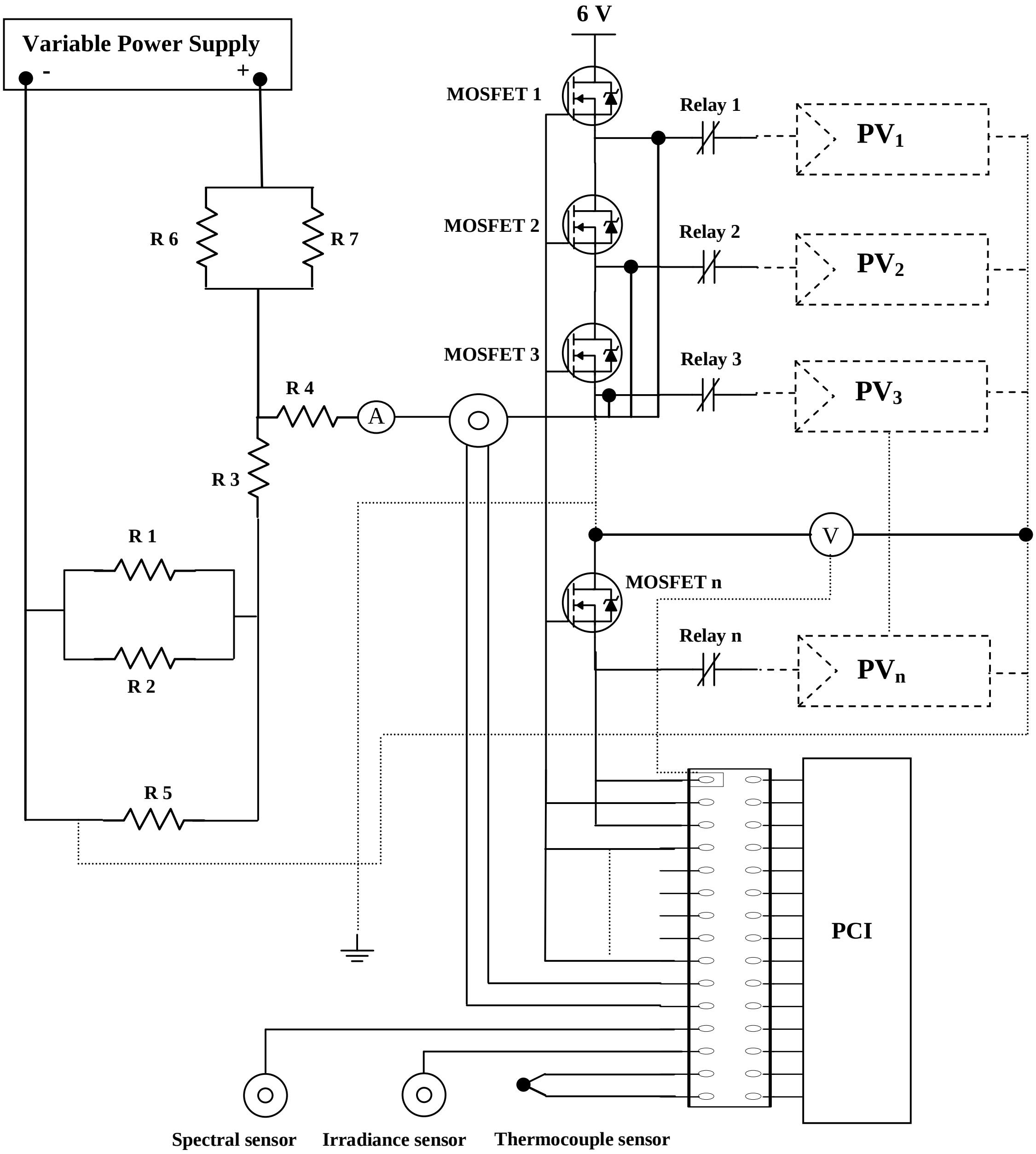

Figure 4.7: *Circuit diagram of the I-V tester used in this study.*

The operational algorithm of the I-V tester is as follows: A digital signal (5 V on high or 0 V on low) from the PCI-card is sent through channel 1 to switch an n-channel power Metal Oxide Semiconductor Field Effect Transistor (MOSFET) connected to it. The MOSFET are connected separately to a digital output channel of the pci-card through the

NI DAQ SCB-68 pin shielded connector block. One main reason for the use of power MOSFETs for switching is their unique characteristics and capabilities that are not offered by ordinary transistors. The n-channel MOSFETs are controlled for switching 'ON' (high) and 'OFF' (low) by a gate-source voltage (V_{gs}) from a digital signal. The applied voltage V_{gs} allows drain current to flow. Since these devices can not handle high current flow between drain-source, an external constant DC- source of 6 V is connected to the drain-source. When the external DC source is switched ON by the MOSFET, the source therefore energizes the high current electromechanical relay connected to it, and the relay switches ON, allowing the PV module current that is connected to the output terminals to have a complete flow path. The reverse process happen when a low digital signal is sent to the MOSFET which switches to OFF state, disconnecting the external DC source; therefore deselecting the module.

Once the PV module is selected, a signal is sent to an analog channel so as to output a signal in the range of 0-10 V in steps of 0.5 V. Analog out signal connected to the PSU input channel through the signal isolator, steps the PSU voltage. The 0-10 V output signal is equivalent to the 0-30 V output on full scale of the variable PSU. The output voltage signal from the PSU through channel 2 is interfaced to the main unit of the I-V tester for a full I-V curve data points. Once the first module I-V curve is completed, the module is deselected and the digital signal from channel 2 is sent, and the complete procedure for module 1 is repeated until all the eight modules are complete. Data is stored in an external ASCII file for easy processing.

The I-V tester takes approximately 2 seconds to obtain an I-V curve form I_{sc} to V_{oc} of a particular module. Within this time meteorological parameters such as irradiance, ambient temperature and back-of-module temperature are constant for all practical purposes. The measured I-V data points for each module are saved as an external ASCII file, which can be imported into spreadsheets or a database. Also measured are meteorological parameters such as plane-of-array irradiance and ambient temperature. Back of module temperature is also measured. The system's electrical components are communicated with through Labview programming language. Figure 4.8 shows the complete system and its interface in operation at our outdoor research facility.

Figure 4.8: *Computer interface I-V tester deployed at our outdoor research centre*

4.3.6 I-V tester data validation using solar cell theoretical model

In order to accurately determine the important parameters for device performance characterization, the results from measuring devices should be of acceptable accuracy with regards to the cost. The tester was subjected to some experimental tests before actual data logging was conducted. Different module technologies were used and the results were compared to the one obtained using one of the solar cell models to ensure a good correlation exists. The model [Hanitsch, R; 1996] makes use of many assumptions whose effect greatly affect the performance of the device in real operating conditions. The shunt resistance (R_{sh}) of the module is assumed to be infinite, neglecting the current flow within the R_{sh}. The series resistance is assumed to be independent of the incident solar radiation and the surface module temperature. The third assumption is that the short-circuit current (I_{sc}) is equal to the light generated current [Ahmad, 2003]. Figure 4.9 illustrates the measured and modeled mc-Si I-V curve. It should be noted that the day in question when this experiment was conducted, the global irradiance was 1047 W/m^2, ambient temperature (T_{amb}) was 31^{o}C and the back-of module temperature (T_{back}) was 61^{o}C.

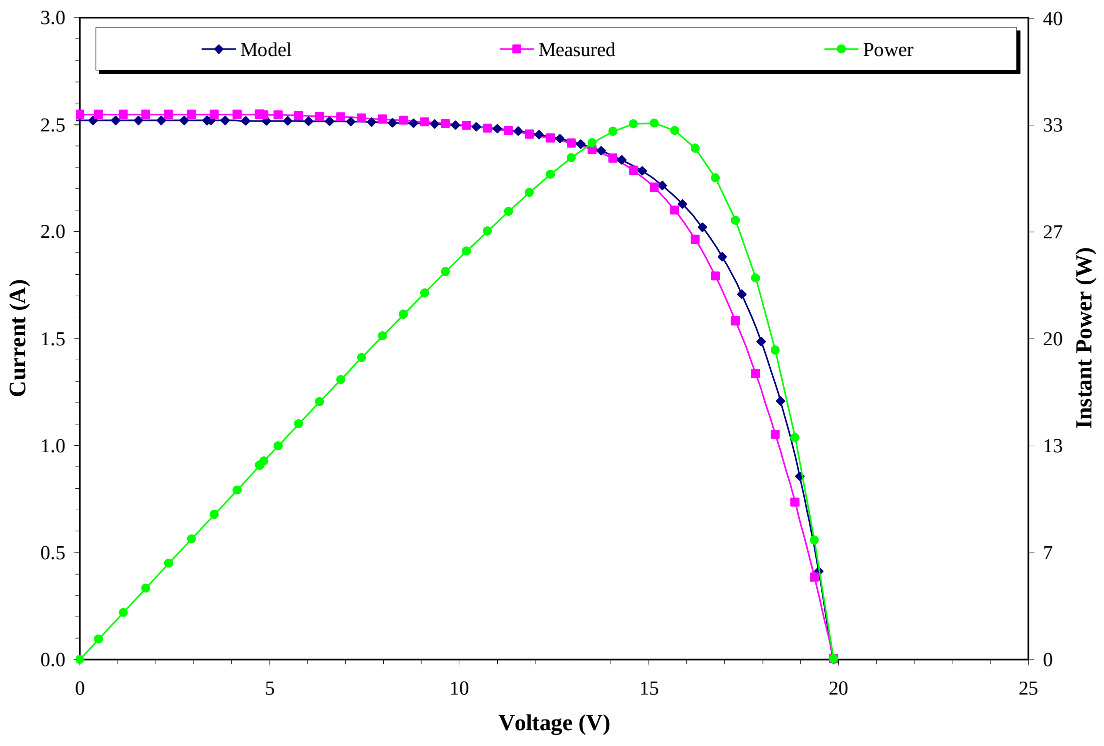

Figure 4.9: *Measured mc-Si I-V curve compared with the calculated I-V curve using the solar cell model in equation 4.3. The ambient conditions were irradiance = 1047 W/m^2, T_{amb} = 31^{o}C and T_{back} = 61^{o}C.*

The results illustrated in figure 4.9 demonstrate a good match between the measured and I-V curves. The assumptions adopted for modeling have a great effect in determining the final performance parameters of solar cells, but the point remains that it is a good tool for quick data comparison at little cost.

4.4 METEOROLOGICAL PARAMETERS

Accurate measurement of full spectrum solar irradiance is fundamental to the successful implementation of photovoltaic solar systems. Historically, acceptable accuracy of measurement has been achieved using expensive thermopile-based pyranometers and pyrheliometers. The following sections describe the devices for accurately monitoring the solar irradiance used in this work.

4.4.1 Plain-of-array Irradiance Measurements

Thousands of photovoltaic systems, large and small, are now being installed worldwide. As a result, there is a growing demand for inexpensive devices for accurately monitoring the solar irradiance. For most system application, reasonable accuracy (±5%) at low cost is usually preferred as opposed to high accuracy (±2%) at high cost [King, et al., 1998]. As a result, silicon photodiode pyranometers manufactured by companies such as LI-COR Incorporated and Kipp & Zonen are now commonly used for solar resource measurements and photovoltaic system monitoring. The pyranometer (CM 6B type) from Kipp en Zonen Incorporated Company was used to measure the plane-of-array (POA) irradiance at our research centre.

The CM 6B type pyranometer is designed for field measurement of global solar radiation in agriculture, meteorological and solar energy studies. In clear unobstructed daylight conditions, the CM 6B pyranometer compares favorably with first class thermopile type pyranometer.

4.4.2 Temperature Measurements

The Standard Testing Condition (STC), (1000 W/m² irradiance, 25 °C temperature) is used as reference to compare modules' performances under the same condition. The 25°C is practically too low, since most outdoor conditions result in cell temperatures closer to 50°C [Sandia, 2004]. Unfortunately, this difference between the actual operating temperatures and the STC temperature has often been a source of array design error and user dissatisfaction. Taking this into consideration, it was therefore imperative in this study to measure the back-of-module temperature and the actual 'user site' ambient temperature for full characterization mode.

Type-K (Chromel/Alumel) thermocouples were used in this study to measure the back of module temperature and the ambient (user site) temperature. The operational principle of thermocouple is based on the potential difference between a junction formed between two dissimilar metals. This potential difference is a function of temperature. Figure 4.10 shows a typical Type-K thermocouple used in this study.

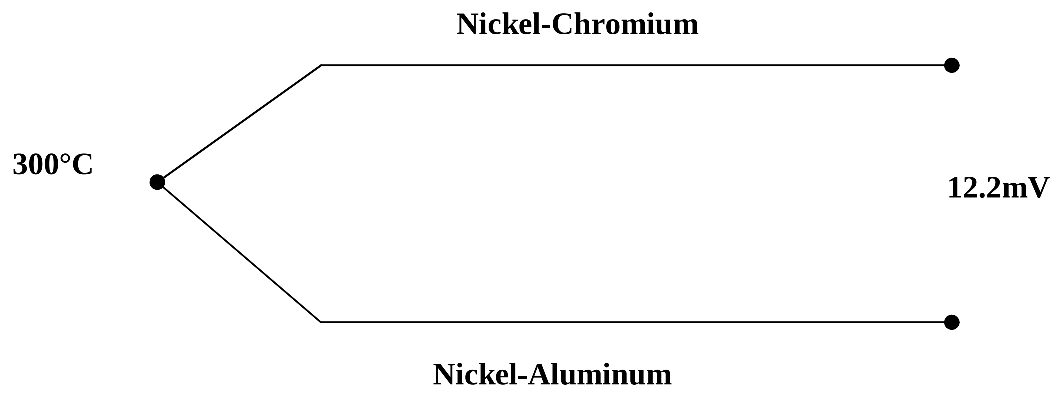

Figure 4.10: *Model of the Type-K thermocouple commonly used in temperature measurements.*

Practically, it is not desirable to simply connect a voltmeter to the thermocouple to measure the observed potential difference since the connection of the voltmeter lead will make a second, undesired thermocouple junction. This is compensated for by using cold junction compensation (CJC) [Picotech, 2004].

The typical cold junction temperature is measured through a precision thermistor in good thermal contact with the input connectors of the measuring instrument. This second temperature reading, along with the reading from the thermocouple itself is used by the measuring instrument to calculate the true temperature at the active junction. All temperature sensors are interfaced via NI TBX-68T terminal block with cold junction compensation settings. Type-K thermocouples have a temperature range of -200°C to +1200°C, with a sensitivity of approximately 41µV/℃ [Picotech, 2004].

4.4.3 Outdoor Spectral Measurements

The difference in outdoor spectrum from the standard reference indoor spectrum (AM 1.5) calls for a need to monitor and evaluate the effect of such changes. Understanding the spectral variations from location to location is of paramount importance in designing systems that are reliable and efficient. For outdoor spectral measurements, a portable EPP200 fiber optic spectroradiometer was used to take spectral measurements in the UV-VIS-NIR ranges. This device provides 2048 wavelengths for each scan from 350 nm to 1200 nm. The range and coarse resolution are determined by the spectrometers installed grating groove density. Resolution quality is determined by the installed slit size. The device is connected to the computers using the USB2EPP cable for best performance via USB-2 port.

4.4.3 Infrared thermography measurements

Infrared (IR) Thermography as a technique for failure analysis modes in electrical industries, has find its way also into the energy sector, photovoltaic being one. IR Thermography's operation is based on the use of infrared spectral band. The thermal radiation signal detected by the Infrared (IR) camera is the product of the temperature dependent black body radiation and the value of the local IR emissivity, which usually equals the absorbance and is always less than 100% [Breitenstein, et al., 2006].

A black body is defined as an object which absorbs all radiation that impinges on it at any wavelength. Max Planck described the spectral distribution of the radiation from a black body as:

$$W_{\lambda b} = \frac{2\pi hc^3}{\lambda^5 \left(e^{hc/\lambda kT} - 1\right)} \times 10^{-6} \left[Watt/m^2 \mu m\right] \qquad \text{...........4.2}$$

where:	c	=	speed of light
	h	=	Planck's constant
	k	=	Boltzmann's constant
	T	=	Absolute temperature (K) of a black body
	$W_{\lambda b}$	=	Black body spectral radiant emittance at wavelength λ

The device used in this study is a Thema CAM™ E300 manufactured by FLIR Systems. The system has the following specifications:

1. It is adjusted manually and has a start-up time of 15 seconds.
2. It comes equipped with a detector type of Focal Plane Array (FPA) and a spectral range of 7.5 – 13 µm
3. Has a 2.5″ color LCD
4. Temperature range which is subject to customer configuration.
5. Accuracy of ±2 ^{o}C or 2% of the reading
6. It has a semiconductor AlGaInP diode laser, of wavelength 635 nm and power of 1 mW.

Before outdoor deployment of PV modules, the ThermaCAM was used to determine the presence of defects through the variation of thermal distribution under both forward and reverse bias.

4.5 SUMMARY

A set of techniques used to evaluate various phenomena observed in this study was discussed in terms of the operational principles. A full description of the I-V tester used in this study including its main components and the operational mode was discussed. The sequence guideline of the I-V tester together with a clearly elaborate circuit diagram was also presented. A good fit between the I-V curve obtained using the solar cell model and the one obtained using the I-V tester was high lightened in this chapter. The use of Infrared thermography in PV application for diagnosing faults in solar cells was also discussed. The importance of and need for evaluating the varying outdoor spectrum were identified. Spectroradiometry as a methodology for measuring such spectral shifts during the course of the day and its basic operation was presented.

4.6 REFRENCES

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