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## **AC 2011-1842: A LOW-COST LABORATORY EXPERIMENT TO GENERATE THE I-V CHARACTERISTIC CURVES OF A SOLAR CELL**

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# A Low-cost Laboratory Experiment to Generate the I-V Characteristic Curves of a Solar Cell

## Abstract

Renewable energy is rapidly becoming a high priority of the United States and other countries as the search continues for renewable energies to replace our rapidly dwindling supply of fossil fuels that are so heavily relied upon. It is up to the instructors of today to teach the technologists and engineers of our future how to utilize these renewable energies effectively. This paper discusses a low-cost laboratory experiment that will generate the I-V curve of solar cells that can be used in a curriculum. This experiment uses a low-cost data acquisition system, the LabVIEW program, and a current sink circuit made of discrete components. The development of the I-V characteristic curve experiment was partially funded by the Science, Engineering and Technology Gateway Ohio (SETGO) Summer Research Program at Bowling Green State University which facilitated undergraduate research and was sponsored by the National Science Foundation.<sup>1</sup>

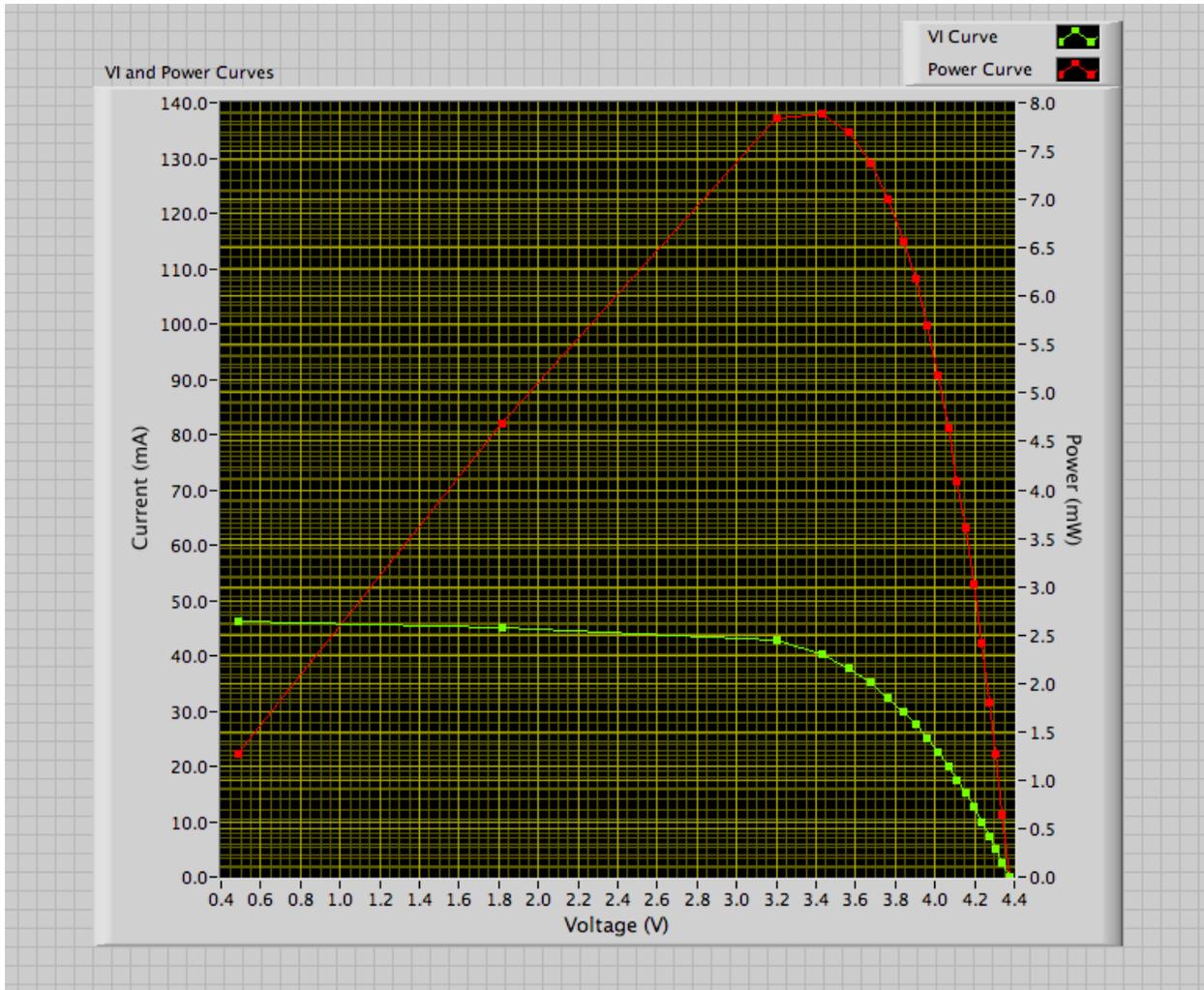
## Solar Cell I-V Characteristic Curves

Solar cells are characterized by their current-voltage (I-V) characteristic curves.<sup>2,3</sup> An example of one is shown in green in Fig. 1. This curve shows how the voltage generated by the solar cell varies with the current drawn from it. The I-V curve shows how the solar cell will operate under varying parameters such as light intensity and temperature. Ironically, the hotter the solar cell gets, the less efficient it becomes. With the solar cell being underneath the sun all day, this becomes an issue.

Two important points on the I-V characteristic curve are the short circuit current  $I_{SC}$  and open circuit voltage  $V_{OC}$ .<sup>2,3</sup>  $I_{SC}$  is the current measured when the output to the solar cell is shorted and the voltage across the solar cell is zero.  $V_{OC}$  is the voltage measured when the solar cell has no load and thus, the current through the cell is zero. These parameters will vary with increasing temperature as  $I_{SC}$  will increase slightly and  $V_{OC}$  will significantly decrease.

There is a point on the I-V characteristic curve at which the power drawn from the solar cell is at its maximum which is called the maximum power point (MPP).<sup>2,3</sup> The power drawn by the solar cell is plotted in red in Fig. 1. It can be seen that the MPP of the I-V curve is just below the knee of the curve. Multiplying the current  $I_{MP}$  at the MPP by the voltage  $V_{MP}$  at the MPP will result in the maximum power  $P_{MAX}$  that can be drawn:<sup>3</sup>

$$P_{MAX} = V_{MP} I_{MP}$$



**Fig. 1.** LabView front panel (right side)

Operating the solar cell at the MPP will achieve the maximum efficiency of the solar cell:

$$\eta = \frac{P_{MAX}}{P_{in}}$$

where  $P_{in}$  is the product of light intensity ( $\text{W}/\text{m}^2$ ) with the surface area of the solar cell ( $\text{m}^2$ ).<sup>3</sup> Thus, the MPP is the optimal operating point for the solar cell.

Another parameter that is used to characterize solar cells is the Fill Factor (FF) which is the ratio of  $P_{MAX}$  to the product of  $V_{OC}$  and  $I_{SC}$  and measures how well the I-V curve approaches an ideal square shape whose edges are defined by  $V_{OC}$  and  $I_{SC}$ .<sup>3</sup>

$$FF = \frac{P_{MAX}}{I_{SC}V_{OC}}$$

Solar cells can be connected in combinations of series and parallel to form solar modules or solar arrays. For modules and arrays, the shape of I-V curve does not change although it will be scaled based on number of cells in series and parallel. For N cells in series,  $V_{OC}$  will increase by N times. For M cells in parallel,  $I_{SC}$  will increase by M times.<sup>3</sup>

### **Generation of the I-V Characteristic Curve**

The I-V curve can be generated using a voltmeter, ammeter, and a variable resistive load.<sup>2</sup> The load can be used to vary the current drawn from a solar cell in steps. The voltage across the solar cell is measured at each step. The curve is difficult to generate by this method because of the number of data points required to generate a smooth curve. This process can get especially tedious if I-V curves are required at varying parameters such as light intensity and temperature. Instruments exist that can generate these curves automatically, however, they are too expensive for the typical laboratory experiment.<sup>4,5</sup> As an alternative, a low-cost system to generate the I-V curve was developed. This system consisted of a laptop, a data acquisition (DAQ) device, a current sink circuit, and a solarimeter or solar power meter.

The low-cost system was designed to be portable and to be powered by the laptop's USB port and a 9V battery. This was done so that the system could be carried outside to use the sun as the light source as artificial light sources accurately simulating the spectrum of the sun are also too expensive for the typical laboratory experiment.

To automatically generate an I-V curve, a circuit was needed to control the solar cell current. A current sink circuit was chosen to connect to the solar cell so that the solar cell current could be varied and the resulting voltage across the solar cell measured. A data acquisition (DAQ) device running LabVIEW was chosen to output a voltage to control the amount of current the current sink would draw, and then measure the resulting solar cell current and voltage. The DAQ and current sink circuit were used together to automatically generate an I-V curve. To help locate the MPP, the power curve was also plotted.

Commercially available current sink systems such as the National Instruments PXI-4130 Power Source Measure Unit cost around \$2,000-\$5,000 depending on the hardware and software combination used.<sup>5</sup> Purchasing the parts for the low-cost current sink circuit will total out to

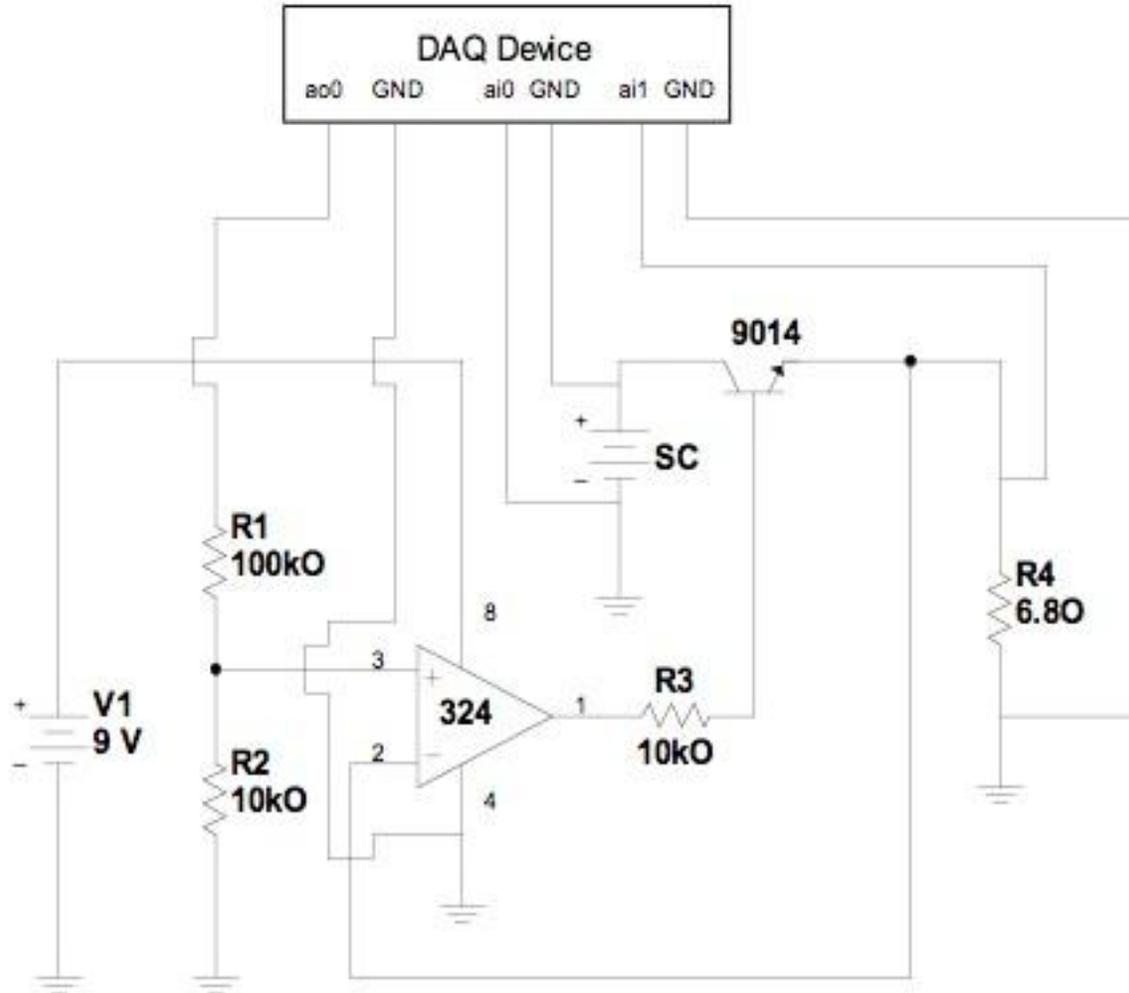
about \$5-\$20, depending on whether or not the circuit will be built temporarily on a solderless breadboard or more permanently on a printed-circuit board.

The low-cost current sink circuit is shown in Fig. 2. It is essentially a linear current regulator which will be connected to the solar panel represented by the voltage source SC. This circuit was designed to work with a solar module with a  $V_{OC}$  from around 4 to 5V and an  $I_{SC}$  from 40 to 50mA. The NPN transistor operates in the active mode and will control the current from the solar panel which will be proportional to the base current. The base current is supplied by the operational amplifier (op-amp). The inverting input of the op-amp is connected to the resistor R4 which acts as a current sensor for the solar panel as the voltage across it is proportional to the current running through it. The non-inverting input of the op-amp is connected through the voltage divider formed by R1 and R2 to the analog output ao0 of the DAQ. Connected with negative feedback, the op-amp will adjust the transistor base current so that the voltage at the non-inverting input is close to the voltage at the inverting input. Since the voltage across R4 is directly proportional to the current through it, this will allow ao0 to control the current drawn from the solar cell.

The drawback of the current sink circuit in Fig. 2 is in the measuring of  $I_{SC}$ . With any current running through it, the voltage drop across the current sensing resistor R4 will not be zero, thus the actual value of  $I_{SC}$  can not be measured. In addition, the transistor will have a voltage drop from its collector to its emitter. The effects of this drawback can be seen in Fig. 1 where the lowest voltage on the I-V curve is about 0.5V.

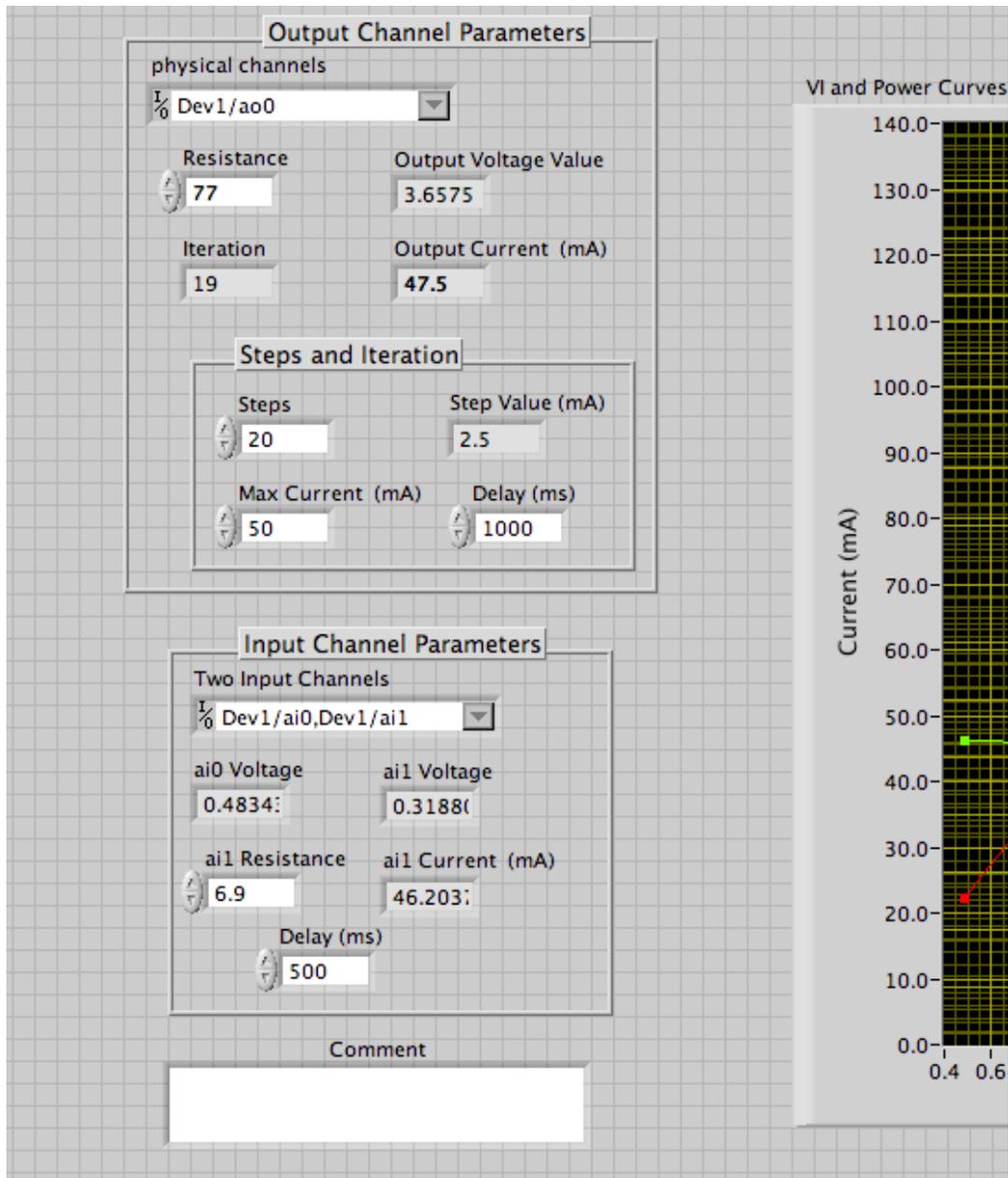
The DAQ used was the National Instruments USB-6008.<sup>6</sup> The DAQ device is programmed through and powered by a USB port on the laptop. The DAQ consists of 12-bit analog to digital (A/D) inputs and digital to analog (D/A) outputs. The DAQ was wired into the current sink circuit as shown in Fig. 2. The DAQ output ao0 is used to output a voltage to control the amount of current drawn by the current sink. Input ai0 is used to measure the voltage across the solar cell. An additional input, ai1, is used to measure the actual current drawn by the current sink as the current sink is limited in range and its current to control voltage transfer function is nonlinear.

The DAQ system was programmed with LabVIEW.<sup>7</sup> LabVIEW is a graphical based programming platform which uses a programming language called G. It consists of a front panel and a block diagram. The front panel shows controls and indicators which are used to change and display variables of the program. The block diagram portion displays a block diagram representation of the program.



**Fig. 2.** Current Sink circuit

Fig. 1 and Fig. 3 show the front panel for the I-V characteristic curve LabVIEW program. The front panel allowed for the setting of parameters for the DAQ input and output channels. For the output channel, controls were used to select the DAQ output channel, the ratio (resistance) of the control voltage to sink current, the maximum current sink current, and the number of steps of current that are to be used for the I-V curve. A control was also included to set the delay between changing the sink current and measuring the resulting solar cell current and voltage. Indicators were used to show the control voltage for the current sink, the current drawn by the sink and the change in current for each step. For the input channels, controls were used to select the DAQ input channels, the resistance of the current sensing resistor, the time delay between measuring the resulting voltage across and current through the solar cell and changing the control voltage to the current sink. Indicators were used to show the voltage across the solar cell, voltage across the current sensing resistor, and the current through the solar cell.

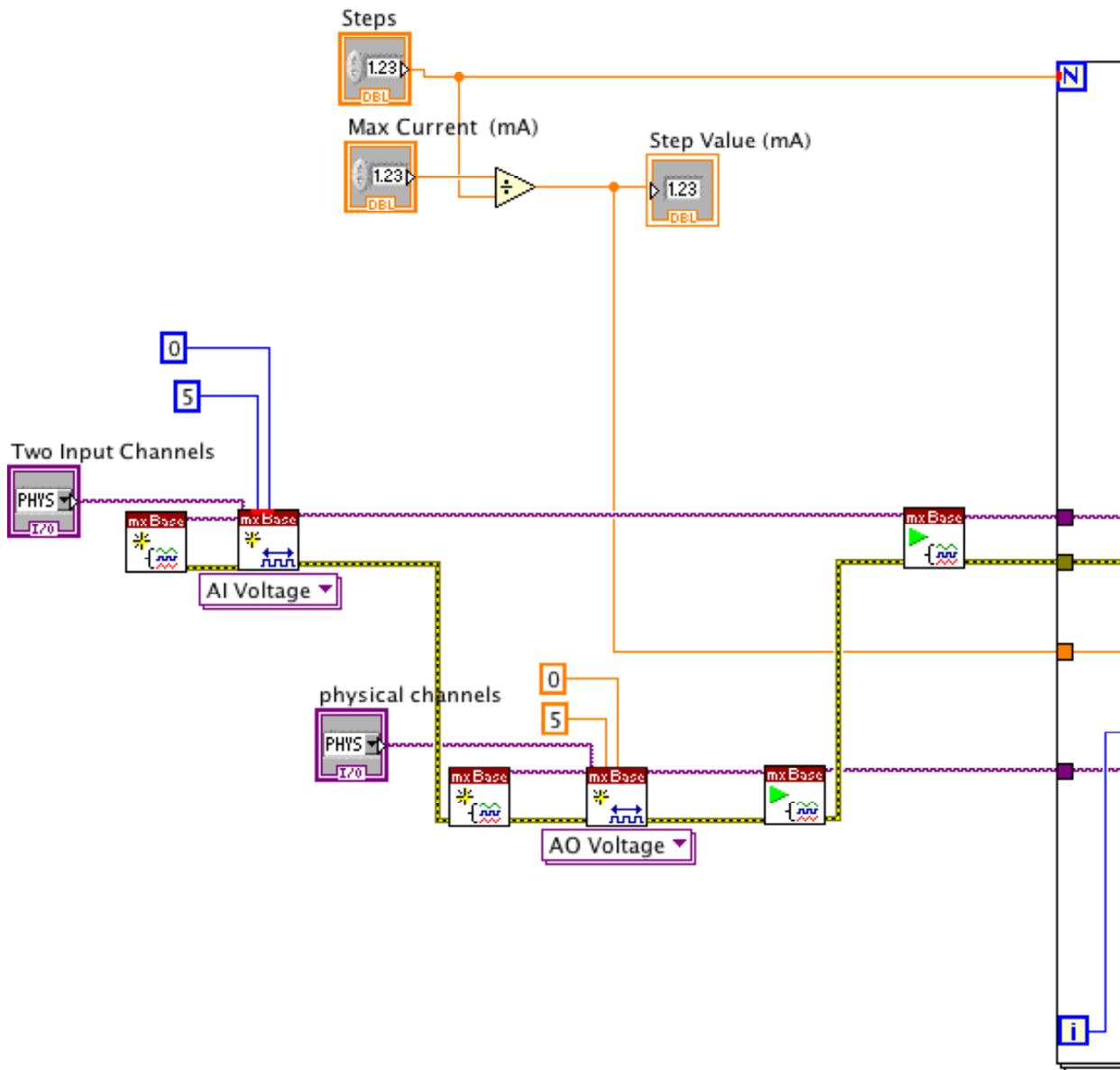


**Fig. 3.** LabView front panel (left side)

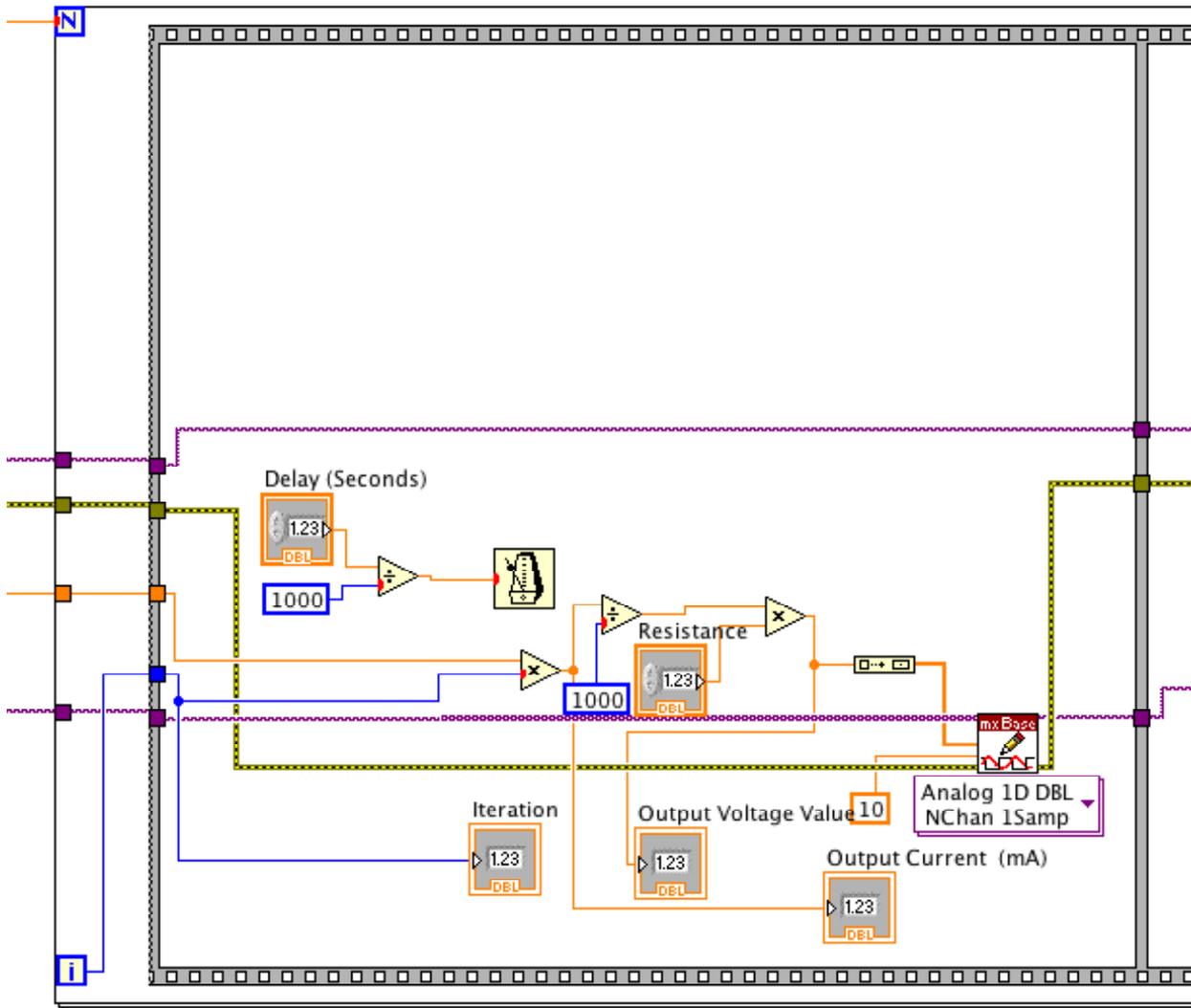
Fig. 4 through Fig. 7 show the block diagram for the LabVIEW program. This is where all the mathematical and programming operations are actually carried out. Blocks representing the controls and indicators on the front panel can be seen. Fig. 4 shows the setting up of the input and output channels and the step values of current. The DAQ needed to output a voltage to the current sink, delay a specified time, obtain two voltage measurements, delay again, and repeat. To sequence this, NI-DAQmx Base blocks and a Flat Sequence Structure were used.

The Flat Sequence Structure operates similar to a film reel in which the left frame in Fig. 5 executes first, then the right frame in Fig. 6. The frame in Fig. 5 outputs a voltage to the current

sink and delays. The frame in Fig. 6 then measures the voltage across the solar cell and current sensing resistor, calculates the current, and delays. Since the frames are repeated, the Flat Sequence Structure has been placed inside a While Loop. The While Loop performs all actions that are placed inside the loop for a specific number of times as specified by the “N” in the top left corner.



**Fig. 4.** Block Diagram (part 1)



**Fig. 5.** Block Diagram (part 2)

In Fig. 7, the current, power, and voltage information are wired to an XY Graph as well as to a Measurement File. Here, the I-V and power curves are plotted on the front panel and the data is recorded in a file that can be used in Microsoft Excel.

### **I-V Curve Experiment Evaluation**

The goal of this research project was to develop a lab to acquire the solar cell I-V curve that would be low-cost. The parts for the current sink circuit will cost about \$5-\$20 depending on the source and whether a solderless breadboard or printed-circuit board is used. These parts and appropriate substitutes are common and may be already be present in the laboratory. A solarimeter or solar power meter can be purchased for around \$150. The National Instruments USB-6008 DAQ device came packed with a Student Version of LabVIEW software and priced

at \$169. The price of the DAQ can be offset by its use in other lab experiments as only a small portion of this device's functionality was utilized.

One drawback of this experiment is using the sun as a light source. Whether or not the experiment can be successfully performed will depend on the weather. The data shown in Fig. 1 was taken while a solar cell was at a 90° angle to the sun's rays on a clear day. Once a clear day presents itself, varying the intensity of the light is not difficult as different intensities can be obtained by tilting the solar cell at various angles to the sun's rays. Although, care must be taken to make sure a cloud does not drift in front of the sun during performing the experiment as this will distort the I-V curve.

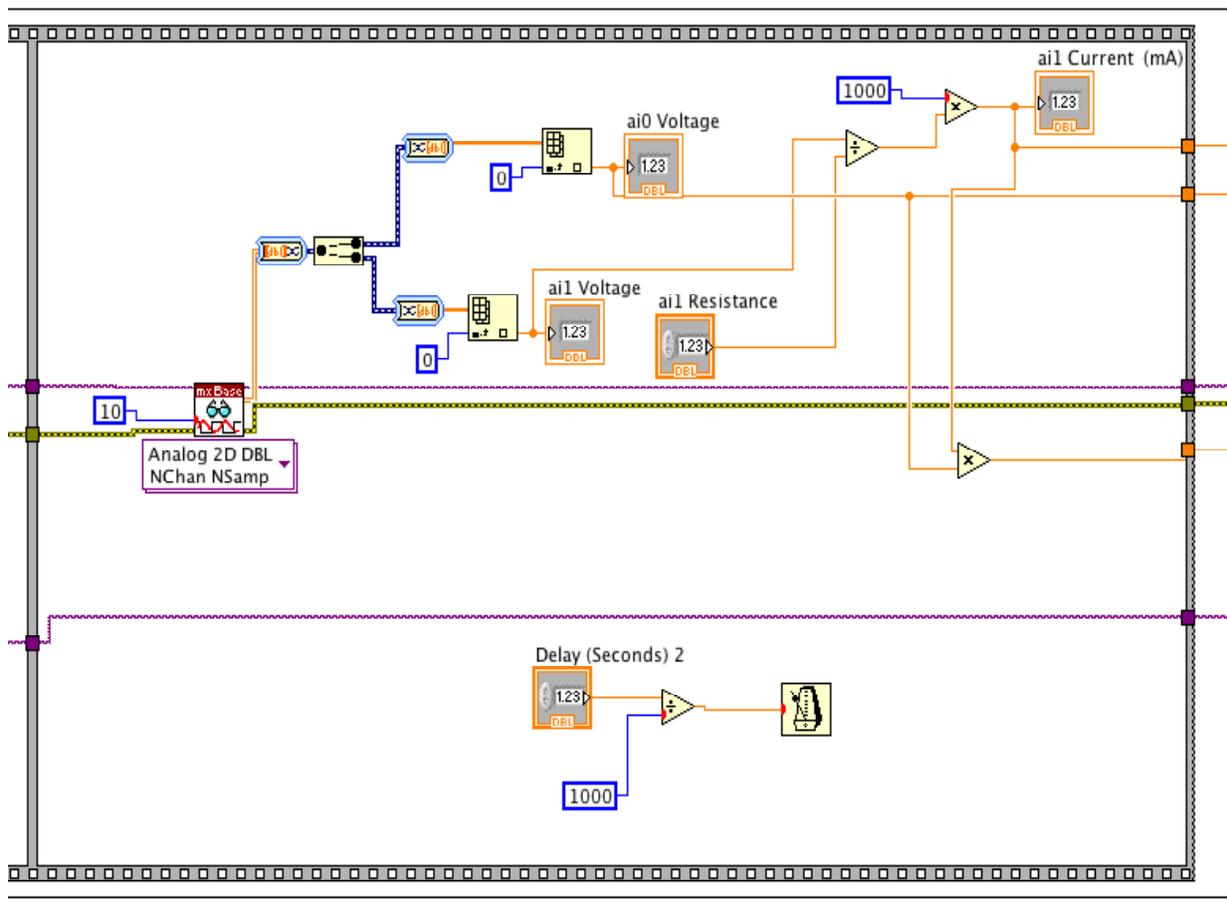
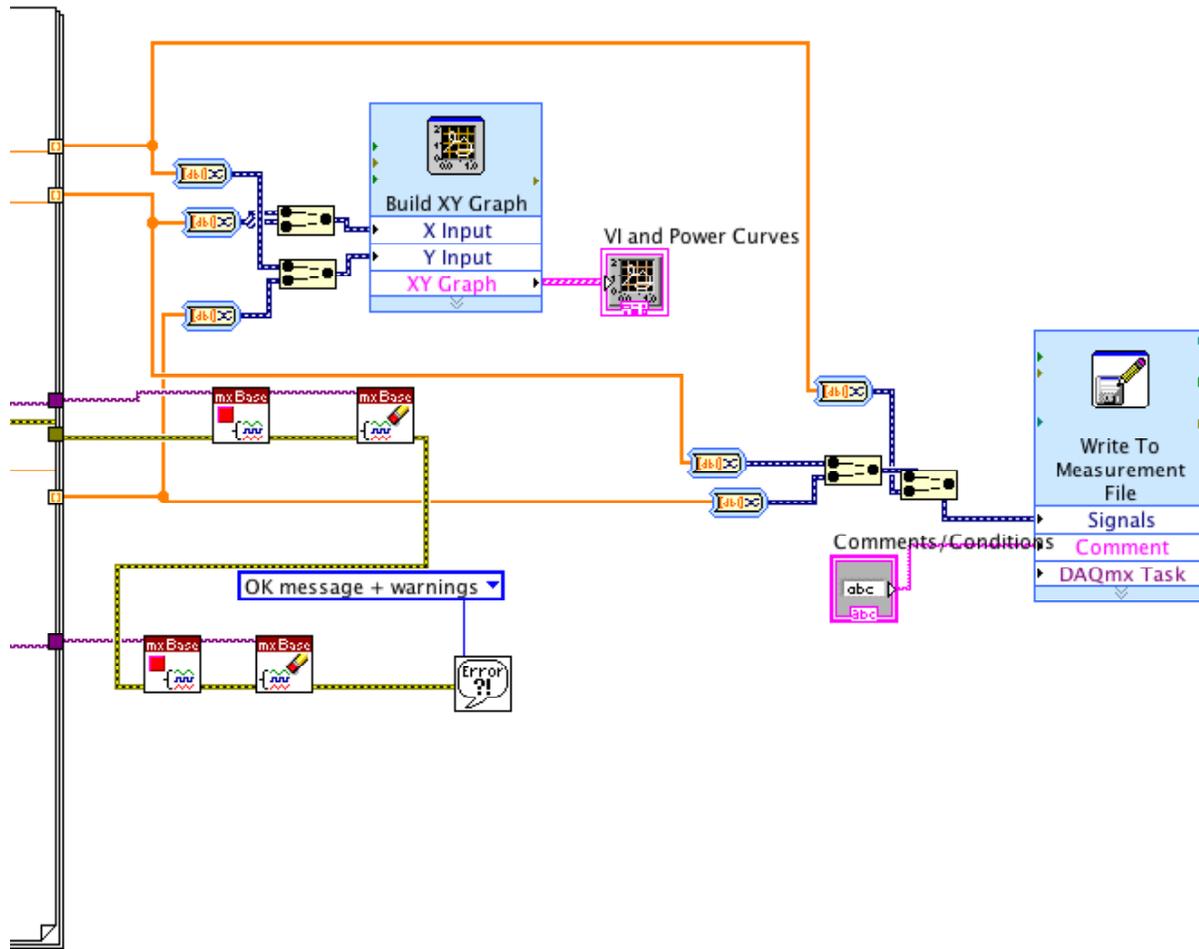


Fig. 6. Block Diagram (part 3)



**Fig. 7.** Block Diagram (part 4)

Safety considerations for this lab are minimal. The lab was designed to work with a solar module with a  $V_{OC}$  from around 4 to 5V and an  $I_{SC}$  from 40 to 50mA, so low currents and voltages are present. The current sink circuit uses a 9V battery while the DAQ is powered by a USB port.

Various components of this lab can be preassembled and preprogrammed depending on its intended use. For example, for a simple lab to obtain an I-V curve for a renewable energy class, the current sink circuit lab could already be built and the LabVIEW program already completed and downloaded into the DAQ system. The current sink circuit could be built by the students in class that focusing on linear integrated circuits or op-amps. The LabVIEW program itself could be programmed in a class covering instrumentation. The number of students that this experiment can accommodate will depend on what components are preassembled and preprogrammed and

the amount of time allocated for the lab. As this lab was developed as an undergraduate research project, it has not been run as a group lab yet.

The choice of which components of the lab that will be preassembled and preprogrammed will also depend on the knowledge level of the student and the amount of time available for the experiment. The student who developed this lab as an undergraduate research project successfully assembled the current sink circuit, developed the LabVIEW program, loaded the appropriate firmware into the DAQ, programmed it, and acquired I-V curves. This was done over the course of a summer, and the student previously had only a freshman electronics class and no prior experience with LabVIEW or op-amps.

The student outcomes for this lab were to make the student more aware of renewable energy techniques, in particular the use of solar cells, and what role they played in the generation of energy. Student outcome assessment was performed with a questionnaire with the following questions: How did this experiment influence your career choices? Are you more likely to consider a career in renewable energy in the future? How did this experiment affect your awareness of environmental issues? How did this experiment affect your knowledge of solar cells and how they are used? The student who developed this lab answered the questionnaire stating that it made him more interested in a renewable energy career and that he wanted to get involved in research developing more efficient materials for solar cells. It also made him realize that the solution to the energy and environmental problem will probably not lie with just one method of energy generation, but with a combination of them. He also learned about the importance of the maximum power point in solar power generation and the effect of the angle of the sun rays hitting the solar cell.

## **Conclusion**

In conclusion, a low-cost laboratory experiment that generates the I-V characteristic curve of a solar cell has been developed. It has been shown that the cost can be minimized by using a National Instruments USB-6008 DAQ with a Student Version of LabVIEW and by building a current sink from discrete components. Although, due to its low cost, the sun was used as the full spectrum source, and this puts a limit on the times when the experiment may be performed. Minimal safety requirements are needed with this experiment as low voltages and currents are present. Different components of the lab may be preassembled or preprogrammed depending on the curriculum, time available, and skills of the students. The student outcomes of making the students more aware of renewable energy techniques and the role they play in energy generation were achieved.

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