Evaluation of a More Efficient and Cost Effective Method for Interfacing the Power from Solar and Other Types of Distributed DC Generation with the AC Power System

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Abstract

Undergraduate research can be an important part of the engineering education. A good type of engineering project can allow students to demonstrate basis concepts, learn a generally accepted method, identify a potentially better alternative and then perform the related tests and analysis to evaluate the alternative. The results can be used in the class room as well as having the potential of being adapted as a substantially improved accepted practice.

This paper will describe such an evaluation. Specifically, the generally accepted method for interfacing distributed generation devices that produce direct current (DC) with our existing alternating current (AC) power system is to install inverters to convert the DC to AC in synchronism with the AC power system. It also requires assuring safety and equipment protection. The inverter adds significant cost and has conversion losses. It is also challenging to design an inverter that produces a sine wave that is compatible with the AC system. A less than perfect sine wave will produce higher harmonics that can cause static and distorted patterns on radio and tv reception and erratic action of some radio controlled devices such garage doors.

An alternative method of interfacing distributed DC power producing by distributed generation, such as photo voltaic panels and fuel cells, with the electric power system would be to convert the distribution system from AC to DC. The result would be a potentially simpler DC to DC interface. Such a system raises new issues over matching the DC voltage characteristics of distributed generation device with the DC distribution system in a manner at which losses are minimized while equipment is protected and safety is assured.

This authors have performed the preliminary tests that demonstrate some inherent voltage vs solar insolation characteristic photovoltaic panels. The results show a good compatibility for interfacing and supplying power to a fixed voltage DC distribution system. This is because the open circuit voltage is nearly constant over a wide range of solar insolation, while the current is proportional to solar insolation. Similar tests are recommended to determine the compatibility of interfacing the DC power from fuel cells with a fixed DC voltage distribution system.

The other consideration in converting the distribution system from AC to DC is to identify whether DC can be compatible with the full range of electric using equipment. Electric loads range from pure resistance of light bulbs and heaters, electronic such as computers and television and mechanical loads that are served by motors. It was determined that all end use equipment either works inherently or better on DC or can be with comparable or decreased difficulty to operate on DC rather than AC power.

1. Introduction

As primary fuels are depleted there there will be increased incentive and need to install distributed generation. The most promising is solar produced electricity because it consumes no fuel. The challenge with distributed generation such as solar is how to use it efficiently and cost effectively. The option of separation from the grid is fundamentally wasteful since supply can never continually match demand, and thus expensive and wasteful electric storage equipment is required. The other option has been to operate grid connected which now requires the wasteful and expensive conversion of the DC power from the solar cells to AC power in synchronism with the grid. A new and potentially more efficient and cost effective method would be to convert the end use service from AC to DC and thus interface the DC power from the solar panels directly with a DC system of comparable voltage.

The issues related to this option include the compatibility of the variety of end use equipment to operate on DC rather than AC, and the voltage and power transfer characteristics of the photovoltaic panels over a range of conditions. This analysis classifies end use equipment as 1) pure resistance loads such as most lights and heating elements 2) electronics and 3) motors. All this equipment can either operate on DC or be designed to operate on DC with no or minimal additional cost, and with some potential efficiency improvement of motors. The enabling technology is the combination of power electronics controlled by low price process computers.

Most existing photo voltaic devices are fabricated into panels, but the potential exists to dramatically decrease cost and increase area and output by embedding the cells in roof and outside wall materials. This dramatically increases the potential power production from solar and calls for some new thinking and analysis related to best utilization.

The new option the authors considered is the DC to DC interface between the solar panels and the system. A complication is that a DC distribution system will be nominally constant voltage, while the voltage versus the amount of solar input for solar panels is potentially variable. A fundamental quest became how variable. If nominally constant a simple interface without a voltage regulator on the solar panel is possible. If substantially variable a voltage regulator is required.

The other issue will be the amount of current back flow and power consumption by the panel if it remains connected when the sun does not shine or anytime the open circuit voltage is less than the DC distribution system voltage. A solar cell with no sunlight is nominally a diode and thus back flow will be small. Thus, it may or may not be significant. If insignificant no reverse flow protection is required. If significant a reverse current sensing and circuit opening device will be necessary.

Accordingly, the authors measured performance of photovoltaic panels in terms of output voltage, forward current and reverse current as a function of the solar power input. The results confirm support the potential for a much simpler and more efficient DC to DC interface with the electric distribution system. Other types of distributed generation include fuel cells that could also be interfaced with a DC distribution system in a more efficient and cost effective manner, but will require similar types of operating characteristics testing.

2. Background

A vital part of engineering education is to convey to students the engineering marvels that exist and how they were developed. A prerequisite for this evaluation is also requires a fundamental review and understanding of the history, design and operation of the existing central electric power system. It works so well that it is typically ignored or is taken for granted, except for the very rare system failures that are dubbed blackouts. It should always be appreciated as the technological marvel that is now vital to life and civilization as we now know it. The students developed a web page tracing some of the history of the electric power system (reference 1).

Our existing multiple voltage and transformer based electric system operates primarily on AC. This is not because AC is better than DC. It is because 1) AC generators are simpler than DC generators, 2) multiple voltage is needed to provide a combination of efficiency and safety and 3) traditional voltage transformers require alternating current.

Most electricity is produced at moderately high voltage in the stationary windings of generators that contain a strong and controllable strength electromagnet mounted on a rotating shaft that is driven by a turbine or any other source of mechanical power. The frequency of the alternating current (60 cps in the United States and 50 cps in many other countries) corresponds to the mechanical speed of the shaft. The voltage and/or phase relationship between the generator output current and voltage is controlled by the strength of the rotating magnet that is typically called the field. All generators on the system must be synchronized to operate at the same frequency.

The amount of power that can be transferred while retaining synchronism is proportional to the square of the voltage, while the resistance loss in the wires decreases with the square of the voltage. Thus, transmission voltage should be high as possible. This is achieved by a step up transformer at each power plant that is installed between the generator and outgoing transmission wires.

The voltage is decreased by step down transformers to safer levels such as 230 volts or 115 volts for residential service. End use equipment such as lighting, motors and electronics have been designed and standardized to operate at these conditions.

3. Legislative Initiatives for More Renewable Energy

Another objective of the engineering education process is to experience the legislative and regulatory processes. The authors took part in a related public hearing while performing this research.

The governor of New York has set a goal of producing 25 % of the energy from renewable sources. The lead agency is the State of New York Department of Public Service, which has held several public forums at various locations in the state. An administrative law judge has recommended that wind, fuel cells, solar, tidal, biomass and landfill gas be counted as renewable sources, while the more controversial and polluting trash incineration should not be considered renewable.

The authors attended and provided comments at the forum that was held in Albany in June, 2004. A document entitled the New York State Renewable Portfolio Standard (Reference 2) was made available. This document shows that the renewable energy portion is now going in the wrong direction. It has actually decreased from a high of 33 % in 1962 to 19 % in 2004. The reason for the decline is that most renewable is from hydro. The last major projects were the large Moses power dam on the St Lawrence River in 1959 and the expansion of Niagara Falls Hydro power in 1962. The decreased portion of hydro since 1962 is because the increased demand that has been supplied by building new nuclear, coal, oil and gas fueled plants.

One comment provided by the authors is that conservation should be included as an option to increase the portion of renewable sources. Another author comment was that the residential Electricity Producing Condensing Furnace that produces electricity along with home heating should also be identified as an option. The justification for this proposal is that large scale use of such a system represents a large potential for fuel conservation, cleaner air, lower costs and new job and business opportunities.

The authors recognized the benefits of hydro and landfill gas produced power, while understanding that new opportunities are limited. Other types of biomass and wind power can increase only moderately. Thus, solar powered photovoltaics offer the most potential for the future expansion. The solar contribution can be increased dramatically and cost effectively if the technology is improved for embedding photovoltaic solar cells in roof and outside wall materials.

This defines the need to identify a more efficient and cost effective method to utilize large amounts of distributed photovoltaic. One method is to operate isolated with battery storage, which is both expensive and wasteful. The other method has been to use inverters to convert the DC power from solar cells into AC power that must be compatible in voltage and synchronized in frequency with the electric power system while assuring safety and equipment protection.

4. Testing to Support the Proposed Better Interface Technique and Evaluation

Engineering education should include identifying and performing appropriate tests. The new technique that the authors are suggesting is to convert the service from AC to DC by means of power rectifiers. AC to DC rectifiers are passive devices that are fundamentally simpler than DC to AC inverters that require a control signal to produce the desired frequency. Inverters produce the fundamental sine wave along undesirable higher harmonics that have been described as electric power pollution.

However, the proposed better method of interfacing raises different questions and challenges. One issue is the adaptability of the total range of end use equipment to operate from a DC rather than an AC power supply. The other issue is the voltage, current and power output of a solar panel as a function of the amount of input solar power and the voltage of the distribution system. If the solar panel open circuit voltage is too low, no solar power will be transferred. If the solar panel open circuit voltage is too high power will be lost. Thus, the voltage at which the maximum solar power will be produced was determined. The other issue is reverse flow of power from the electric power system to the panel under conditions of low solar power to the panel. If the back flow is significant, a reverse power sensing and prevention device will be required.

Existing AC System and Equipment Modification Requirements for DC

The myriad of residential electricity using equipment has been standardized to operate at the 115 volt and 230 volts alternating current at 60 cps that has become the standard throughout the United States. The input from the utility to service panel is three wires. One wire is the neutral that is grounded by the utility at a distribution location outside the residence. The other two are hot wires (ie carry a voltage) and have voltage amplitudes of 163 volts relative to ground and a 180 degree phase difference. When one wire is plus 163 volts the other wire is minus 163 volts.

The effective average of a sine wave is called the root mean square (rms) voltage which is the peak voltage divided by the square root of two. Thus the line-to-neutral potential is 115 rms volts and the line-to-line potential is 230 rms volts. Nominally half of the house is wired from one hot to neutral, while the other half is wired from the other hot to neutral for the 115 rms volt devices. The larger power requiring devices such as the electric stove, clothes dryer, central air conditioning and large electric heaters have been designed to operate at 230 rms volts which is supplied by the two hot wires.

It is recognized that any electric equipment that can be powered by the existing AC can be modified to operate on DC. The next question is what is required for each type of end use equipment. The authors conducted an equipment survey along with estimates of power and energy usage. They then considered the adaptability of this equipment to a DC rather than an AC power supply. The equipment was classified as pure resistance (eg light bulbs and electric heaters), motors (primarily AC induction motors that are largely invisible to the resident) and electronics (eg television and computers).

The pure resistance devices require no modification to operate on DC rather than AC. There is also a benefit in terms of electrical insulation. At a specified peak voltage, a wire can transfer twice as much DC power than AC power without insulation breakdown.

The question of conversion of motors from AC to DC should include a historic perspective. The DC motor was invented by a Vermont Blacksmith named Thomas Davenport in the 1830s (reference 3). His power supply was relatively weak batteries. He mounted an electromagnet on a frame and another on a rotor. The rotor turned until the unlike poles were in line. He then devised what is now called a brush and commutator. This automatically reversed the voltage and thus current and the polarity of the rotor mounted magnet each time the rotor made half a turn. The result was continuous rotation.

Thomas Edison used batteries for convenience as a power supply for the invention of the light bulb in 1878. However, when he built the world's first central utility in lower Manhattan in 1882 he used a Davenport type motor in reverse which became a DC generator when driven by a steam engine. This system could provide DC electricity for DC motors in factroies during the day and DC electricity for lights at night. Power was produced, transferred and used at about 100 volts.

George Westinghouse and Nikola Tesla studied the Edison system and envisioned a multiple voltage system that could transfer power efficiently at high voltages over larger distances, and step down voltage for safe use. The DC generator became a simpler and more durable AC generator by replacing the continuous switching commutator with slip rings. Thus, the rotor magnetism was fixed in time rather than in space, and alternating voltage was generated is the stationary windings by the rotating magnet.

George Westinghouse designed a simpler to build and more efficient transformer that could be wound on a lathe (Reference 4). The first transformer based multiple voltage AC system was built in Great Barrington, Massachusetts in 1886. It provided street lighting from a hydro power plant about a mile away. However, this system could not produce mechanical power, because there was no AC motor.

The expert opinion was that an AC motor was not possible until Nikola Tesla demonstrated what is now called an induction motor (Reference 5). The genius of the induction motor was the ability to magnetize the rotor by wireless transfer of power from the stator. This eliminated the need for brushes and commutators. Thus, lack of an electric motor went from being a serious limitation of an AC system to becoming an additional advantage of the AC system with the development of the Tesla motor.

Without the advent of power electronics, the problem of converting electric service from AC back to DC would be a regression back to less desirable brush and commutator motors. However, power electronics can now be used to combine the simplicity of an AC induction motor with the continually variable speed advantages of a DC motor. The DC power supply is inverted to variable frequency AC which allows for a continually variable speed AC induction motor.

While most electronics are designed to operate from the existing 115 volt power supply, all such devices can be redesigned with no additional cost or complication to operate on DC. Many devices such as lap top computers and portable radios are now routinely designed to operate either from DC batteries or AC power.

Photovoltaic Panel Tests and Results

Any solar panel on earth will be dependent upon the variations of incoming solar power, or insolation, which ranges from about 1000 watts per square meter in the noonday sun to virtually zero at night. The daytime insolation will also vary as a function of cloud cover and the time of day.

The amount of electric energy that can be produced and transferred to the electric power system by the proposed DC to DC connection will depend upon the voltage and current that are produced over this range of conditions. An engineering challenge is to design the panels so that the maximum electric power and energy can be transferred to the system.

No power will be transferred if the open circuit voltage from the panel is lower than the system voltage. Less than maximum power will be transferred if the open circuit voltage of the panel is too much higher than the system. Thus, there will exist a ratio of open circuit voltage from the panel to system voltage at which the maximum power will be transferred.

The authors designed and performed an experiment to determine this voltage ratio that will result in the maximum production of power and energy from the panel. Figure 1 is a schematic of the test apparatus. It is comprised of the panel, radiation input from the sun or from sun lamps with variable output, a variable external resistance, and instruments to measure voltage across the resistance and current to the resistance. Figure 2 is a picture of the panel under sun lamps with power supplied by a variable transformer to provide the desired continually variable and steady insolation for a range of performance data.

The test was performed by varying the external resistance over a range from zero (ie short circuit) to infinite (ie open circuit) and with increments of 1 volt. The corresponding power as the product of current and voltage and resistance as the ratio of voltage and current was calculated at each point. The lost power, percent lost power, the ratio of operating voltage to optimal operating voltage, and the ratio of operating voltage to open circuit voltage at each voltage condition was also calculated at each condition.

The results of this test are shown in Table I. The corresponding lost power versus the ratio of operating voltage to open circuit voltage are shown in Figure 3. These results show that maximum power is transferred when operating voltage is about 92 % of the open circuit voltage. Further examination and consideration shows that there is less lost penalty power if the system voltage is less than optimal, rather than higher than optimal. Thus, less of a lost power penalty will result if the panel open circuit voltage is too high rather than too low.

It is noted that the authors developed the parameter “lost power” for the purpose of performing this evaluation. The “lost power” term may require some additional explanation. Power is the product of current and voltage. According, there are two extremes under which no power can be transferred and thus all will be lost. One extreme would be to interface with a system at zero voltage. Current will be maximum but power will be zero. The other extreme is to connect with a system with a DC voltage higher than the open circuit voltage of the solar panel. No current can flow from the panel, and thus all will be lost. It follows that there is some intermediate line voltage or equivalent load resistance at which maximum power can be supplied from the panel. The “lost power” is the difference between this maximum power and the actual power is transferred for the non ideal system DC voltage or equivalent load resistance.

The engineering education value of this project is further enhanced by the recognition that the results are predicted by the particle and quantum physics theories of notable physicists such as Max Planck and Albert Einstein. The vital issue is how the panel operates over the full range of solar power or insolation. The ideal performance is also predicted by the photoelectric effect as described by Einstein. His theory predicts that more radiation corresponds to more photon flux, but the average photon has the same energy in bright light as in dim light. Thus, flux causes electron flow or current, but it is energy that causes voltage. Thus, more radiation will cause more current, but not more voltage.

This experiment was performed by adjusting the voltage to electric sun lamps that were mounted above the panel. The voltage versus radiation result is shown in Figure 4. These results confirm a nominally constant voltage over a wide range of radiation up to 700 watts per square meter. The corresponding short circuit current was measured and was found to be approximately proportional to the radiation as shown in Figure 5.

At night or on extremely low insolation, the open circuit voltage drops toward zero. Thus, current and thus power from the electric power system can back flow through the photovoltaic panels. The amount of back flow should also be limited by the fact that the cells are made of p-n junctions that should act like current limiting diodes with back voltage.

Thus, a test was performed to measure the current flow through the panels over a range of applied voltage conditions. The results in Table II show that the reverse current and thus the electric power absorbed by the panels is small but possibly not insignificant. Thus, a device to measure reverse current and open the circuit under such conditions may be desirable, but not vital.

4. Results and Conclusions

This test results and analysis shows a potentially better method of interfacing the DC power from photovoltaic with the electric power system. Fuel cells that produce direct current are another potential source of distributed generation. A DC to DC interface should also provide a better method of connecting fuel cells with the power system.

It has also been suggested that a more efficient electric power system would make better use of new solid state power electronics technology (Reference 4). Such a system would continue to generate electric power with AC generators and use AC transformers to increase voltage at the central power plants. The power would then be rectified to high voltage DC for transmission, and use power electronics, in the form of DC voltage transformers, to step the voltage down for distribution and safe use.

Such a DC transmission and distribution system should also be more compatible for interfacing with the power produced by wind turbines that operate most efficient with variable speed in response to varying wind conditions.

It has been noted that it is hard to change a system that works well. Our existing electric power system is a technological marvel that does work extremely well. However, it has been built before the development of solid state power conditioning devices such as diodes, inverters, frequency converters and DC transformers. These devices are now used to correct the shortcomings of the existing AC system. This paper has demonstrated the potential using these devices as building blocks for a new and better type of system.

This subject also provided an excellent engineering education opportunity for both the two student authors and the two engineering professor authors. It combined an important issue with tests and analysis, along with involvement in the regulatory process and with test results explainable by quantum physics that engineering students often considered abstract and without practical considerations. Thus, the material presented in this paper can be used to enhance most energy conversion related courses for the betterment of the engineering students, faculty and ultimately for helping to sustain our energy based society and civilization.

Acknowledgement:
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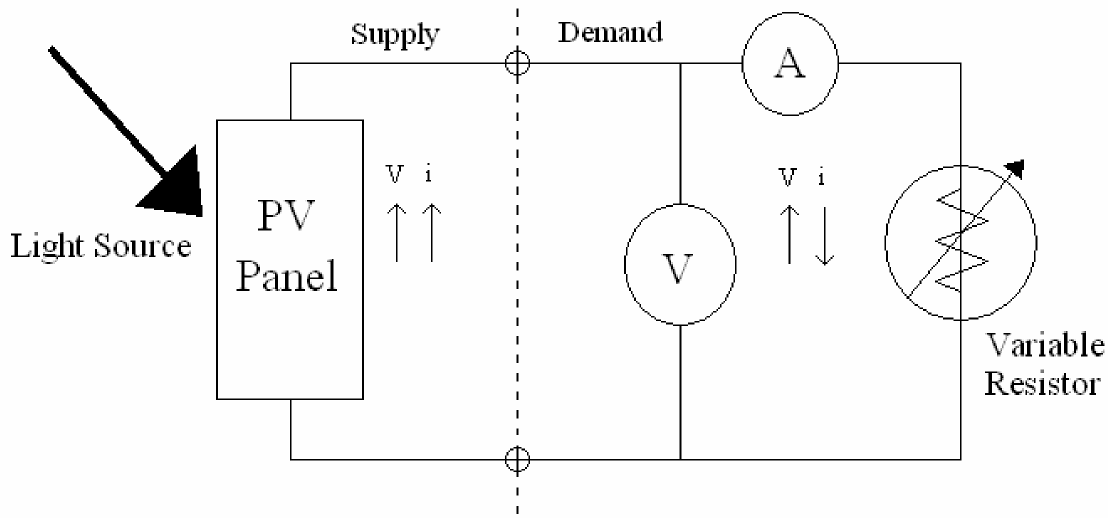

Figure 1: Schematic of Solar Panel Test Apparatus

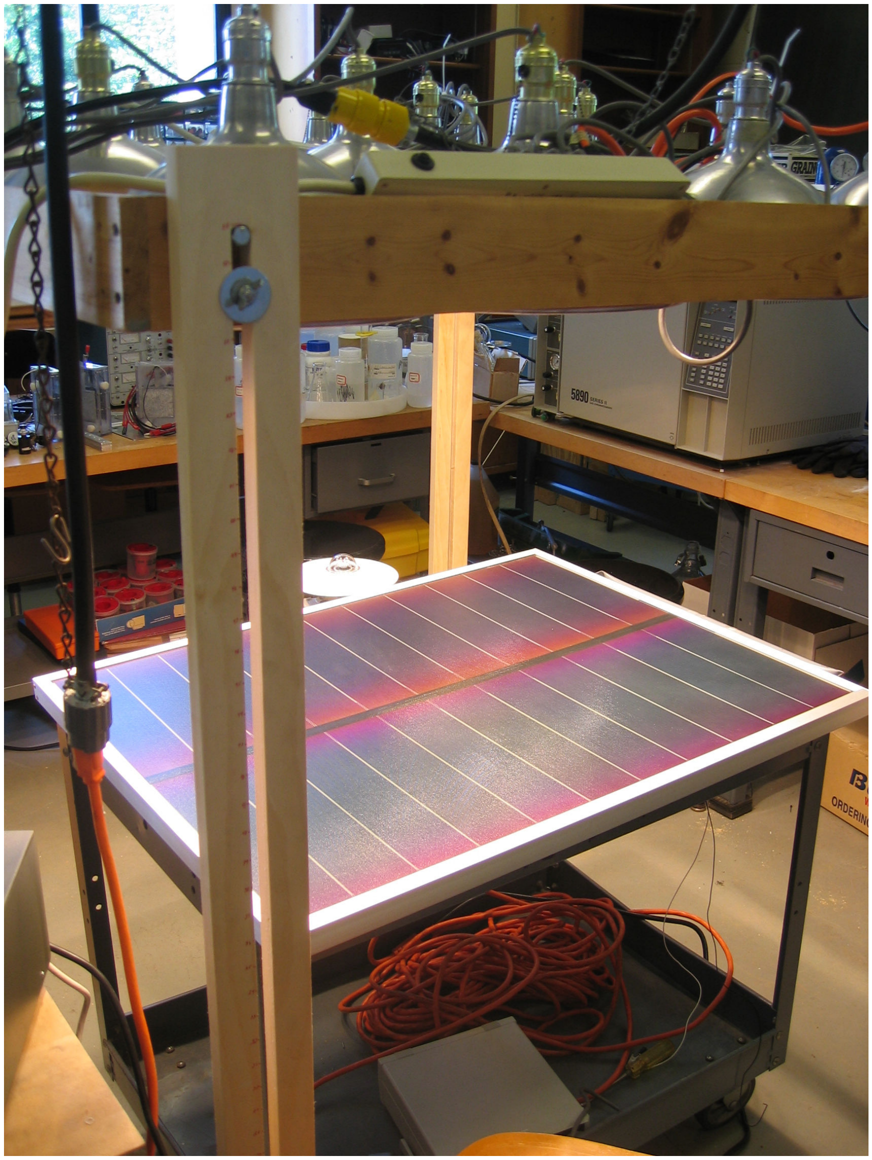

Figure 2, Picture of Apparatus for Measuring Photovoltaic Panel Performance

Table I: Panel Performance Test and Calculations

V (V)	i (A)	P (W)	R (Ω)	Plost	%Plost	V/V*	V/V(i=0)
0	0.156	0.00	0.0	2.01	100.0	0.00	0
1	0.154	0.15	6.5	1.85	92.3	0.06	0.05
2	0.153	0.31	13.1	1.70	84.7	0.12	0.11
3	0.152	0.46	19.7	1.55	77.3	0.18	0.16
4	0.151	0.60	26.5	1.40	69.9	0.24	0.22
5	0.149	0.75	33.6	1.26	62.9	0.29	0.27
6	0.147	0.88	40.8	1.12	56.0	0.35	0.32
7	0.145	1.02	48.3	0.99	49.4	0.41	0.38
8	0.143	1.14	55.9	0.86	43.0	0.47	0.43
9	0.141	1.27	63.8	0.74	36.7	0.53	0.49
10	0.138	1.38	72.5	0.63	31.2	0.59	0.54
11	0.136	1.50	80.9	0.51	25.4	0.65	0.59
12	0.134	1.61	89.6	0.40	19.8	0.71	0.65
13	0.131	1.70	99.2	0.30	15.1	0.76	0.70
14	0.129	1.81	108.5	0.20	10.0	0.82	0.76
15	0.126	1.89	119.0	0.12	5.8	0.88	0.81
16	0.122	1.95	131.1	0.05	2.7	0.94	0.86
17	0.118	2.01	144.1	0.00	0.0	1.00	0.92
18	0.078	1.40	230.8	0.60	30.0	1.06	0.97
18.5	0	0.00	∞	2.01	100.0	1.09	1

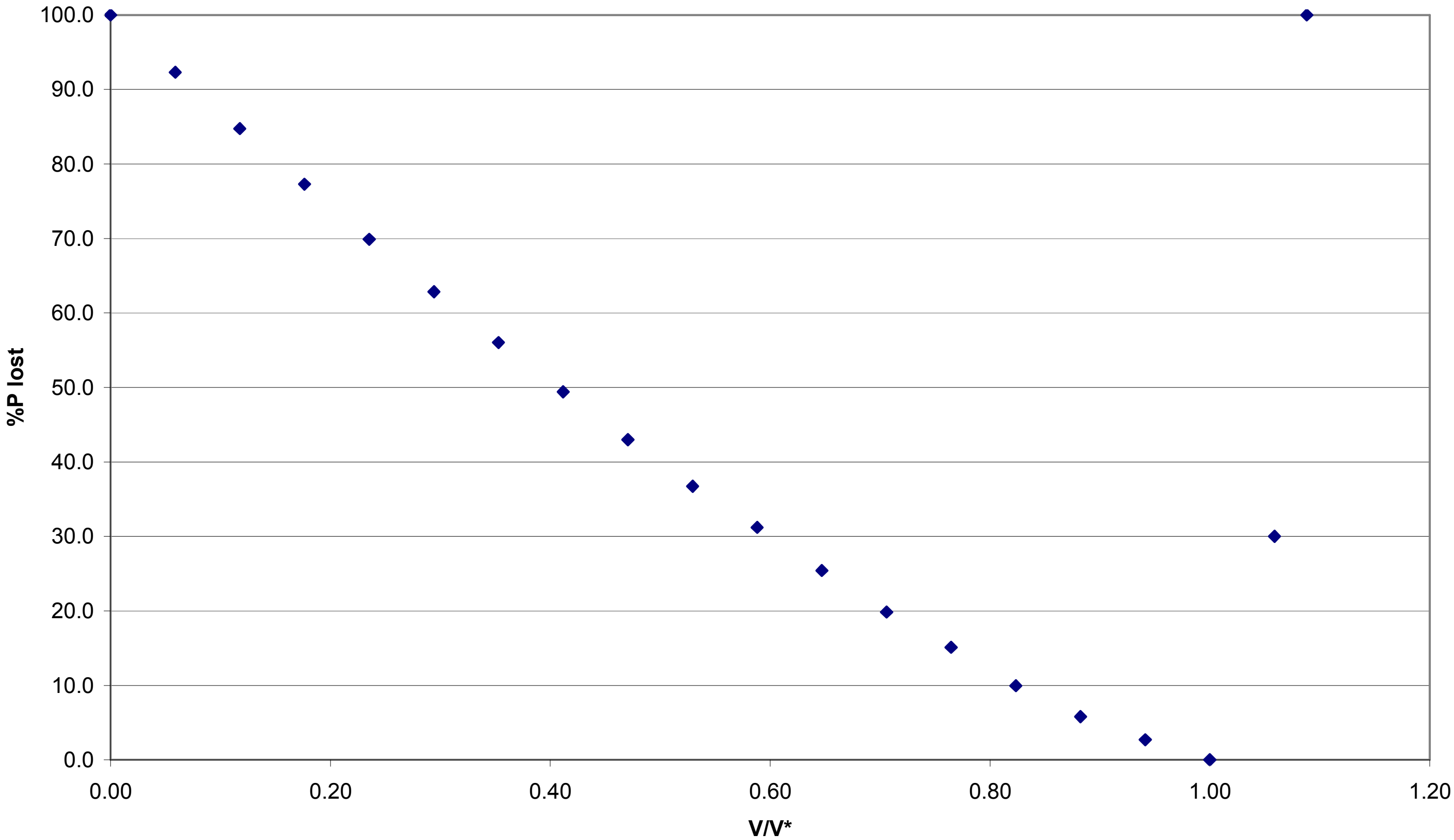

Figure 3
Percent Power Lost vs. Voltage Ratio

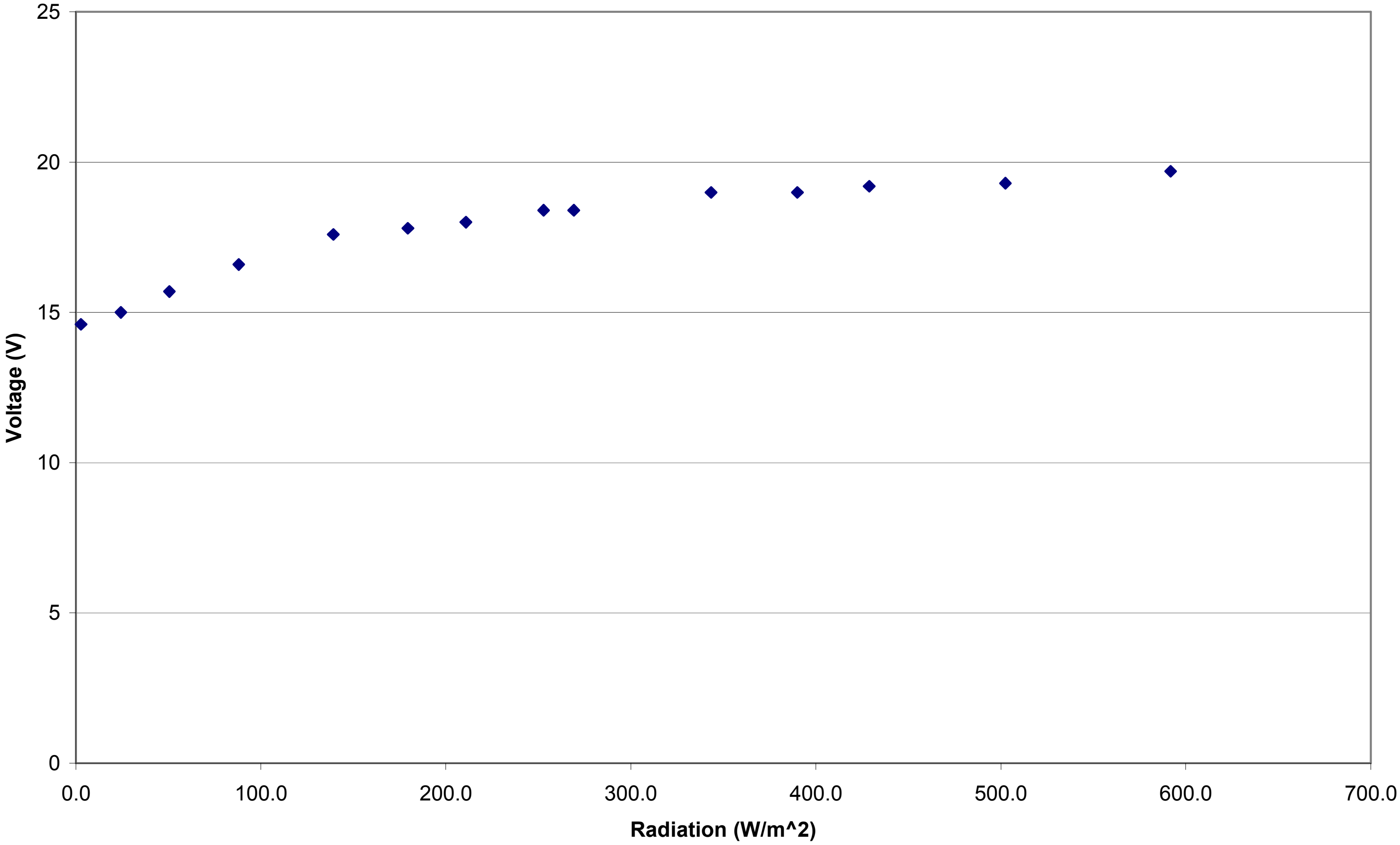

Figure 4
Open Circuit Voltage vs. Insolation

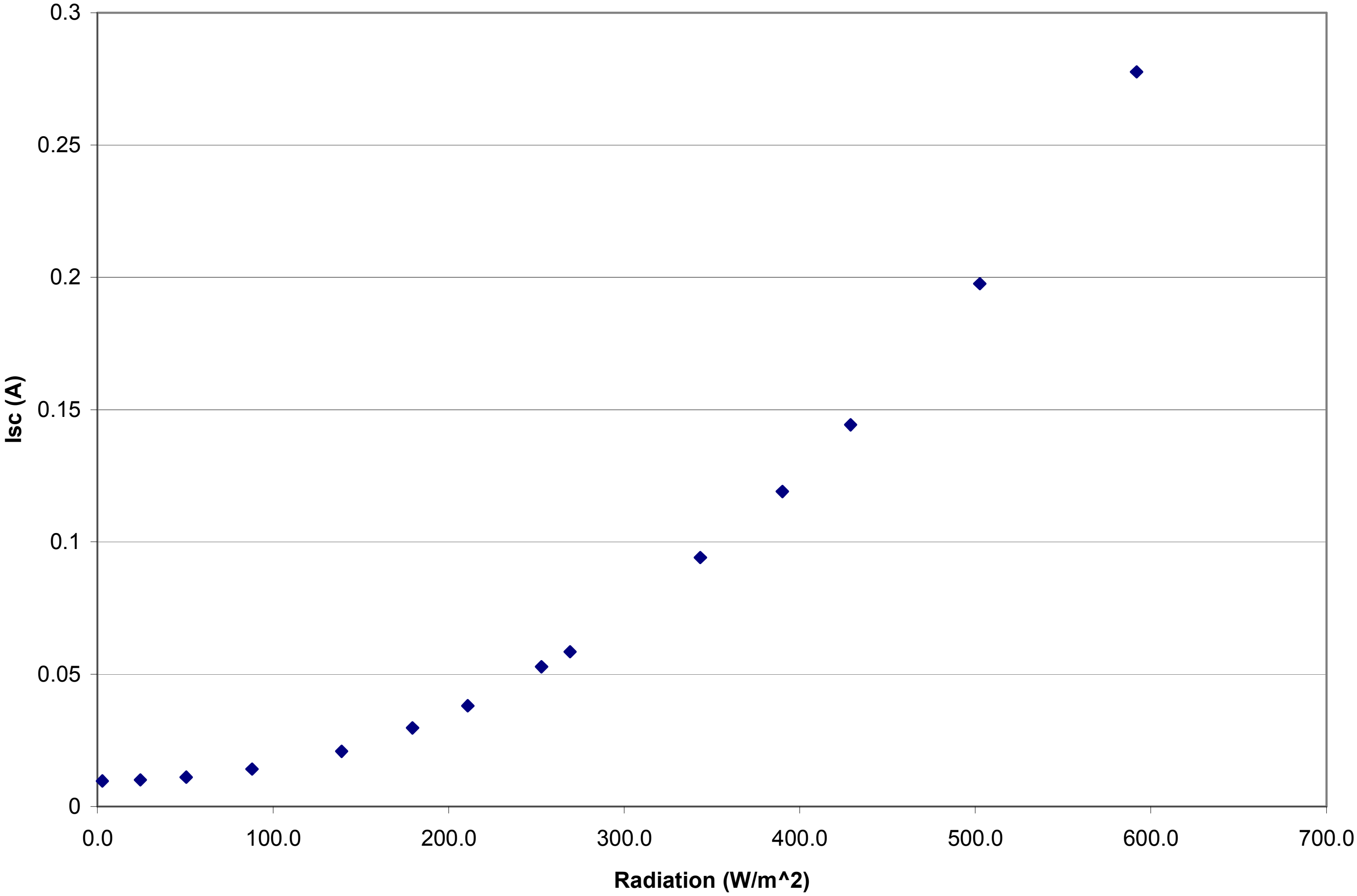

Figure 5
Short Circuit Current vs. Insolation

Table II: Current and Power Consumed vs. Applied Voltage

V (V)	I (A)	Pconsumed
25	1.089	27.225
20	0.093	1.86
17	0.019	0.323
15	0.006	0.09
10	0.0011	0.011
5	0.00034	0.0017
0	0.000006	0
-0.1	0.0093	-0.00093
-0.2	0.0123	-0.00246
-0.3	0.0202	-0.00606
-0.4	0.0227	-0.00908
-0.5	0.031	-0.0155
-0.6	0.0397	-0.02382
-0.7	0.0393	-0.02751
-0.8	0.0511	-0.04088