Design and Implementation of a data-acquisition system to monitor and control a photovoltaic power generation system

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Abstract— **A computer-based data-acquisition system to monitor and control photovoltaic power generation systems using a novel method, based on Agilent data-acquisition board (U2353A) and graphical programming software (Agilent Vee Pro), has been designed and implemented. Prior to designing the data-acquisition system, a small-sized PV power generation system, consisting of a 20W BP Solar panel, batteries, a charge controller and a DC-to-AC inverter, has been assembled. Light dependent resistors have been utilized to measure the amount of irradiance incident on the solar panel. A 4-channel relay card is used to enable the switching of power supply from the inverter to the grid power programmatically. At the same time, if the power generation system is not producing the amount of power that it should, based on the readings of the light sensor, the program would also automatically send a sms to the user to inform him of the condition. Besides these functions, the written program is able to monitor the photovoltaic panel's instantaneous voltage and current, the voltage across the inverter and the current flowing into it, hence the solar panel's output power and power being consumed by the electrical appliances connected to the inverter. Although the size of the power generation system being monitored in this project is experimental, the data-acquisition system can always be interfaced to larger power capacity renewable energy system plants.**

I. Introduction

Energy Information Administration of US estimated in 2005 that, 86% of primary energy production in the world came from burning fossil fuels, with the remaining non-fossil sources being hydroelectric 6.3%, nuclear 6.0%, and other (geothermal, solar, wind, and wood and waste) 0.9 percent.[1] Fossil fuels take millions of years to form, and reserves are being depleted much faster than the rate at which they can be replenished. Furthermore, burning fossil fuels produces around 21.3 billion tones of carbon dioxide per year, which is double of the amount that natural processes can absorb. [2] Carbon dioxide is one of the greenhouse gases that enhances radiative forcing and contributes to global warming, causing major adverse effects, including reduced biodiversity and rise in sea-level. This factor, coupled with that of dwindling resources, is pushing a global movement towards the generation of renewable energy to meet increased energy needs.

According to European RES-E directive[3], renewable energy sources include hydro power (large and small), biomass (solids, bio-fuels, landfill gas, sewage treatment plant gas and biogas), wind, solar, geothermal, wave and tidal energy and biodegradable waste. More specifically, Renewable energy is energy that is derived from natural processes that are replenished constantly. In its various forms, it derives directly or indirectly from the sun, or from heat generated deep within the earth. Renewable energy systems convert these natural energy sources into useful energy (electricity and heat).

The rapid evolution of renewable energy sources (RESs) within the past two decades has led to the installation of many RES power systems all over the world. Although they are still not prevalent in Singapore currently, the trend seems to suggest that the renewable energy sources will be taking a more central role soon.

In this project, a computer-based data-acquisition (DAQ) system for monitoring solar irradiance and photovoltaic power generation system's operational parameters is designed and implemented. Four light dependent resistors are used to measure the solar irradiance incident on the solar panels. The photovoltaic voltage and current, battery's voltage and the power being consumed are the system's parameters being monitored. The various data is captured by the DAQ system and then is interfaced to the PC through USB cable. The collected data are further processed, displayed and saved using the Agilent VEE Pro software.

This system has the advantage of great flexibility in case of changes, and more importantly, the ability to control the PV power system from the computer. For example, this system has implemented an automatic power supply switch design to ensure uninterrupted power supply to the electrical appliances connected to the PV power output. The monitor program can also be remotely monitored over the internet.

The above mentioned DAQ system has been interfaced to a low-power photovoltaic power system for test purposes, but this DAQ system can certainly be extended to be used on large power capacity Renewable Energy Sources plants.

II. A Stand-alone PV System with Battery Storage

A. Introduction

For experimental purpose, a low-power stand-alone PV system with battery storage has been designed and implemented in this project. In this chapter, each component of the PV system will be described, and the rationale for each choice explained. Overall, the PV generation system consists of BP Solar SX-20U 20 W solar panel, Sunsei CC10000 charge controller that allows up to 10 A of charging current, Yuasa 12V, 7Ah rechargeable lead-acid

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battery and Elektro Automatik EA-TWI 150-12 DC/AC inverter.

B. Solar Panel

The solar panel chosen for this project is BP Solar SX-20U. It has a module rated power of 20W, nominal voltage of 12V, open-circuit voltage of 21V, short-circuit current of 1.3A, voltage at rated power of 16.8V and current at rated power of 1.2A. These values are tested under standard test conditions of irradiance of $1000W/m^2$, AM 1.5 spectrum, and cell temperature of 25°C. As this PV power system is just for experimental purpose, there is not a need for a solar panel with higher rated power. That, coupled with the fact that the total cost of the entire setup should be under S$1000, the amount given by Agilent Technologies for this project, the price and electrical specifications of SX-20U manage to strike a balance, making it first choice among all available panels.

SX-20U consists of 36 semi-crystalline silicon solar cells electrically configured as two series strings of 18 cells each. These strings may be placed in series or in parallel in the field, providing 6V or 12V nominal output, by moving leads in the junction box. The cell strings are laminated between sheets of ethylene vinyl acetate (EVA) and tempered glass. Among its many features, the most salient one essential for this project's purpose is its ability to provide sufficient voltage to charge batteries efficiently in virtually any climate.

C. Charge Controller

Sunsei CC10000 Charge Controller is chosen over other available options, mainly due to its compatibility with almost all types of batteries and solar panels and its high efficiency of 98%. It operates at a nominal voltage of 12V and can withstand a maximum charging current of 10A. It uses pulse width modulation (PWM) to charge the battery in two stages: boost and float charge. It also has over-charge protection, by floating battery at safe voltage when battery is full, and reverse leakage protection to prevent power loss at night. Furthermore, its circuitry that controls the charging process is 100% solid state, thus promising robust operation.

The operation of the Sunsei CC10000 is completely automatic. It will regulate the charging of batteries during conditions of heavy usage, or when left unattended for long periods of time. On a typical day, as the charging starts for the day and battery state of charge is low, charging will be continuous and the "Charging" LED will be on all the time. This is after the utilization of the battery the previous night, leaving it discharged. The battery will be charged up to 14.5V, the Boost Voltage, and kept at this level for two hours using PWM control. Then, the controller goes into float mode and will maintain the battery at 13.7V indefinitely as long as the load current does not surpass the charging current.

D. Battery

To store the energy produced by the solar panel, Yuasa NP7-12 lead-acid rechargeable battery was chosen. It has a rated voltage of 12V and capacity of 7Ah. NP7-12 batteries are uniquely constructed and the sealing technique applied ensures no electrolyte leakage from case or terminals. Furthermore, NP batteries utilize unique electrolyte suspension system incorporating a micro-fine glass mat to retain the maximum amount of electrolyte in the cells. The electrolyte is retained in the separator material and there is no free electrolyte to escape from the cells. The oxygen recombination technology incorporated into the design of the NP batteries effectively control the generation of gas during usage. Also, the batteries are equipped with a simple, safe low pressure venting system which releases excess gas and automatically reseals should there be a build of gas within the battery due to severe overcharge. On top of that, the heavy duty lead calcium alloy grids provide an extra margin of performance and life in both cyclic and float applications and give unparalleled recovery from deep discharge. Lastly, the use of the special separator material provides a very efficient insulation between plates preventing inter-plate short circuits and prohibiting the shedding of active materials.

E. DC-AC Inverter

The last component to make up the whole of this PV power generation system is a DC-AC inverter to convert the DC power, being produced by the solar panel, into AC power. An inverter is added to this system to allow electrical appliances, a majority of which utilizes AC power, to be powered by it. Although the inverter eventually chosen – Elektro Automatik EA-TWI 150 – has only a rated power output of 140W, which is not sufficient to drive most home appliances, it is sufficient for this project's purpose.

EA-TWI 150 takes in an input DC voltage of 12V and outputs 230V 50Hz AC voltage. It has an efficiency of more than 90% and outputs modified sine wave output voltage. The unit is equipped with extensive protection facilities such as overload, overheat and battery protection.

III. DATA ACQUISITION SYSTEM

With the PV power generation system in place, the data-acquisition system can then be designed to measure the parameters of interest. The data-acquisition system is essentially based on Agilent U2353A USB modular multifunction data-acquisition device. Its analog input channels are for voltage measurements whose dynamic ranges can be set independently within the maximum ranges of ±10V. Since this range is lower than the voltages that are to be measured, external signal conditioning, based on voltage dividers and current shunts, is required to condition the measured values to fall within the required range. Lastly, the data-acquisition system also comprises of 4 light dependent resistors' circuits to measure the light intensity incident on the solar panel.

A. Agilent U2353A

The main component of this data-acquisition system, Agilent U2353A packs a wide array of features. However, only those features that are utilized in this project will be mentioned in this report. U2353A can sample up to 500 kSa/s with a resolution of 16 bits. This sampling rate, however, depends on the number of channels specified in the scan list by the user. This is because U2353A is designed with multiplexing analog input. Hence, if two channels are specified in the scan list, the maximum sampling rate is actually 500 kSa/s divided by two, which is 250 kSa/s for each channel. Regarding analog input channels, U2353A provides 16 single-ended (SE) or 8 differential analog input channels.

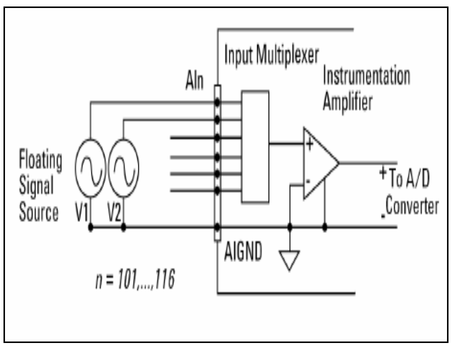

Figure 1 Single Ended Analog Input

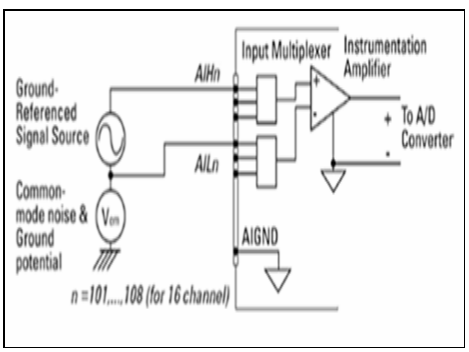

Figure 2 Differential Analog Input

A single-ended connection is applicable when the analog input signal is referenced to a ground and can be shared with other analog input signals. The differential input mode provides two inputs that respond to the difference of the signal voltage. As can be seen from the diagram above-right, the analog input of U2353A has its own reference ground or signal return path. The differential mode can be used for common-mode noise rejection. This analog input feature is used to collect the electrical parameters, such as solar panel's voltage and current, battery's voltage and current and the readings from four light dependent resistors, which will be explained in greater details below.

U2353A also features a 24-bit programmable general-purpose digital I/O (GPIO), which is TTL compatible. The 24-bit GPIO are segmented into four channels (CH 501 to 504). Channel 501 and 502 consists of eight data bit while channel 503 and 504 consists of four data bit. All four channels are programmable as input and output. This feature is utilized in this project to drive a 4-channel relay card to implement the power supply switch function, which will be described in chapter ??.

Other than the above-mentioned features, U2353A also have two D/A channels that are available. The two analog outputs are capable of supplying output voltages in the range of 0 to 10V and ±10V. Each DAC channel drives a maximum current of 5mA. The two analog outputs can be used as voltage sources to the devices under test. In addition to this, the analog outputs are also used to output predefined function generators or any arbitrary waveform. The predefined waveforms are sine wave, square wave, triangle wave, sawtooth wave and noise wave. In this project, the analog output is used as a voltage source to the light dependent resistors' circuit. This provides an almost constant voltage source, while reducing the area that would have been necessary for a voltage regulator to be constructed.

B. Voltage Divider

The voltages that are to be monitored – solar panel's voltage and battery's terminal voltage – exceed the analog input range of ±10V of U2353A. Thus, there is a need to condition the signal and bring it down to the acceptable range before interfacing it to the data-acquisition module. This is achieved by voltage divider circuits, designed to obtain a negligible power dissipation and influence on the measured values. These measured values are then converted back to the actual values inside the VEE program being run on the PC.

To measure the voltage across the solar panel, whose voltage can reach up to 21V, the above potential divider is utilized. The resistors' values are chosen to be high so as to limit the amount of current that will be drawn through this branch. To reduce 0-21V range to 0-10V range means that the measured voltage should be reduced to approximately half its value before being collected by the data-acquisition module. Hence, the values of the resistors indicated in the diagram above should accomplish the task.

The same method applies to the battery terminal voltage. For the battery, however, the maximum voltage that it is expected to reach is 14.5V. Hence, reducing the measured values down to two-third will fit the input range better. To achieve this, the resistors' values should be 12 kΩ and 6 kΩ, with the data-acquisition module reading the voltage across the 12 kΩ resistor.

C. Current sense resistor

Caddock precision current sense resistors are used to measure the current flowing through the wires. These current sense resistors utilize Caddock's Micronox resistance films to achieve a low cost resistor with non-inductive performance. The resistor's terminals are constructed for Kelvin connections to the circuit board, which means that as the picture shows, the current sense resistors are equipped with four terminals, two for carrying the measured current, and two for resistor's voltage drop to be measured. This way, the data acquisition module only measures the voltage dropped across the precision resistance itself, without any stray voltages dropped across current carrying wires or wire-to-terminal connection resistances.

Shunt resistors function as current measurement devices by dropping a precise amount of voltage for every amp of current through them, the voltage drop being measured by a voltmeter. In this sense, a precision shunt resistor "converts" a current value into a proportional voltage value. Thus, current may be accurately measured by measuring voltage dropped across the shunt.

The current sense resistor used for this project has a resistance value of 0.01Ω, so only a modest amount of voltage will be dropped at full current, hence having negligible effect on the current that is to be measured.

D. Light dependent resistor

As mentioned above, this data acquisition system's objective is to monitor that the photovoltaic generation system is performing at its expected level. To know what its expected level is, there is a need to measure the electrical parameters under its normal working condition. That, however, would only be one side of the equation. The other side will consist of the light intensity that is incident on the photovoltaic panel. With that information, the monitor program can then decide if the power being generated is in accordance to the amount of light intensity being received. Hence, it is necessary for light dependent resistor to be included in this data acquisition system.

A light dependent resistor is an electronic component whose resistance decreases with increasing incident light intensity. The relationship between the resistance R_L and light intensity (lux) for a typical light dependent resistor is

$$R_L = \frac{500}{lux} k\Omega$$

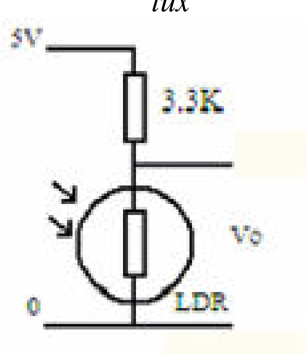

Figure 3 Light dependent resistor to measure the light intensity

With the light dependent resistor connected to 5V through a 3.3kΩ resistor, the output voltage of the light dependent resistor is

$$V_o = 5 \times \frac{R_L}{(R_L + 3.3)}$$

Rearranging the equations, we get the light intensity

$$lux = \frac{(\frac{2500}{V_o} - 500)}{3.3}.$$

The lux is the SI unit of illuminance and luminous emittance. It is used in photometry as a measure of the intensity of light, with wavelengths weighted according to the luminosity function, a standardized model of human brightness perception. Appendix A shows a table of examples of light sources and their corresponding illuminance.

The light dependent resistor utilized in this project is NORP12 from RS. It is made of two cadmium sulphide photoconductive cells with spectral responses similar to that of the human eye. Cadmium sulphide is a high resistance semiconductor. If light falling on the device is of high enough frequency, photons absorbed by the semiconductor give bound electrons enough energy to jump into the conduction band. The resulting free electron (and its hole partner) conduct electricity, thereby lowering resistance. NORP12 has a resistance range from 400Ω to 1MΩ.

With a circuit similar to the one shown above, the light dependent resistor will receive its voltage supply from U2353A analog output, while V_o in the diagram is measure by U2353A analog input. The input configuration utilized here will be single-ended, different from the differential input employed for the measurement of voltages and currents. This is due to the fact that the light dependent resistor is already connected to the U2353A's reference ground as it is receiving the voltage supply. Hence, a single-ended input will be sufficient.

The data acquisition system now is able to measure light intensity and use it to evaluate if the electrical parameters being measured are within the acceptable range. One possible anomaly that can occur is when tree branches shade part of the photovoltaic panel, thus affecting the power output. If the light sensor is beyond the shade, the monitor program will be able to take note of the discrepancy and trigger off. However, if the light sensor falls under the shade as well, the monitor program will not capture this triggering event. Hence, four light dependent resistors' circuits are included in the data acquisition system. This can also help to improve the accuracy as the average of the four readings is taken if they don't differ beyond a certain range.

With the data acquisition system complete, the readings measured are transferred to the PC via the USB cable from U2353A. A monitor and control program in the PC will then process, display and store all the data, monitor for unusual events and trigger off control actions.

IV. Program to monitor and control a photovoltaic generation system

Now we will describe in details the program designed to monitor and control a photovoltaic generation system. This program was written in the hope that users of this program can have a clear and concise picture of the photovoltaic system's performance at a glance. Currently, photovoltaic systems are still rather expensive to install. Hence, for average consumers to take the plunge and install such a system at home, they would want to know how the system is performing and how much power it is producing for them.

Besides the reassurance that it offers, it can also ensure that if any situation is causing the photovoltaic system to not perform at its expected level, the owner can be informed early and remedies can be carried out. One scenario is that of branches or litter shading part or whole of the photovoltaic array. The power output will then differ from what the light intensity sensor suggests that it should be producing. The owner then can go and check on the photovoltaic array. Another scenario will be that of the charge controller breaking down and the battery not being charged. When there is sunlight, as suggested by the light intensity sensor, but the battery is still not being charged, the owner will then know that a fault has occurred and the charge controller can be repaired. To prevent owners from having to monitor the program constantly, the program is able to send a sms to the owner when such triggering events occur, allowing them to take the necessary actions.

Making use of a 4-channel relay card, the program is also able to switch the connected electrical appliances to grid power supply when the photovoltaic array is not producing sufficient power and the battery has a state of charge lower than 50%. This ensures uninterrupted power supply for critical appliances, such as computers.

VEE Pro 8 also allows remote monitoring, hence offering the owners the convenience of checking the monitor program from work or anywhere with a computer connected to the internet.

A. Display of voltages, Currents, Powers and Light intensity

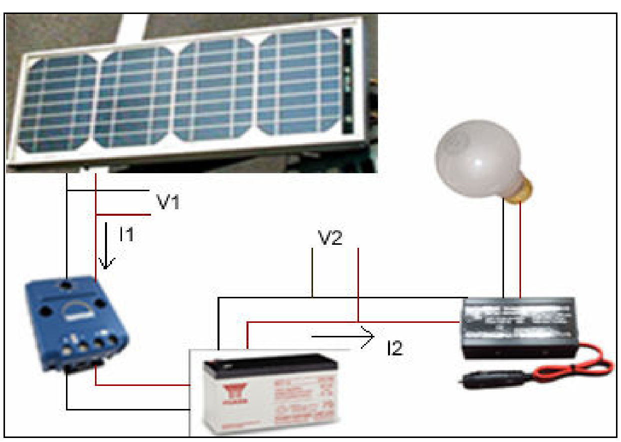

Figure 4 Wiring of the whole system

The above diagram shows the points at which the voltages and currents are measured. The multiplication of V1 and I1 should give the instantaneous power output of the photovoltaic panel. At the same time, the multiplication of V2 and I2 will give the power being consumed by the inverter. Neglecting the power lost in the inverter due to its efficiency, that will be the power being consumed by the electrical appliances. At the same time, V2 will be the terminal voltage of the battery. Thus, this value can be used to monitor the battery's state of charge.

As mentioned in chapter 5, the voltages are attenuated by the potential dividers. So, in the VEE program, after it has obtained the measured reading, it is required to multiply the reading with appropriate constants according to the values of the resistors used. For the solar panel where two resistors of 10 kΩ each are used, the readings are multiplied with 2.

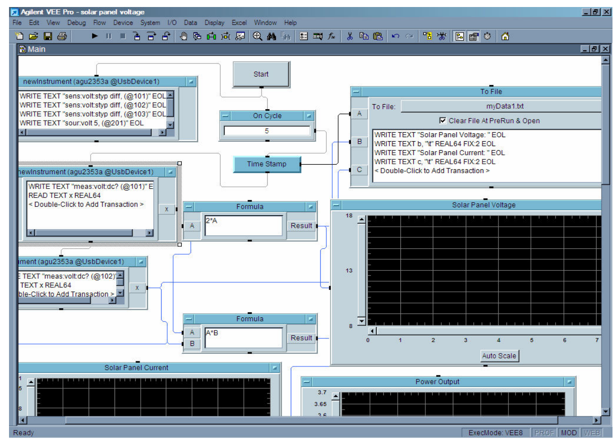

Figure 5 Screenshot of VEE program in detail view

This is the screenshot of part of the Program where the solar panel's voltage, current and power are being processed, plotted and stored. As the screen space is limited, not every object can be squeezed into it. The battery's voltage, current and power consumed are processed in a similar manner to the diagram above. In the diagram, the "Time Stamp" object gets the current date and time and send it to "To File" object, which is used to write to the text file indicated in the program. This is used to log the electrical parameters in a text file and saved for future reference.

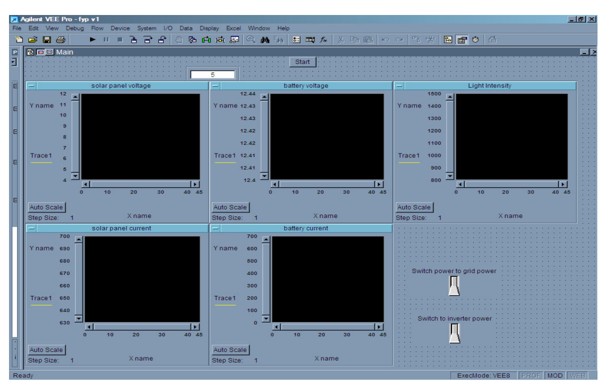

Figure 6 Screenshot of the program in panel's view

B. Switching Power Supply

In a lot of applications, it is critical that the power supply is not interrupted, so as to prevent loss of data or damage of chilled food, to name a couple of examples. Hence, the monitor and control program has the function to switch the power supply to grid power supply when the photovoltaic array is not receiving sufficient light intensity and the battery's state of charge is low as well.

This function is implemented by using a 4-channel relay card.

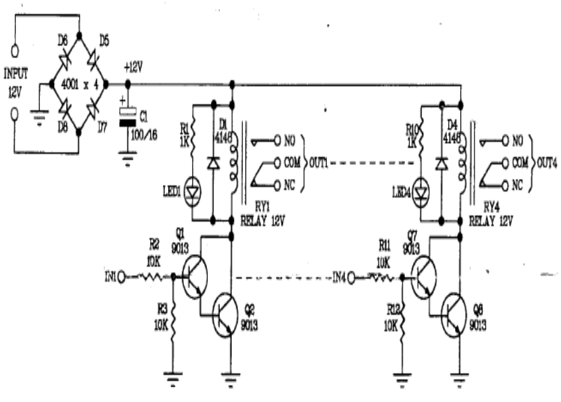

Figure 7 Circuit diagram of the relay card

The above diagram shows the circuit diagram of this relay card. It is controlled by 4 TTL inputs to switch on or off the 4 relays. These TTL inputs are supplied by U2353A digital output channels.

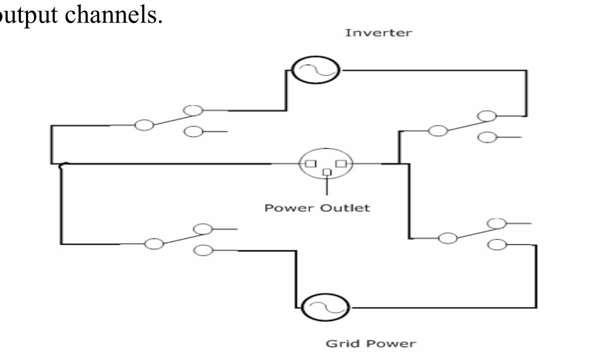

Figure 8 The connections of inverter, grid power and power outlet to relay card

The four relays were used to connect to the grid power, inverter power supply and a power outlet in the above configuration. So, during normal operation, the electrical appliance connected to the power outlet will receive its power from the inverter. But, when the program sends out "1111" to the four inputs, so that the four relays will switch to normally open side, the electrical appliance will now receive its power from the grid power.

V. Conclusion

With the global warming effects becoming increasingly harsh on mankind, the trend seems to be that people are becoming more accepting of renewable energy sources. Among them, solar energy is the one that is most suitable for Singapore, an island with sunlight all year round. A photovoltaic generation system, however, is rather expensive. Hence, a monitor and control program that operates from a computer or laptop, thus having their great processing speed and large memory space at its disposal, to ensure that the photovoltaic system's working parameters are within the expected range will allow the users peace of mind and full utilization of the system's potential. This small amount of extra cost shouldn't deter the users from installing the data acquisition system and this program, as they will earn back the money very soon through decreased down time and optimum usage of their photovoltaic power system.

The experimental low-power stand-alone photovoltaic generation system, assembled for this project's sake, shows that there are many areas with a photovoltaic system that can go wrong. For example, loose contact alone can cause the whole system to perform badly.

Furthermore, the data acquisition system and the monitor program are very flexible to new additions and changes. Hence, there is no limit on the extensions to this system that can be done. One improvement that can be done to this system is to use the readings from the four light dependent resistors' circuits to make a solar tracker, so as to have maximum sunlight falling on the solar panel at all times. Another improvement that can be done is to connect more electrical appliances to the power outlet from the inverter, but with relay switches in between. Hence, the owners will be able to switch on or off the electrical appliances from work when they see that the photovoltaic array is producing sufficient power. This can be done easily by making use of remote access feature of Microsoft Windows, which will give the users the control of the computer. They can then send out TTL logic highs and lows to switch on or off the switches.

Acknowledgment

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