Solar Array Monitor (S.A.M.)

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***Abstract* — The purpose of the solar panel array monitoring (S.A.M.) project is to improve upon the existing industry standard of monitoring the array's total output power. Monitoring only the total output power is great for billing purposes, but it is not enough. It cannot monitor at the panel or the string level which in necessary to save on troubleshooting time and expenses. QuickBeam Energy has requested a monitoring system that delivers closer monitoring, for instance, monitoring of individual panel's voltage and current or string of panels. These readings should be remotely assessable and the measurements should be updated frequently.**

***Index Terms* — Current measurement, microcontroller, photovoltaic cells, solar energy, solar power generation, voltage control, voltage measurement.**

I. Introduction

Monitoring and troubleshooting of large arrays of solar panels is difficult and time consuming. A system is needed to regularly monitor each panel or row of panels that reports any failure or malfunction promptly. The Solar Array Monitor (S.A.M.) is a device attached to the leads of the strings of panels inside the combiner box to periodically measure their instantaneous voltage and current and then transmits the data to the QuickBeam Energy through the internet. Knowing ahead of time which panels are affected helps to quickly troubleshoot and correct any problems that may be hindering the solar power system from producing the most energy possible.

The design of the S.A.M. consists of several components. A major part of the design consists of the sensors that will monitor the current and voltage being produced by each string of panels in the solar array system. These sensor circuits will have to accurately measure the current and voltage being produced to an accuracy of within one percent. The next major component is the microprocessor, the choice of which depends on the need to be able to handle the number of analog signals from the sensors, convert them to a digital value with enough precision to meet the requirements and send the information out to a serial port in an energy efficient manner. The communication system is designed to accept the serial input and format the information and interact with protocols that allow it to transmit to QuickBeam's FTP server, again in an energy efficient manner. The next major component is the power supply of the S.A.M. The power supply will need to provide 5Vdc at 300mAmps consistently within +/- 1% and be reliable. Finally, the S.A.M. will have to be put together into a package that will fit comfortably within the combiner box of the solar array system as shown if figure 1 below.

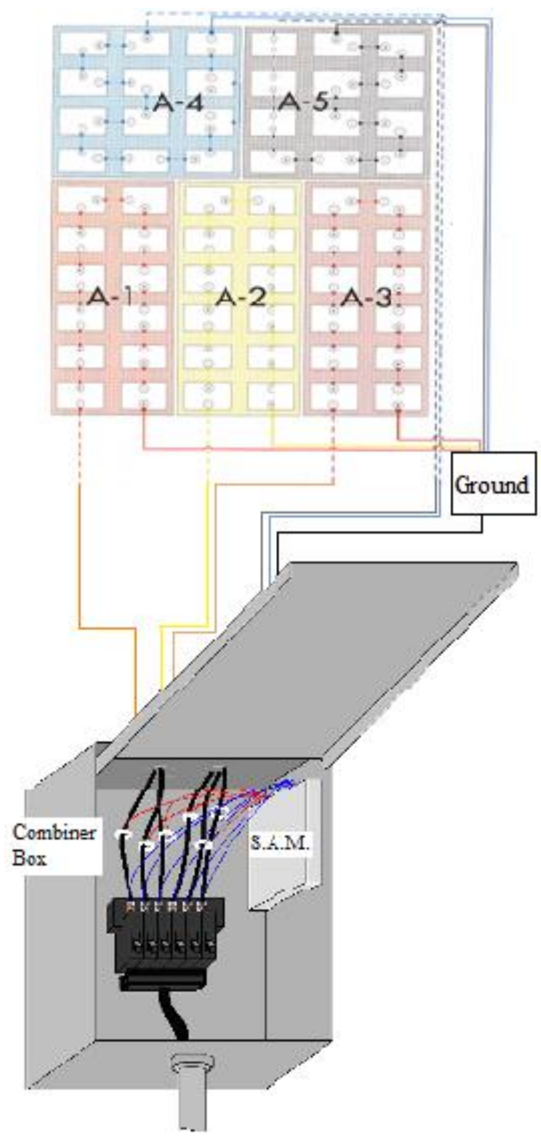

Figure 1: S.A.M. installed in combiner electrical panel box. Blue wires go to the voltage sensor, and the red wires are from the current sensors.

The system is designed to consist of one unit per combiner box that will be able to monitor up to five strings of solar panels. The number of units that will be deployed to a solar array site will depend on the size of the solar array installation and the amount of strings present.

II. SPECIFICATIONS

The project sponsor gave only a few specifications, such as cost and type of electrical data, but the designers added others that seemed suitable for the task.

1) The system will consist of one unit that will be able to monitor up to 5 strings of solar panels.
2) The cost of the S.A.M. will be less than $5 per solar panel.
3) It will be able to monitor the current and voltage at least every 15 minutes and transmit the results back to the central computer.
4) It will also have to alert the central computer of any interruptions or problems that can arise in the system such as a sudden drop in performance.
5) The size of the unit will be small enough to fit inside the existing combiner box, no larger than 5"x 10"x2".
6) The data will be transmitted to the internet preferably via wirelessly.
7) The S.A.M. should have a life of 15 to 20 years.

III. SYSTEM COMPONENTS

A. Current and voltage sensing

The monitoring system needs reliable voltage and current sensors that will stand the heat and give accurate reading during a rough weather. In addition, these sensors have to be affordable and easy to install so QuickBeam Energy can install one system for each array. The cost was the main issue in looking for the right sensors, so after much research, the CSA-1V SENTRON current sensor was the one that fit the requirements needed. It is a low-cost sensor at around $5, reliable in all weather conditions, and can be installed without disassembling the conducting wires. For voltage sensing, a voltage divider circuit was implemented because it is cost-effective and doesn't dissipate significant power.

B. *Microprocessor and serial communication*

Since our input data is in analog form and our output communication is in digital form, it is necessary to employ some kind of microcontroller for reading, interpreting, and communicating the data. MicroChip's PIC18F4458 was chosen for its twelve AD converters with twelve bits of precision, FLASH program memory, and internal clock.

To simplify testing the prototype hardware and software a serial communications module was featured. It is possible that in production this will be dropped and a direct Ethernet connection will be engineered.

B. Ethernet communications

In order to determine the type of transmission device to use it was necessary to approximate the amount of data that was going to be transmitted by the S.A.M. back to QuickBeam Energy. The microprocessor being used has 12 bit analog to digital converters which means that each sample will be encoded with 12 bits of precision. This being the case each sample will occupy 2 bytes of storage. With ten samples being necessary in order to measure the voltage and the current for each of the five lines this translates into 20 bytes of data. This is miniscule in terms of the bandwidth required to transmit the data. The most convenient and low cost transmission medium that was decided based on this information was an Ethernet controller.

Communication with QuickBeam Energy will be done through the internet using the device WIZ110SR. QuickBeam Energy will have an internet connection available onsite that will have an Ethernet port free for the S.A.M. Transmission of data will be sent to a QuickBeam server using the FTP protocol.

D. *Power Supply*

The power supply system was designed to be a distributed, vice an integrated system, since all the S.A.M.'s subsystems operated at 5Vdc. With a maximum expected current draw on the supply to be 254mA the power supply was therefore designed to provide 300mA. The power supply consists of a 15watt solar panel with a maximum current output of 1amp and is regulated by a buck regulator to achieve the desired 5Vdc 300mA.

IV. HARDWARE DETAIL

A. Current Sensors

CSA-1V current sensor is a single-axis Hall Effect sensor. It produces a linear output voltage proportional to the applied magnetic field parallel with the chip surface. The sensing plate is located approximately 0.3mm below the top surface of the chip as shown in figure 2.

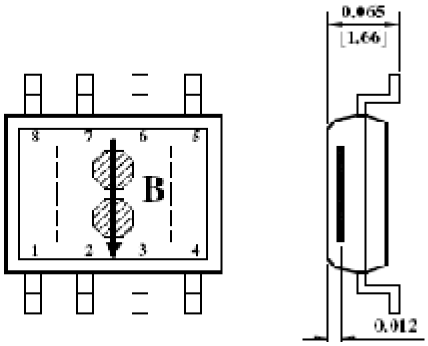

Figure 2: Direction of sensitivity and location of sensing element.

The figure 3 shows that the CSA-1V SENTRON sensor output voltage depends on the current sensed and the distance between the chip and the center of the wire carrying the current. The formula, $V_{out} = 0.060 \times I/(d + 0.3mm)$, calculates the output voltage using I and d, where I is the current sensed and d is the distance in millimeter between the center of the wire carrying current and the CSA-1V SENTRON current sensor.

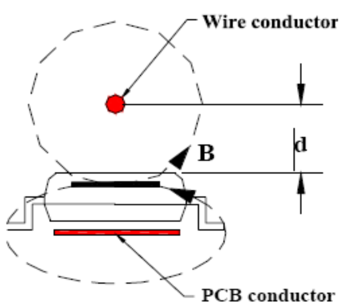

Figure 3: CSA-1V SENTRON Front View

CSA-1V sensor has two different outputs. Single ended output configuration which provides a 0 to 5V analog output with respect to the ground and a differential output which provides a 0 +/- 2.5 volts with respect to an internal reference voltage.

S.A.M. system is going to use a differential output configuration because there is a linear relationship between the current sensed and the differential output voltage, based on the formula

$$V_{out} = 0.060 \times I/(d + 0.3mm)$$

The figure 4 shows the differential output configuration of the CSA-1V current sensor. The differential output voltage is always provided between pins 1 and 8. And the figure 5 depicts the relationship between magnetic field and the output voltage in the differential mode.

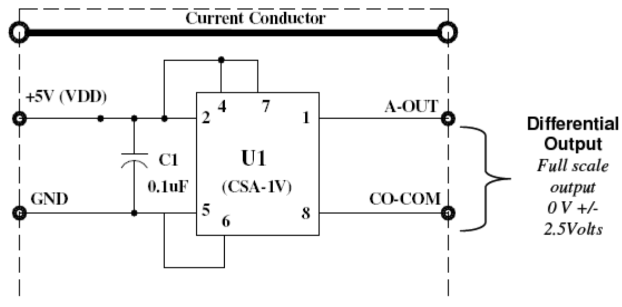

Figure 4: Differential output configuration

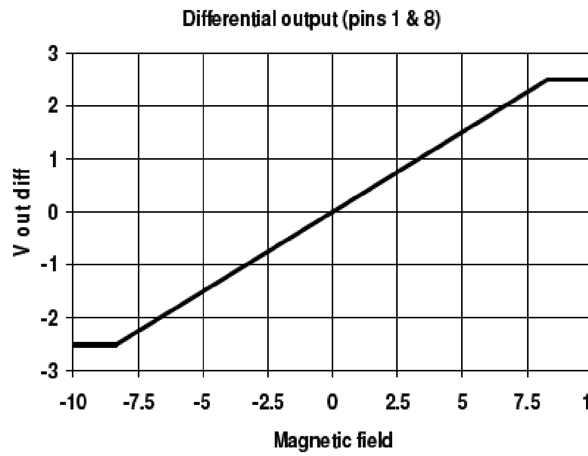

Figure 5: Differential output voltage vs. magnetic field

The circuit in figure 6 is used to provide differential to single ended output 0V to 5V. This circuit has a gain of 2 to 1. To change this gain, simply change the value of 200K resistors.

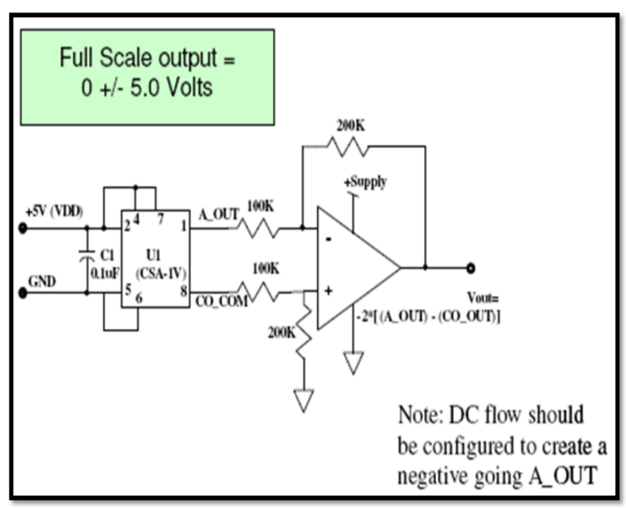

Figure 6: Differential to single ended, 0-5 V swing for DC currents

The op-amp used in the current sensor circuitry is OP491GPZ. It is quad micropower single supply, rail-to-rail input and output op-amp. It operates under a voltage between 2.7V and 12V and a current of 300µA/amp. This type of op-amp has the ability to swing rail-to-rail at the input and the output. It has high signal-to-noise ratios. These characteristics makes it the perfect one to use with the Hall Effect current sensor CSA-1V SENTRON because most of Hall Effect applications requires rail-to-rail input amplifier to increase the accuracy.

The accuracy of the measurement is going to be infected by several factors: First, the Distance between the conductor and the sensor. The closest the conductor to the sensor, the highest the accuracy will be. In S.A.M. case the conductor wire will be touching the top of the sensor. This will give the highest accuracy achieved. Second, the sensor is an open filed magnetic sensor; therefore, it can sense fields from other sources. In S.A.M. case the distance between the wires is about 1.5 inches. From the graph in the figure 7 the sensitivity to an adjacent field will be inconsiderable.

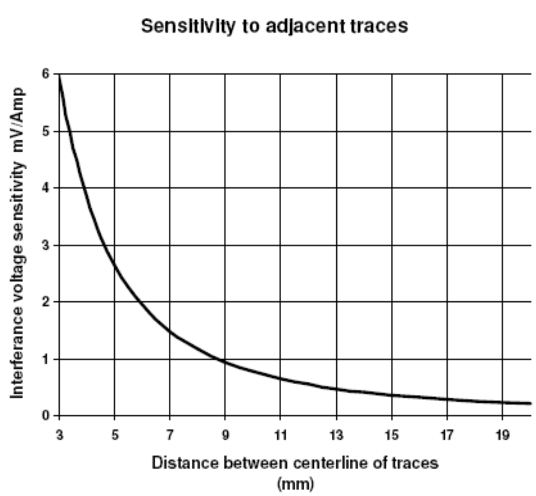

Figure 7: shows the affect of other current conductors which are parallel and placed on the same side of the PCB

The third factor that can affect the accuracy of the current sensor is the temperature. The CSA-1V current sensor has different reading when the temperature changes. Since S.A.M. system will be in a hot environment, a temperature sensor was added to find the linear relationship between the temperature and the differential output voltage.

The LM34DZ is the temperature sensor that is chosen for this application. It is an analog sensor that has a linear output 10mV per degree Fahrenheit. This sensor can measure a temperature between −40° to +230°F and has an accuracy of ±1.0°F (at +77°F).

The figure 8 depicts the physical dimensions of the LM34DZ precision Fahrenheit temperature sensor.

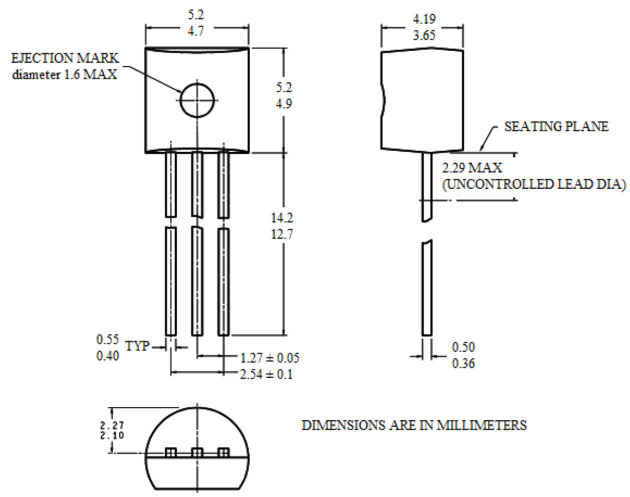

Figure 8: LM34DZ precision Fahrenheit temperature sensor's physical dimensions.

The graph in the figure 9 shows the relationship between the current sensed and the differential output of 5 CSA-1V SENTRON sensors at a temperature of 78°F.

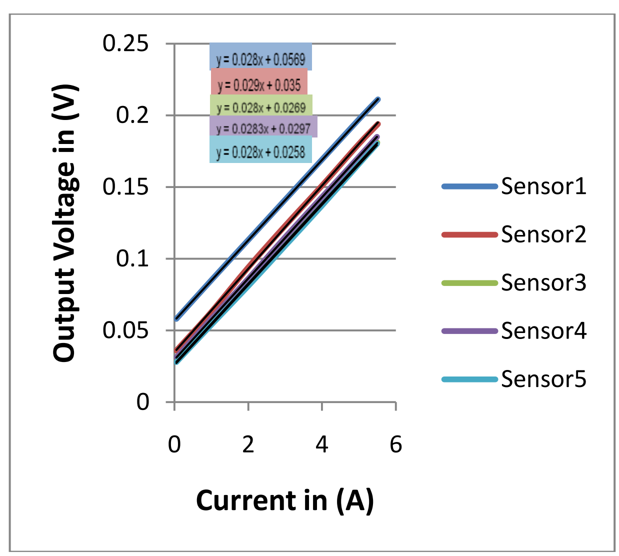

Figure 9: Differential output voltage based on the current sensed

B. Voltage Divider

The maximum voltage that a series-connected solar panel string can produce by law in Florida is 600 volts. Given this information, the maximum amount of power that our resistors must be able to handle has to be enough to prevent damage to the resistor, and our whole device, in case the voltage does reach the maximum value of 600 Volts.

$$V = 600V \quad P_{1W} = 1W \quad I = \frac{P_{1W}}{V} \quad I = 1.667 \text{ x } 10^{-3}$$

As you can see from the calculation above, it is important to not exceed .00167 Amps or approximately 1.60 milli-amps of current through a 1-Watt resistor in order to prevent resistor damage. The S.A.M. voltage sensing circuit was designed to limit this current too far below this value of 1.6 mA as will be shown in the following calculation.

$$R = 10\text{x}10^{6}\Omega \qquad I_1 = \frac{V}{R} \qquad I_1 = 6\text{x}10^{-5}\text{ A}$$

As you can see from this calculation the current will be approximately 60 micro-amps with a 10 Mega-Ohm resistor. This is far below the limit of 1.60 milli-amps for a 1-Watt resistor by a factor of approximately 1000. The following calculation shows the actual power being used by the 10 Mega-Ohm Resistor.

$$P_{res\ max} = V \text{ x } I_1 \qquad P_{res\_max} = 0.036W$$

As you can see the max power usage for the 10 Mega-Ohm resistor at a max voltage of 600 volts will be 0.036 Watts. This measurement actually justifies purchasing lower wattage 10 Mega-Ohm resistors that will still satisfy the job and will likely help us lower our cost of the resistors which will be used in the actual implementation of the voltage sensor circuit.

Furthermore, as can be seen from the calculations above, we can safely use half-watt resistors or even as low as quarter-watt resistors without exposing our circuit to damage. The following calculations are the maximum currents allowed through a 1/2-Watt and a 1/4-Watt resistor:

$$I_{.5W} = \frac{(.5W)}{V} \qquad I_{.5W} = 8.333\text{x}10^{-4}\text{A}$$

Limit will be 0.833 milli-amps

$$I_{.25W} = \frac{(.25W)}{V} \qquad I_{.5W} = 4.167\text{x}10^{-4}\text{A}$$

Limit will be 0.416 milli-amps

The figure 10 shows the circuit chosen for voltage divider. As seen, for an input of 350V the output voltage is 3.536V. By adjusting the potentiometer, the value 3.5V can be obtained. The same for 180V if applied to the input, the output voltage will be 1.815V as shown in figure 11. Also, by adjusting the potentiometer, the value 1.80V will be obtained.

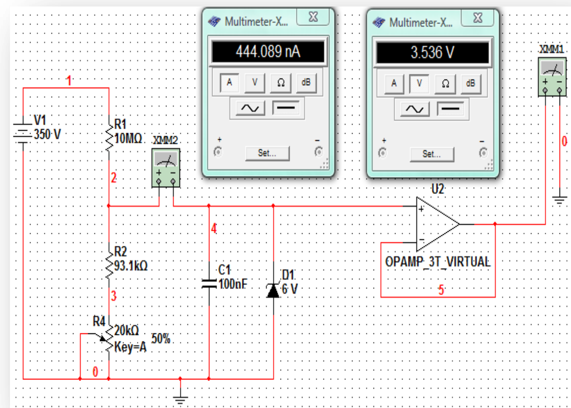

Figure 10: Voltage divider circuit shows an input of 350V and an output of 3.536V

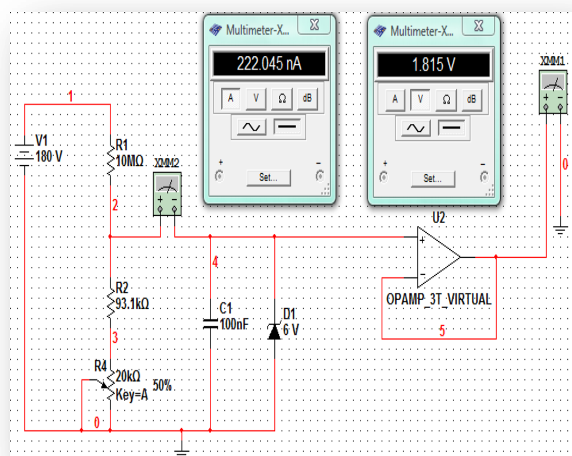

Figure 11: Voltage divider circuit shows an input of 180V and an output of 1.815V

C. Microcontroller

Literally tens of thousands of microcontroller models are available on the market for prices starting at about a dollar. Some criteria were necessary to decide among them.

Since project specifications require an error of less than one percent in the voltage and amperage measurements, it is necessary to have analog/digital converters with at least twelve bits of precision, yielding 4095 increments into which the input voltage can be divided. Thus a line voltage of maximum 480 V. can be divided into 4095 increments of 117 millivolts each. As a result we can meaningfully express voltage in tenths of volt increments, such as 351.8 V., and still be within project criteria of accuracy.

Furthermore, to simplify circuit design a microcontroller was needed with at least ten AD converters, two for each of five strings of solar panels. A single AD converter could have been made to work, but that would have entailed adding three input multiplexers to the design.

Finally, MicroChip's PIC18F4458 was chosen for its twelve AD converters with twelve bits of precision, FLASH program memory, and internal clock. In the end, it was fortunate that the chip had extra ADC's because a temperature sensor later had to be added to the design.

The circuit connections for the microcontroller are shown in Figure 12 below.

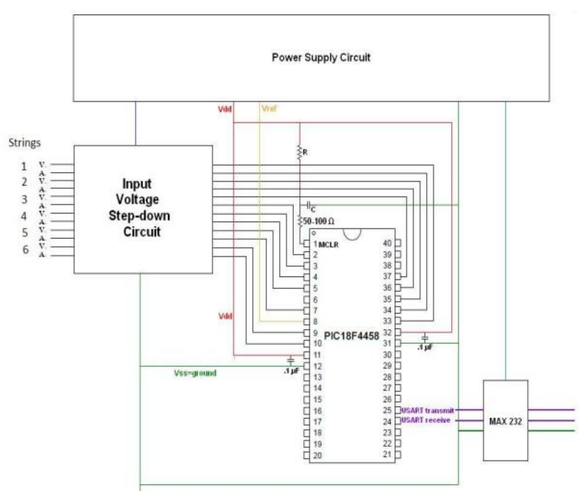

Figure 12: Microcontroller circuit connections

Since the serial port of the PIC18 does not supply the voltage levels required by the RS 232b standard, it is necessary to add a serial transmitter/receiver chip to bring the logic HIGH output to (-5 to –15V) and the LOW to (+5 to +15V).

D. Ethernet

Many different devices were looked at for the purposes of transmitting data back to QuickBeam Energy. Serial communication through the microcontroller was desired because of its ease of implementation. The next issue was to take this serial signal and send it over the internet back to the QuickBeam server. In order to do this we used WIZ110SR. The WIZ110SR is a protocol converter that transmits data sent by serial equipment to Ethernet. The input received by the serial port on the WIZ110SR is sent to a W5100 by MCU. The device will operate in client mode and will initiate a connection to the QuickBeam Energy servers approximately every 15 minutes. The IP address of the device will be static and the IP address of the QuickBeam Energy servers will be static or acquired through a DNS query. Transmission will occur every 15 minutes when the readings from the solar array transmission lines are sampled.

D. *Power supply*

One of the original goals was to make this monitoring upgrade as easy to install as possible for one technician to be able to complete it within 30mins and needing only a screwdriver. To accomplish this 5Vdc buck regulator would get its power from the one of the incoming strings of panels. To minimize the solar power system's loss, a buck regulator was chosen because it has greater efficiency than a linear regulator, roughly around 30% greater. The main hurdle in S.A.M.'s power supply design was the incoming voltage range on a string of panels, 180V to 450Vdc. To step this voltage down to a range the buck regulator could handle various topologies were investigated. The first idea was a simple voltage divider but was found to be too wasteful. Next, a series resistor was investigated to try and increase the efficiency. The most complicated design was to convert the needed power to 240Hz AC, then use a (10:1) step-down transformer, followed by a full-wave bridge rectifier then a simple RC filter to feed the 5Vdc buck regulator. Out of these three design ideas the voltage divider design eventually won out, but with a load current of roughly 300mA and a buck efficiency of roughly 60%. When the solar panel string voltage was 450Vdc the voltage divider's wasted power was about 225watts – more than a single panel from the system that S.A.M. was monitoring. This of course was unacceptable. This the highly wasteful voltage divider design would have required mounting the high wattage resistors in a separate enclosure than the combiner box and therefore not meet the ease of install goal, and once this goal was abandoned another design option was available. The use of a separate solar panel located near the combiner box.

The solar panel chosen is a 15watt panel that will put out a maximum current of 1amp. The solar panel was marketed to charge 12V car/boat batteries and claims to work even in cloudy and low light conditions.

The regulator chosen was the LM22675-5 made by National Semiconductor. It has an input range of 4.5 to 42Vdc and an efficiency of about 80% at an input of

21Vdc [1]. The regulator circuit was designed using National Semiconductor's Webench program and the circuit board is their evaluation board for that regulator chip. The 300mA load current design included in the circuit provides at least 400mA to load. The LM22675 chip is capable of providing a current of 1amp with the correct output inductor and filter capacitor. Therefore, the regulator and the board will be able to meet the future power needs if more current is required.

IV. SOFTWARE DETAIL

A. *Software*

This implementation of solar array monitoring has the virtue of simplicity, which is reflected in the software. All the microprocessor has to do is read the AD converters, interpret this in terms of real voltages and amperages, then send a formatted message out the serial port to the user. A flow chart for the program is shown in Figure 13.

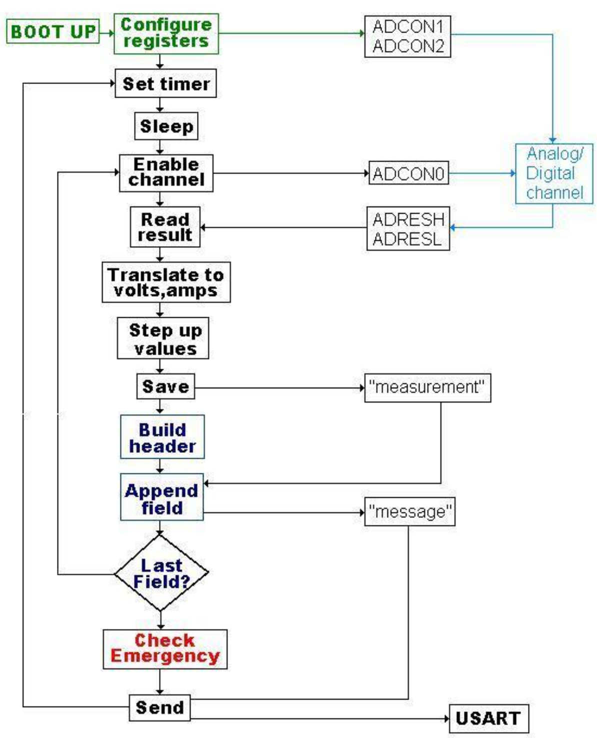

Figure 13: Software flow chart.

B .Communication Detail

Communication is done through Ethernet using the TCP/IP protocol. Serial data from the microcontroller is sent into the WIZ110SR which converts the data for transmission over Ethernet. The WIZ110SR is configured through a serial connection. The WIZ110SR will be configured in TCP Client mode and it will actively establish a TCP connection to the host server when power is supplied. If the connection is complete then data can be transmitted to QuickBeam Energy. The DNS function will be used to acquire an IP address for the QuickBeam FTP server. After the connection is established there is a time limit in which data transmission will have to be completed or the connection will be closed automatically. This time limit will be sufficient for the S.A.M. to transmit all of its data. The amount of data being transmitted will be less than 1Kbyte so transmission time will be much less than 1 second.

V. CONCLUSION

This two-semester long project was a valuable experience causing challenging decisions resulting in the group making a lot of design compromises. But by sampling the string of panels at the combiner box, the project met its main goal of being under $5 per panel monitored

ACKNOWLEDGEMENT

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The group gratefully appreciates the help of the Daniel Parker for spending his time guiding along and providing valuable information to help the group succeed in the project.

We would like to also thank our project manager Dr. Ritchie for his guidance.

We also offer our thanks and gratitude to the professors who have so kindly agreed to review our project we have worked so hard on.

THE ENGINEERS

Steve Parker has a degree in Chemical Engineering from Oklahoma State University (1977) and is completing one in Electrical Engineering at UCF in May 2010. Prior to UCF he worked as a journeyman electrician in Orlando for five years. He intends to specialize in electrical systems design.

Mike Telladira is a former Nuclear Reactor Operator and Electronics Technician First Class in the U.S. Navy. He will be graduating this semester with a BSEE degree from the University of Central Florida. He plans to work as an engineer and continue his education to at least the Master's level in either electrical or computer engineering. He has numerous research interests and is a member of the National Scholars Honor Society.

William Adrobel will be graduating with a BSEE. He is a veteran of the U.S. Air Force and worked as a communications operator for the 32nd Combat Communications Squadron at Tinker AFB, Oklahoma. He would like to continue in the field of communications once he graduates and would also like to pursue a master's degree in Electrical Engineering.

Mohammed Jebari has a degree in Commercial Marines from ITPM Morocco (1998). Currently, he is a senior electrical engineering student at the University of Central Florida. He plans to graduate with a Bachelors of Science in Electrical Engineering in May 2010. He wants to pursue his Master's degree in either Electric Power Systems or Optics but would like to gain some work experience immediately after graduation.

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