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Investigation of Solar Energy Applications with Design and Implementation of Photovoltaic Traffic Light Signal System for Qatar

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Abstract

The objective of this paper is to promote the use of solar energy in powering traffic signal systems for rural areas in Qatar with no power grid. A photovoltaic system is needed in order to use this energy continuously. The results of the investigation of components, design, and market availability are shown in the paper. Solar cells, which are used for absorbing sunlight and generating electric current, are the main source for the system's operation. A charge controller is used to control the flow of charge through the battery and to protect the battery from overcharging and deep discharging. A dc-dc converter is used to regulate the output voltage which depends on the type of dc to dc converter. Lead acid batteries are used as the electric energy storage for the PV system to use electrical energy in the absence of sunlight. The principle operation of the system and the feasibility of using it for rural area with no power grid have been studied. For this project, a mount tracker was constructed that enabled the solar panel to be placed at 0, 15, 30, 45, 60, 75 and 90 degree angles in order to determine which angle and what time provides the optimum voltage. Experimental results for different angles of radiation at different times of the day and different days of the year are shown in the paper.

1. Introduction

Environmental concerns dominate the world today, with terms like ozone depletion, greenhouse effect, global warming and climatic disorder. Therefore, scientists are trying to solve these problems in different ways. Part of their efforts is directed towards limiting the use of fossil fuels, and replacing them with alternative sources of energy that do not cause any harm to our eco-system. Perhaps the most significant and promising technology to have emerged out of this quest is photovoltaic. Solar energy is the most non-conventional energy source gaining interest throughout the world which has no harmful environmental impact. Most manufactures warrantee their solar panels for 20 years. Small photovoltaic systems are excellent supply sources in cases of natural disasters. In such cases photovoltaic systems can be used as power supply sources for medical institutions, schools, street lighting, traffic signalization, road sign illumination, water pumps, and purifying systems.

In this project the circuit has two voltage sources, the battery and the solar cell, in order to keep the traffic light operating at all times in rural areas with lack of electricity. The purpose of the solar panel within the circuit is to provide a clean source of energy to run the traffic light signal and to charge the battery during the day. The second energy source is the lead acid battery which charges by solar cell during the day and supplies electricity to the circuit during periods when the solar cell can't generate enough voltage to run the circuit (during night or cloudy days).

The solar panel consists of an array of solar cells connected in parallel or series to produce dc electricity, with the desired parameters (voltage, current, etc.). The charge controller/ dc-dc converter device, is a two in one component which does two functions. This device protects the battery from overcharging and deep discharging, which is very important to protect the battery from being damaged and to increase its life span. It basically takes the voltage supplied by the solar panel and drops it down to 12 volts so that it supplies both the battery and the stop light. This is mainly because the voltage supplied by the solar cell varies and can reach up to 25 V, therefore the dc-dc converter has to be present to prevent the circuit from malfunctioning and regulating to 12 V.

The load component of the circuit is the traffic light signal. The purpose of the circuit is to build a standalone photovoltaic traffic light signal that is able to function for long periods of time within a rural area with no grid connection. The practical Photovoltaic Traffic Light Signal system with the real components in the project is shown in Figure 1 where V_{SC} is voltage across the solar cell, V_{load} is voltage across the load (12V stop light signal), $V_{CC} = V_B$ is voltage across the charge controller and battery, and I_{load} is current across the load. The specifications of the components of the Photovoltaic Traffic Light Signal system used in this project are shown in [1].

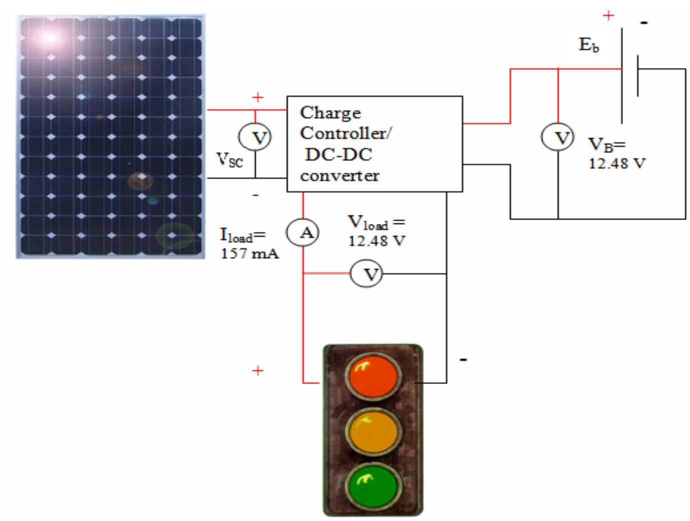

Figure 1: Photovoltaic Traffic Light Signal system with real components

2. Solar Cell Design and Simulation

Photovoltaic energy is the conversion of sunlight into electricity through a photovoltaic (PV) cell, commonly called a solar cell. Photovoltaic cells absorb sunlight and convert it directly into electricity. PV cells are constructed out of semi-conductors so that when light shines onto the cells a certain amount of the light is absorbed. The energy of the absorbed light knocks the electrons loose from their atoms allowing them to flow through the compound. This flow of electrons produces a current that can be extracted and used as electricity [1]. The performance of a photovoltaic cell depends upon the following:

- Sunlight and the angle that the sun rays hit the PV cell. The most optimal position for the rays to hit the PV cell is at a 90 degree angle, which takes place at noon.
- Climate conditions (e.g., clouds, fog, dust, etc.) have a significant effect on the amount of solar energy received by a PV cell and, in turn, its performance.
- Absorption and reflection by the atmospheric layer shrouding the earth reduces the amount of solar energy arriving on earth.
- Temperature [4].

The equivalent circuit of solar cell is shown in Fig. 2 where the total current I is:

$$I = qA\left(\frac{D_h}{L_h} p_{N0} + \frac{D_e}{L_e} n_{P0}\right)\left(e^{qV/k_BT} - 1\right) - qAG(L_h + L_e) \qquad (1)$$

Where I is the load current (amperes), q is the charge of the electron (coulombs), A is the area of the diode (cm^2), D_h is the diffusion constant for the hole, L_h is the diffusion length for the hole (cm), p_{N0} is the density of holes (g/cm^3), D_e is the diffusion constant for the electrons, L_e is the diffusion length for the electrons (cm), n_{P0} density of electrons (g/cm^3), V is the voltage (volts), K_B is Boltzmann's constant, T is the transmission coefficient of coupler in coherent receiver, and G is the generation rate for carriers. The output voltage of the solar cell can be calculated by using:

$$V_{oc} = \frac{k_B T}{q} \ln\left[\frac{L_h + L_e}{\frac{D_h}{L_h} p_{N0} + \frac{D_e}{L_e} n_{P0}} G + 1\right] \qquad (2)$$

where V_{oc} is the maximum voltage obtainable at the load under open-circuit conditions of the diode (volts). [5]

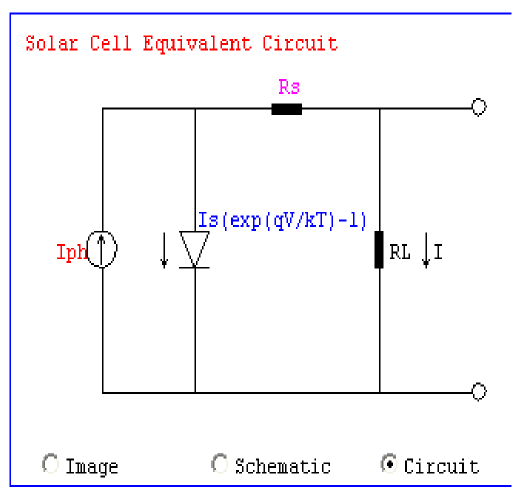

Figure2: Equivalent Circuit of the Solar Panel

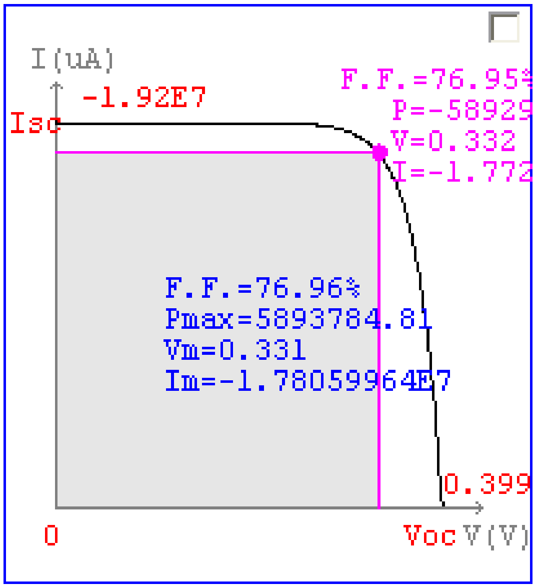

Figure 3: The Output of the Circuit Simulation in Fig. 2

The values of the voltage and current shown in Figure 3 are the values obtained when the area of the solar module is set to 24 cm^2, and the value of Rs is set to 1 Ohm and that of RL is set to 5 Ohms at a temperature of 27^{o}C. The maximum current that could be produced from such configuration is 1780.6 µA with the maximum voltage of 0.331 V.

To produce 12 volts from a solar panel formed by a number of 24-cm^2 cell, the total area needed will be about 870 cm^2. Therefore, the number of cells needed will be 36 cells, which could be aligned in a six-by-six configuration.

3. DC-DC Converter Design and Simulation

A dc-dc converter accepts a variable dc input voltage and produces a fixed dc output voltage that is either higher or lower than the voltage level of the input. There are three basic type of dc converters; buck, boost, and buck-boost converters [6, 7]. A buck-boost converter was chosen because the output voltage of the solar panel varies depending on light intensity. Therefore, the generated voltage will be sometimes more than 12 volts and sometimes less those 12 volts. A non-isolated, (transformerless), topology of the buck-boost converter is show in Figure 4. The converter consists of a dc input voltage source, Vs = Vin, inductor L1, controlled switch S, diode D, filter capacitor C1, and a load resistance R_1 . With the load switch on, the inductor current increases while the diode is maintained off. When the switch is turned off, the diode provides a path for the inductor current [6, 7].

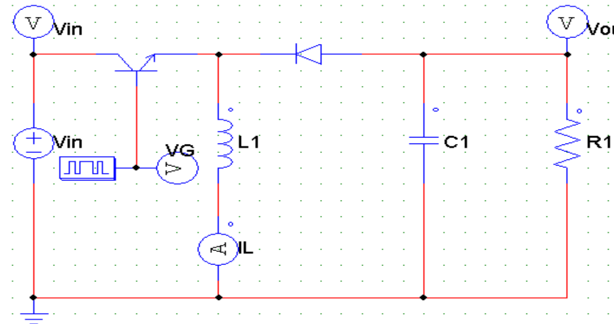

Figure 4: Basic Buck-Boost Converter Circuit

The condition of a zero volt-second product for the inductor in steady state yields:

$$V_s D T = -V_o (1-D) T \qquad (3)$$

Where V_s is Voltage Source, D is Duty Cycle, T is Period, V_o is Output Voltage, and, f is Switching Frequency. Using R equal to 964 Ohms, the values of L, C, and D with switching frequency $f_s = 50\, kHz$ are determined as follows:

Table 1: Different Vin and Their Respective Values of D, L, C

Vout	Vin	D	L	C
12	0.5	0.96	0.000015H	1.9917×10^{-8} F
12	12.5	0.489796	0.0025175H	1.0145×10^{-8} F
12	24	1/3	0.00428H	6.915×10^{-9} F
12	25	0.3243	0.004401H	6.72×10^{-9} F

A simulation of a dc-dc converter was done in PSim [1, 7] using an input voltage of 12.5V and 24V and the results is shown in Figure 5.

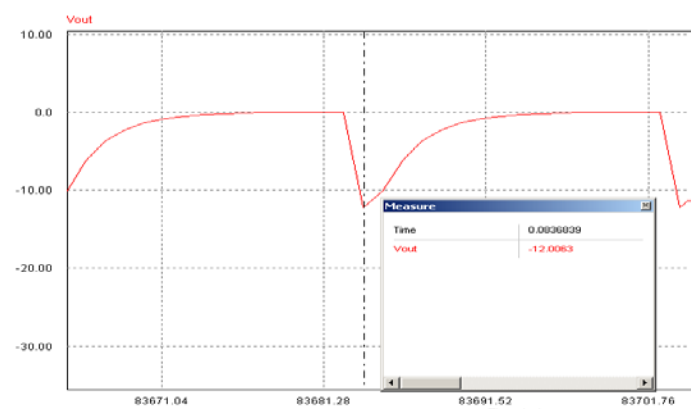

Figure5: Simulation of a dc/dc converter in PSim (Gating Details)- 12.5 V input

4. Design and Simulation of a Charge Controller

A charge controller is used to control the flow of charge through the battery during charging and discharging. A charge controller protects the battery from overcharging and deep discharging in order to protect the battery from damage and also to increase its life span. The simple charge controller will be implemented using the Multisim program [1]. The program will simulate input, output voltages and current through the battery. The circuit built on Multisim program is shown in Figure 6. The graph is obtained by running a DC sweep simulation for V1, the voltage sweeps from 13 V to 20 V (the minimum and maximum voltage produced by solar panel). The corresponding values of the current are graphed against the voltage values and the results are shown in Figure 7.

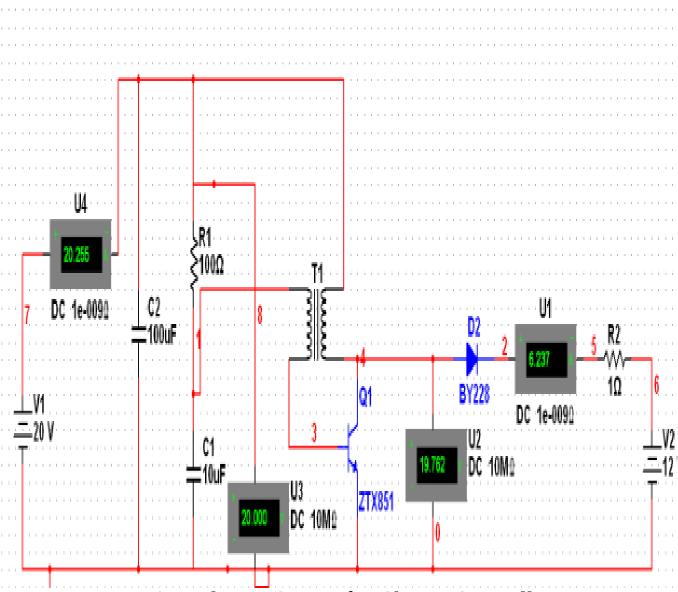

Figure6: Multisim Circuit for Charge Controller

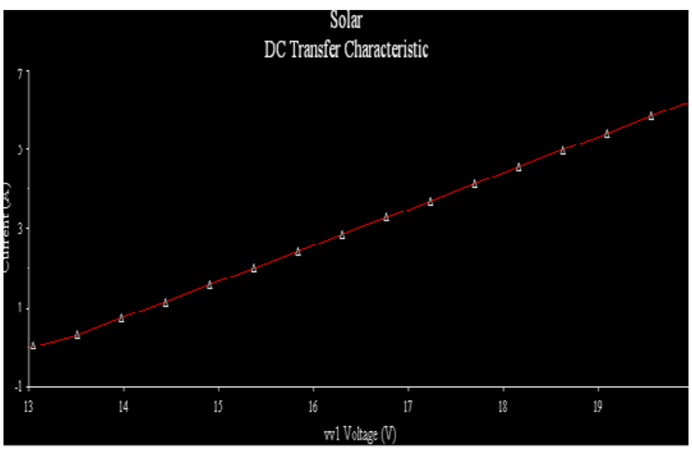

Figure 7: Battery Current vs. Solar Panel Voltage

5. Electric Energy Storage

Chemical batteries are used to store energy in stand-alone systems for use during the night and when solar energy is not available. These batteries have reversible reactions that are rechargeable. The most suitable battery technologies to use in a stand alone photovoltaic system are: lead acid batteries, Lithium-ion batteries, Ni-Cd batteries. For photovoltaic applications in our project, lead acid batteries are the most suitable due to their low cost, low rate of self discharge and their ability to work at higher temperatures. The Peukert model will be used for simulation of the battery [1, 8, 9]:

$$(I^{1.35})(t)=1.1 \tag{4}$$

The circuit battery model used for simulation is the Thevenin battery model as shown in Figure 8

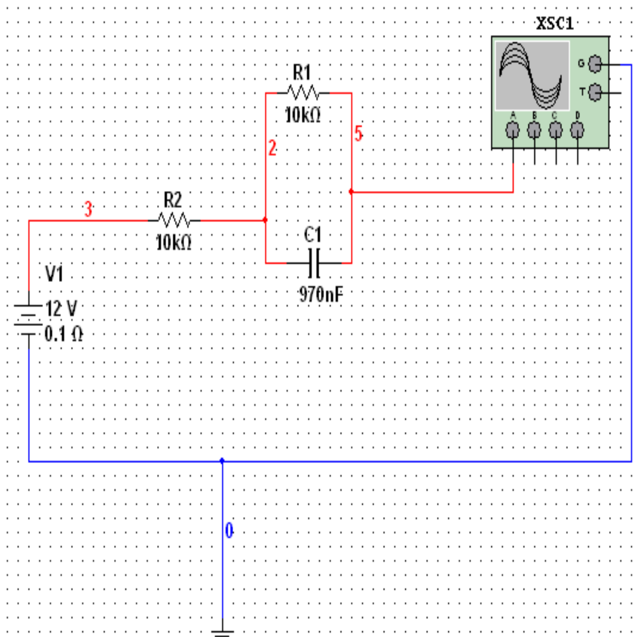

Figure8: Battery Model for Simulation

6. Design of a 12 V DC Stop Light Signal

The purchased stoplight was designed using 220 V AC stoplight available with an extra integrated circuit to control the light shifting. In our project a 12V DC running stop light is needed which has LED lights. These LED need different voltages to produce different colors. This traffic light gets its electric energy from the DC-DC converter during charging time. An integrated circuit was designed and implemented to work with 12 V DC voltage instead of 220 V AC voltage. The integrated circuit and the corresponding block diagram are shown in Figures 9 and 10 [12].

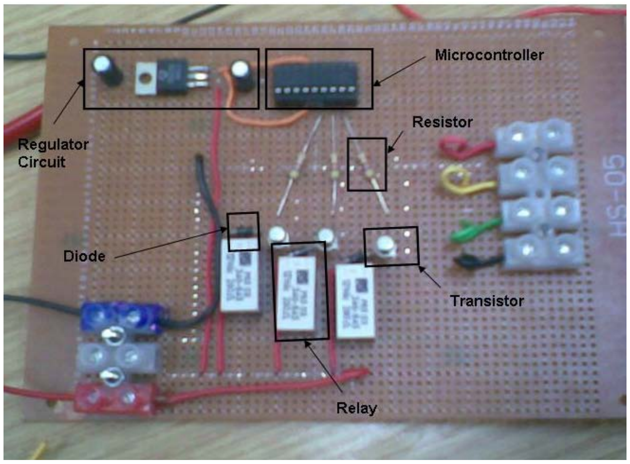

Figure 9: 12 V DC Stop Light Integrated Board

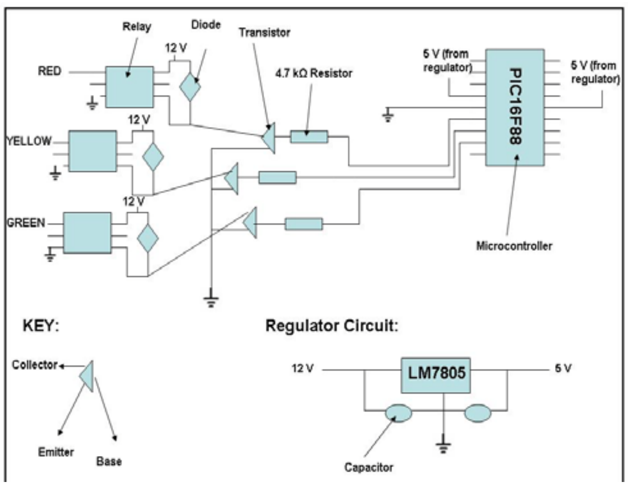

Figure 10: Block diagram of Stop Light Integrated Board

7. Fixed and Movable Solar Array

Mounts are used to support solar panels and install them almost anywhere. Fixed solar arrays are known as solar panel mounts. They help to place the panel at the best angle to absorb the most solar light energy. There are several categories of these mounts: flush mounts, universal roof/ground, and pole mounts. New movable arrays or trackers are being introduced to track the sun all day and get the maximum power output possible [10, 11]. For the purpose of measuring the voltage output of the solar panel at different angles and at different times of the day, a fixed solar mount was constructed as shown in Figure 11. The mount was designed to support the solar panel at fixed angles: 0, 15, 30, 45, 60, 75 and 90 degrees.

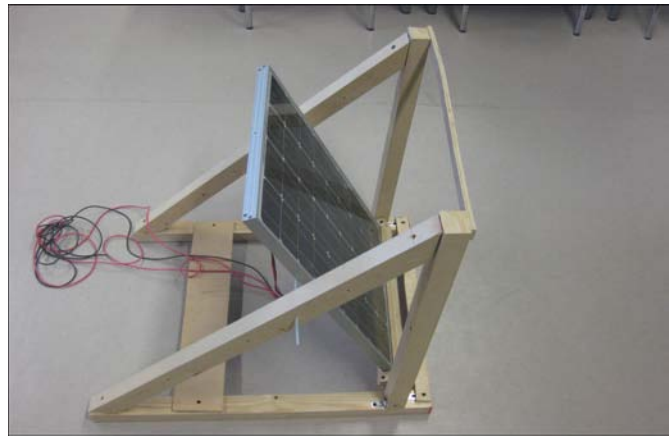

Figure 11: Side View of Fixed Mount Array

8. Test Results

After constructing the fixed solar mount, it was used to measure the voltage for a period of time (8-4) during each day and the results are shown in Figure 12. Also the results from sunrise to sunset for one day is shown in Figure 13.

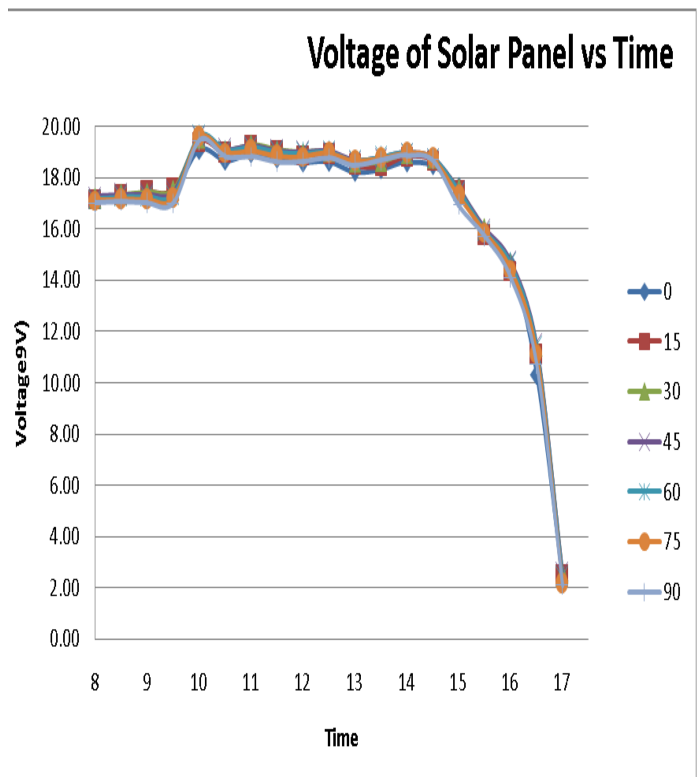

Figure 12: Solar Panel Voltage versus Time for November 8

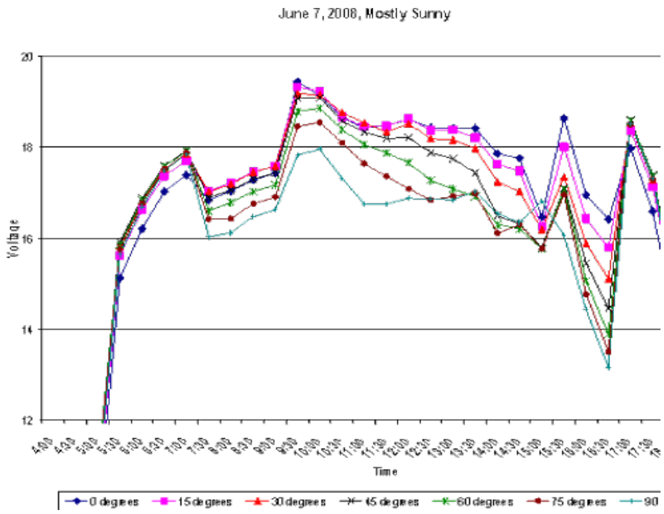

Figure 13: Solar Cell Voltage vs. Time at Different Angles on September 29

The maximum voltage does not only depend on the angle; it also depends on the time of the day, which reflects the position of the sun in the sky. Between 8:00 and 14:00, the variation of the voltage is almost the same. The two highest values are for the angles 0 and 15 degrees, within 15 degrees being the highest most of the time. After that, the voltage decreases when the angle of radiation increases from 30 degrees until 90 degrees. After 14:00, the angles that give the maximum radiation are 60 and 75 degrees with 60 giving the maximum voltage most of the time.

The effect of the day on the voltage output of the panel gives the same angle of radiation. The time of the day has a major effect on the voltage output of the solar panel. A peak value is given between 10:00 and 10:30. The same thing was observed on different days. the voltage starts at about 15.5 Volts at 8:00 and reaches a maximum value between 10:00 and 10:30 in the morning. The voltage then slightly decreases during the day until it reaches a value of around 18 Volts at 16:00. The highest voltage produced by the solar cell was at 15 degrees at the morning time from 8:00 to 12:30.

Figures 14 to 17 show the different graphs for different reading that were taken during November 8th 2008 for a full day. Each graph includes different type of reading for solar traffic light system.

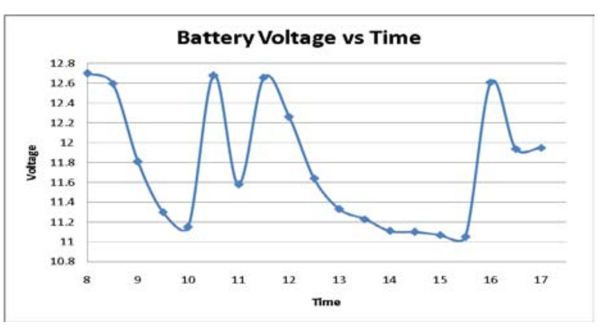

Figure 14: Battery Voltage versus Time for November 8

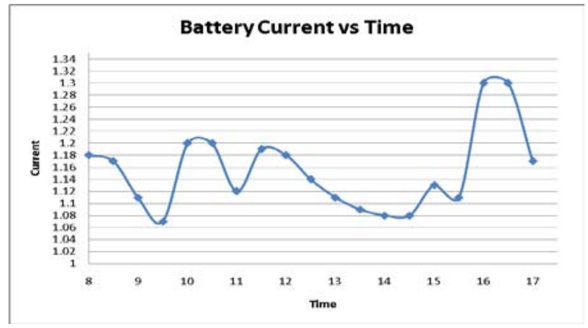

Figure 15: Battery Current versus Time for November 8

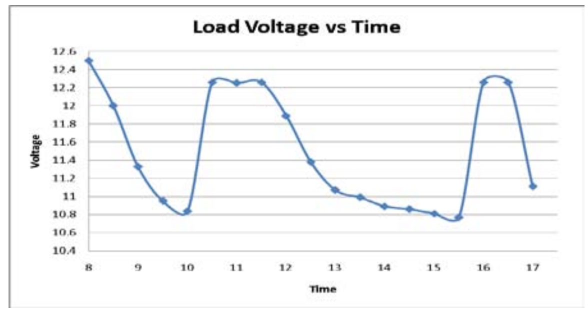

Figure 16: Load Voltage versus Time for November 8

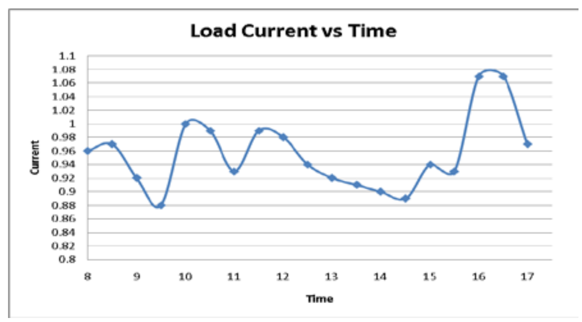

Figure 17: Load Current versus Time for November 8

Figure 18 shows the solar current vs time for different time of the day on November 8, 2008. Figure 19 shows the calculated absorbed power by solar cell in the system where the absorption power is different at different angles and different times of the day.

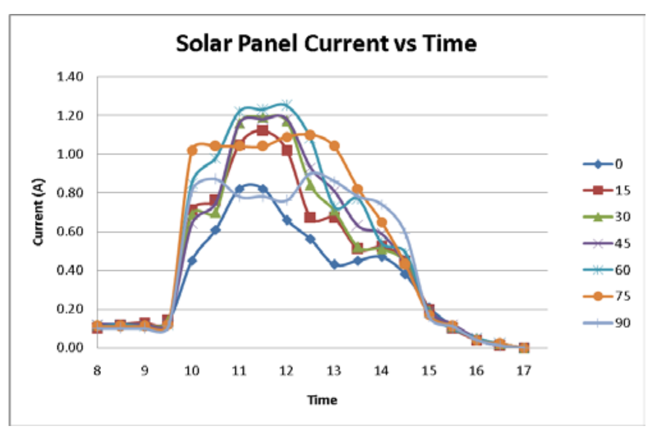

Figure 18: Solar Panel Current versus Time at Different Angles for November 8

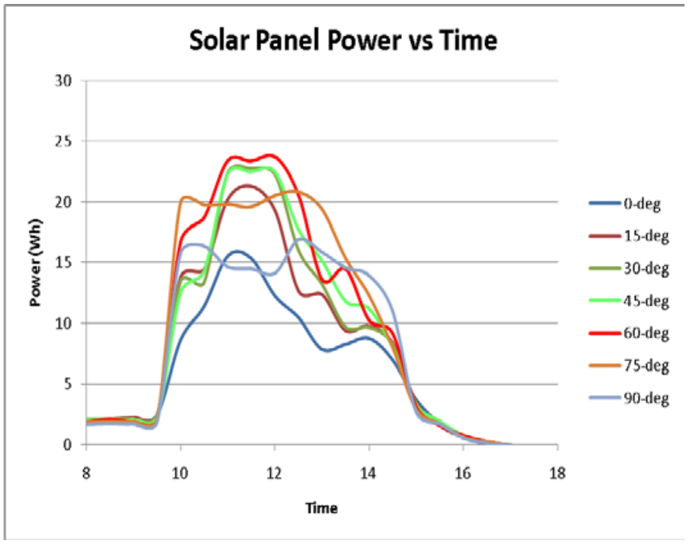

Figure 19: Solar Panel Power versus Time at Different Angles for November 8

Conclusion

Different parts of solar powered traffic light signal systems were examined and designed. These parts include: solar cells, dc to dc converter, charge controller, chemical batteries, traffic stop light signals, and solar fixed array. Additionally, the principle of operation, market availability, and design of different parts were investigated. Crystalline silicon solar cells were proven to be the most favorable type for traffic stop light signals, due to its availability in the market, and its higher efficiency. A buck-boost dc-dc converter was used in order to either amplify or decrease the input voltage so that a consistent 12V output is obtained. The most feasible battery technology used in the solar traffic light project was the lead acid battery since they are relatively inexpensive and have a longer lifetime compared to other batteries. The use of the LED stop light is energy efficient and has a long life span and low maintenance costs. The manipulated stop light used in this project proved to be convenient since the microcontroller could be programmed any time if a phase change was required.

Computer simulations were used to analyze each component and to find their optimum operating conditions in order to use it in the solar system. The complete system was tested for different time of the day and different days of each month and test results were recorded and shown in the paper. The highest voltage was supplied at an angle of 15 to 30 degrees during the morning time up to 12:30. In the afternoon, after 12:30, the angles 60 to 75 degrees showed the highest voltage. Also, as a result of this project investigation, the awareness of using renewable energy was promoted among the students and academic community in Qatar.

Acknowledgments

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Appendix

Individual Component Specifications for Solar Traffic Light Signal System

Table A: Individual Component Specifications

Component and Model Number	Specifications
Solar Cell/ FVG 10 P – FVG 25 M -50106	- Voltage: 0-17.1 V DC - Power: 25 W - Intensity: 1.46 A - Area: 680 x 335 x 23 mm^3
Battery/ ZZ-A-50460 - Rechargeable	- Design life: 5 years in float service. - 12 V - 44 AH - Dimensions 19 x 16,5 x 18h cm - Weight 13.5 kg
Charge Controller and DC-DC converter/ ZZ50050	- Voltage = 12V DC - Charging Current = 5A - Power = 60W
Traffic light signal/ JD303-3	- Voltage: 12VDC - Power: 8W - Size: 300mm (12") - Wavelength: Red: 620-625nm Yellow: 590-595nm Green: 500-505nm - Luminous intensity: 600CD Material: Plastic - Weight: 10 KG - Size: 75*25*15 cm