

Portable Power Supply with Ultracapacitor Application

by

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LIST OF ABBREVIATIONS

DC	Direct-current
AC	Alternating-current
EWB	Electronics Workbench
PV	Photovoltaic
PWM	Pulse-width-modulation
MPPT	Maximum Power Point Tracking
ah	Amp Hours
SOHIO	Standard oil of Ohio
DOE	Department of energy

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Portable power supply requires a means of storing energy for powering applications. Energy storage is typically limited to alkaline or rechargeable batteries. In either instance, the batteries require replacing or recharging. Applications using rechargeable batteries require a secondary set of charged batteries for when the primary set is being recharged. Therefore, in most typical applications, an investment in two rechargeable battery packs is the norm. But even this strategy is not foolproof when the user is waiting for a forgotten battery pack to recharge. Portable devices have a wide range of energy-storage needs. Portable tools have high-power, high-energy needs often necessitating hours of run time between charges, whereas some children's toys only require a few seconds of operation between charges. In many applications, alternative energy-/power-sharing strategies may be employed using a new technology called ultracapacitor.

1.2 Problem Statement

Currently, the army uses customary batteries to operate their radio during outdoor operation [1]. These batteries are heavy and bulky, which is tiresome and restricts their movement to some extent [2]. Besides, it can only support radio usage for some days and not rechargeable. Moreover, the usage of batteries nowadays have exceed it limitations and a new technology must be used to compensate the demanding of portable power supply.

1.3 Objectives

The objective of this project is to design and build a prototype of a DC portable solar-powered electrical device using ultracapacitor as energy storage unit.

1.4 Scope of Study

This project is intended to design a portable power system, focusing on the low voltage use, below 10 V for outdoor used. The main focus is to use ultracapacitor as energy storage unit and at the same time reduce the weight of current portable power system, portability to suit users such as mobile travellers and the army.

1.4.1 Relevancy of the Project

Based on a quick survey done during the early stage of the project, most equipment used for outdoor activities is DC type. The flexibility or option offered by the device will be very useful for this kind of usage. Other than that, similar product in the market also still using batteries as the storage medium. In addition, the project also focuses on using low-cost component to make it economical so that people can afford it.

1.4.2 Feasibility of the Project

This project is expected to be completed within the twenty-five (25) weeks time frame. The first half of the period is to explore and learn more about the solar energy, piezoelectric, photovoltaic system, ultracapacitor and each element in the system. The second half of the time frame will be used to complete and run testing of the prototype.

CHAPTER 2

LITERATURE REVIEW

2.1 Fundamental of Solar Energy

Solar energy is one of the renewable energy that produces power by utilising the energy from the sun. The sun basically provides energy in two forms which are light and heat. Solar thermal using heat to produce hot fluids or air while photovoltaic is used to produced electricity.

Malaysia located near to the equator, has the average daytime between 7am to 7pm and monthly average solar radiation between 4000 to 5000 W h/m² [3]. Although the daytime is almost constant throughout the year, the global solar radiation on any particular day cannot be predicted. This is typical for any location situated in the equatorial climate. The solar radiation pattern could be classified into 5 categories (see Table 1). This pattern would provide a significant effect to the annual electricity production from the grid that connected to solar photovoltaic (PV) system.

Table 1: Distribution of Annual Solar Radiation Pattern [4]

Pattern	Definition	Distribution
Clear	Days of clear sky with direct sunlight to the ground	15.7%
Part cloudy	Days with occasional cloud blocking direct sunlight	51%
Afternoon rain	Days with rain in the afternoon	16.5%
Full cloudy and rain	Total overcast days with occasional rain	13.7%
Special case	Days occasional radiation due to cloud and atmosphere effect	2.8%

2.2 Photovoltaic System

The history of photovoltaic materials goes back to 1839 when Edmund Becquerel discovered the photo galvanic effect, where electric currents were produced from light induced chemical reactions. PV cell was first used in powering satellites but its application nowadays has change and growing rapidly in the power production.

2.2.1 Working principles

When sunlight strikes a PV cell, the photons of the absorbed sunlight dislodge the electrons from the atoms of the cell. The free electrons then move through the cell, creating and filling in holes in the cell. It is movement of electrons and holes that generates electricity. The physical process in which a PV cell converts sunlight into electricity is known as the photovoltaic effect. Normally, a single PV cell can produce up to 2 watts of power, too small for powering calculators or other equipments. In order to increase the power output, PV cells are connected together to form modules, which are further assembled into larger units called arrays. This modular nature of PV has enables designers to build PV systems with various power output for different types of application [5]. Typical solar cell system is as Figure 1 below.

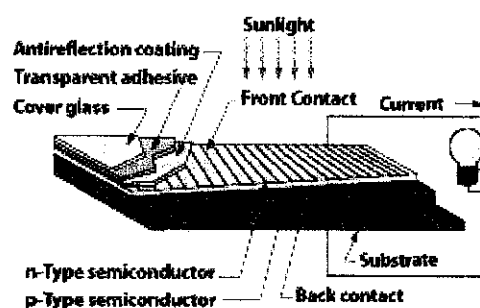


Figure 1: A typical solar cell system [6]

2.2.2 *Materials*

Basically, PV cells are made of semiconductor materials. The major types of materials are crystalline and thin films. Both materials have advantage and disadvantage in terms of light absorption efficiency, energy conversion efficiency, manufacturing technology and cost of production.

Thin Film Materials

1) Amorphous Silicon (a-Si)

Amorphous solids, like common glass, are materials whose atoms are not arranged in any particular order. They do not form crystalline structures at all, and they contain large numbers of structural and bonding defects. But they have some economic advantages over other materials that make them appealing for use in solar electric, or photovoltaic (PV), systems. In 1974, researchers began to realize that they could use amorphous silicon in PV devices by properly controlling the conditions under which it is deposited and by carefully modifying its composition. Today, amorphous silicon is common in solar-powered consumer devices that have low power requirements, such as wristwatches and calculators. Amorphous silicon absorbs solar radiation 40 times more efficiently than does single-crystal silicon, so a film only about 1 micrometer or one one-millionth of a meter thick can absorb 90% of the usable light energy shining on it. This is one of the major reasons that amorphous silicon could reduce the cost of photovoltaic. Other economic advantages are that it can be produced at lower temperatures and can be deposited on low-cost substrates such as plastic, glass, and metal. These characteristics make amorphous silicon the leading thin-film PV material [5].

2) Cadmium Telluride (CdTe)

CdTe is a semiconductor compound that has high light of absorptive level. Advantage of CdTe is that it is relatively easy and cheap to manufacture by processes such as high-rate evaporation, spraying or screen printing. The disadvantage of using CdTe for PV cells is the instability and the characteristic of cadmium which is toxic [5].

3) Copper Indium Diselenide (CuInSe₂ or CIS)

CIS is a polycrystalline semiconductor compound of copper, indium and selenium. Over the years, CIS has become one of the major research areas in the thin film industry. This is due to the highest “research” energy conversion efficiency of the material. Being able to deliver such high energy conversion efficiency without suffering from the outdoor degradation problem, CIS has demonstrated that thin film PV cells are a viable and competitive choice for the solar industry in the future. CIS is an efficient but complex material. Its complexity makes it difficult to manufacture. So far,, CIS is not commercially available yet although Siemens Solar has plans to commercialize CIS thin-film PV modules.[5]

Crystalline Materials

1) Single-crystal silicon

Silicon is one of the earliest materials used for photovoltaic (PV) devices. Currently, silicon is still considered as the most popular material for solar cells. Outranked only by oxygen, silicon is also the second-most abundant element in the Earth's crust. However, to be useful as a semiconductor material in solar cells, silicon must be refined to a purity of 99.9999%. A single-crystal silicon has a uniform molecular structure.

Compared to non-crystalline materials, single-crystal silicon has high uniformity which results in higher energy conversion efficiency. The higher a PV cell's conversion of energy, the more electricity it generates for a given area of exposure to the sunlight [7].

2) Polycrystalline silicon

Multicrystalline silicon devices are generally less efficient than those of single-crystal silicon, but they can be less expensive to produce. The multicrystalline silicon can be produced in a variety of ways. The most popular commercial methods involve a casting process in which molten silicon is directly cast into a mould and allowed to solidify into an ingot. The starting material can be refined lower-grade silicon, rather than the higher-grade semiconductor grade required for single-crystal material. The cooling rate is one factor that determines the final size of crystals in the ingot and the distribution of impurities. The mould is usually square, producing an ingot that can be cut and sliced into square cells that fit more compactly into a PV module [7].

3) Gallium Arsenide (GaAs)

GaAs is a compound semiconductor that made of two elements, gallium (Ga) and arsenic (As). An advantage of using GaAs is that it has high level of light absorptivity. To absorb the same amount of light, GaAs requires only a layer of a few micrometers thick while crystalline silicon requires a wafer of about 200-300 micrometers thick. GaAs also has a much higher energy conversion efficiency than crystal silicon, reaching about 25% to 30%. Its high resistance to heat makes it an ideal choice for concentrator systems in which cell temperatures are high. GaAs is also popular in space applications where strong resistance radiation damage and high cell efficiency are required. The biggest drawback of GaAs PV cells is the high cost of the single-crystal substrate that GaAs is grown on [5].

2.3 Charge controller circuit

A voltage regulator (or charge controller) is an electrical regulator designed to automatically maintain a constant voltage level. A voltage regulator monitors the battery state of charge to insure that when the battery needs charge-current it gets it, and also insure the battery is not over-charged. Voltage regulator may use an electromechanical mechanism, or passive or active electronic components. Connecting a solar panel to a battery without a regulator seriously risks damaging the battery and potentially causing a safety concern.

Voltage regulators are rated based on the amount of amperage they can process from a solar array. If a controller is rated at 30 amps, then the rating current for the solar panel output must equal or less than 30 amps. The most advanced voltage controllers utilize a charging principal referred to as Pulse-Width-Modulation (PWM) – which insures the most efficient battery charging and extends the life of the battery. Even more advanced controllers also include Maximum Power Point Tracking (MPPT) which maximizes the amount of current going into the battery from the solar array by lowering the panel output voltage, which increase the charging amps to the battery [5].

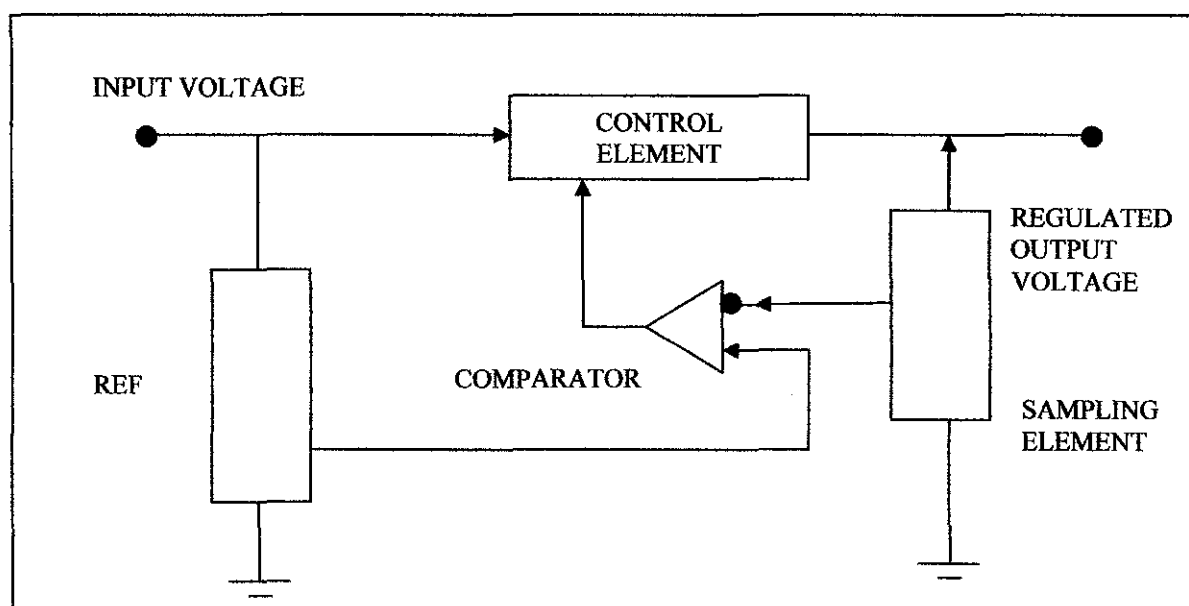


Figure 2: Basic Voltage Regulator Block Diagram [5]

2.4 ENERGY STORAGE UNIT

One of the crucial parts in this project is the storage unit. Storage medium is used to store energy generated by solar panel and to ensure the energy or power produced can be used for the load.

2.4.1 Batteries

DC cell or battery is an electrochemical cell that can be charged electrically to provide a static potential for power or released electrical charge when needed. A battery generally consists of an anode, a cathode, and an electrolyte [8]. The basic cell elements are as shown in Figure 3.

1. The "cathode" or "positive" electrode, which consists of a mass of "electron-receptive" chemical held in intimate contact with a metallic "plate" through which the electrons arrive from the external circuit.
2. The "anode" or "negative" electrode, which consists of another chemical which readily gives up electrons - an "electron donor" - similarly held in close contact with a metallic member through which electrons can be conducted to the external circuit.
3. The "electrolyte," usually a liquid solution that permits the transfer of mass necessary to the overall reaction. This movement takes place by "migration" of "ions" - positively or negatively charged molecular fragments - from anode to cathode and from cathode to anode.

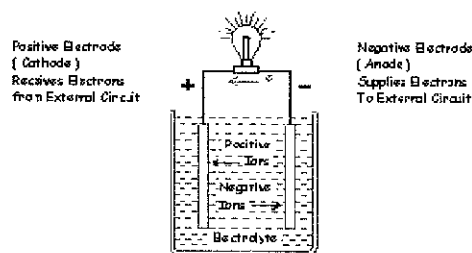


Figure 3: A schematic diagram of basic cell elements [9]

There are two types of batteries which are primary and secondary cell. When the cell can only be used once, it is called a "primary" cell. When the chemical reaction can be reversed repeatedly by applying electrical energy to the cell, it is called a "secondary" cell and can be used in an accumulator or "storage" battery [9]. For this project, secondary cell will be considered as storage medium for the power produce by solar panel.

a) Lithium-ion Battery

Lithium-ion batteries are a type of secondary battery in which a lithium ion moves between the anode and cathode. The lithium ion moves from the anode to the cathode during discharge and from the cathode to the anode when charging. Lithium ion batteries are commonly used in consumer electronics. They are currently one of the most popular types of battery for portable electronics, with one of the best energy-to-weight ratios, no memory effect, and a slow loss of charge when not in use. [10]

b) Thermal Battery

Basically, there are two types of thermal batteries. The most known type of thermal battery is based on the thermo-electric effect which produces electricity directly from heat and the other based on chemical or galvanic reactions. Based on the Seebeck effect, closed circuit made up from two dissimilar metals will create electrical potential between the two junction points when one junction is heated, usually by a gas burner, and the other kept cool. The technique is usually used to charge storage batteries and more recently use to generate emergency power. The setback for the system is not energy efficient and only suitable for low power applications.

c) Pneumatic Battery

Compressed Air Energy Storage (CAES) uses pressurised air as the energy storage medium. An electric motor-driven compressor is used to pressurize the storage reservoir using off-peak energy and air is released from the reservoir through a turbine during on-peak hours to produce electrical energy. Ideal locations for large compressed air energy storage reservoir are aquifers, conventional mines in hard rock, and hydraulically mined salt caverns. Facilities are sized in the range of several hundred megawatts. Air can be stored in pressurized tanks for small systems. [10]

d) Hydraulic Battery

Pumped storage hydroelectricity is a relatively simple method of storing and producing large amounts of electricity to supply high peak demands. At times of low electrical demand, excess electrical capacity is used to pump water into an elevated reservoir. When there is higher demand, water is released back into the lower reservoir through a turbine, generating electricity. Many pumped storage plants have been installed throughout the world.

e) Superconducting Magnetic Energy Storage (SMES)

Superconducting magnetic energy storage systems store energy in the field of a large magnetic coil with direct current flowing. It can convert back to AC electric current as needed. Low temperature SMES cooled by liquid helium is commercially available. High temperature SMES cooled by liquid nitrogen is still in the development stage and may become a viable commercial energy storage source in the future. However, SMES systems are large and generally used for short durations, such as utility switching events.

f) Radioisotope Thermoelectric Generators (RTG)

Radioisotope Thermoelectric Generators (RTG) were designed for space applications and for providing power to remote installations such as lighthouses. Developed in 1959 by the Atomic Energy Commission as Los Alamos and introduced in 1961, these primary batteries are essentially nuclear powered heat generators which use energy emitted by the natural decay of radioactive isotopes of Plutonium (pu-238) to provide the heat which in turn is used to generate electric power in the thermoelectric generator made from an array of thermocouples. It is developed for low power consumer applications. [10]

2.5 Ultracapacitor

Ultracapacitors, also known as supercapacitors or electrochemical capacitors, utilize high surface area electrode materials and thin electrolytic dielectrics to achieve capacitances several orders of magnitude larger than conventional capacitors. In doing so, ultracapacitors are able to attain greater energy densities while still maintaining the characteristic high power density of conventional capacitors. As a result, ultracapacitor based energy storage power system will become an attractive power solution to an increasing number of applications [11].

Ultracapacitor (properly known as electrochemical double-layer capacitors) is based on existing 100-year-old technologies that possess a very high power density along with a substantial energy density compared with electrolytic capacitors. Basically, ultracapacitors are very strong in their cycle capability, power density, safety, environmental, and performance efficiency. Unlike batteries, ultracapacitor can accept charge at a high rate without degradation and also deliver power when needed. Combined with a high-energy source similar to fuel cells, ultracapacitor can provide short bursts of power, while allowing the fuel cell to act as a pure energy source. Because of their light weight and long life, they are becoming the solution of choice for many fuel-cell manufacturers. Today, the best ultracapacitor feature power densities as high as 20 kW/kg. [12]

Ultracapacitor store their energy in an electrostatic field rather than in chemical form. They consist of two electrodes (plates) of opposite polarity separated by an electrolyte. Ultracapacitor is charged by applying a voltage across the terminals which causes charge to migrate to the surface of the electrode of opposite polarity. The energy stored is related to the charge at each interface, q (Coulombs) and potential difference, V (Volts), between the electrodes. The energy, E (Joules), stored in a capacitor with capacitance C (Farads) is given by the following formula.

$$E = \frac{1}{2} q V = \frac{1}{2} C V^2$$

The perspective of ultracapacitor in the future has attracted many companies to do research and develop the components. First patents dated back to 1957 where a capacitor based on high surface area carbon was described by Becker. Later in 1969 first attempts to market such devices were undertaken by SOHIO. However, only in the nineties ultracapacitor became famous in the context of hybrid electric vehicles. A Department of Energy (DOE) ultracapacitor development program was initiated in 1989, and short terms as well as long term goals were defined for 1998–2003 and after 2003, respectively. The ultracapacitor was supposed to boost the battery or the fuel cell in the hybrid electric vehicle to provide the necessary power for acceleration, and additionally allow for recuperation of brake energy. Today several companies such as Maxwell Technologies, Siemens Matsushita (now EPCOS), NEC, Panasonic, ELNA, TOKIN, and several others invest in ultracapacitor development. The applications envisaged are principally as boost components supporting batteries or replacing batteries primarily in electric vehicles. [13].

Another important application of ultracapacitor is in military. The characteristics of the ultracapacitor such as extremely high energy density and high power density are very useful in critical military applications. Potential military applications of the ultracapacitor include power sources for electronic fuse, missiles guidance systems, advance pulse power for rail gun and electromagnetic launcher, laser weaponry and space power conditioning [14]. The high energy density of these components that arises from the electrochemical double layer at extremely high surface is electrodes, while the high power capabilities arise from the use of high conductivity materials.

CHAPTER 3

METHODOLOGY

3.1 Project Flow Chart

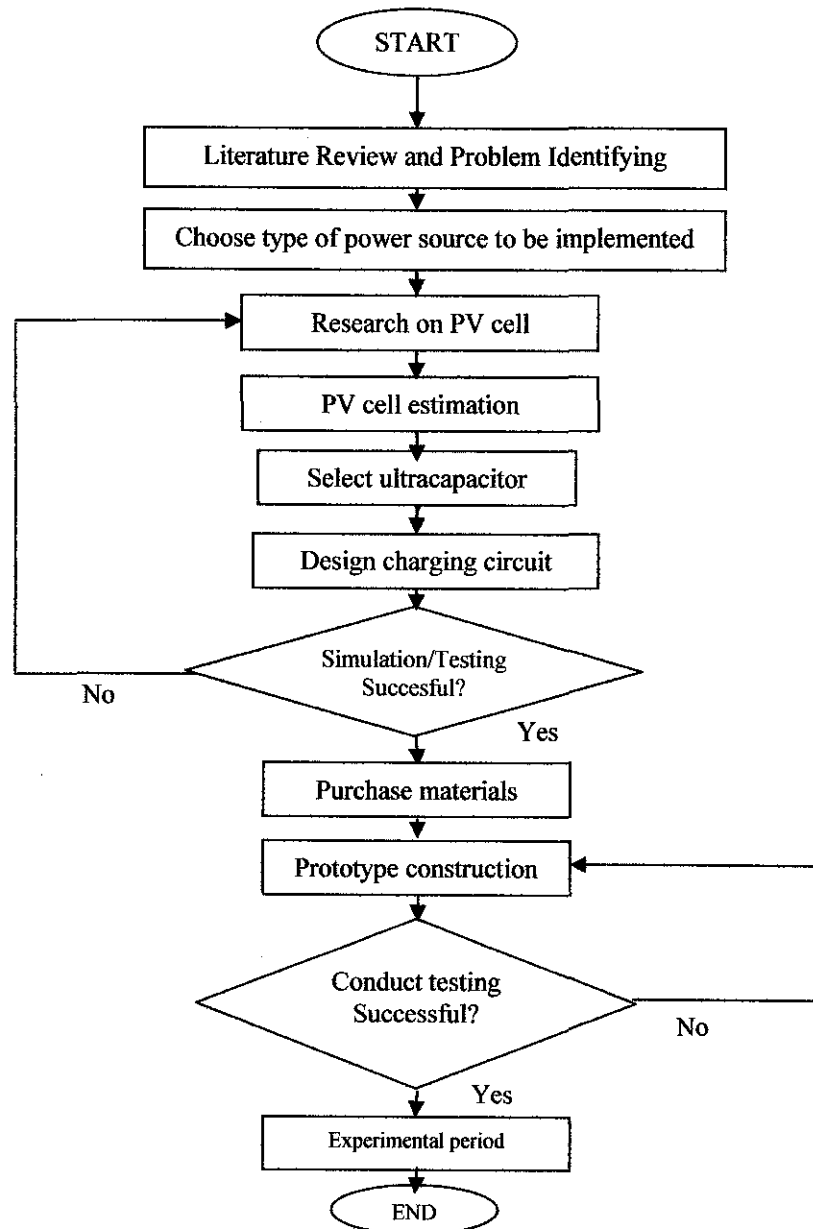


Figure 4: Project flow

3.2 Procedure Identification

In order to make sure that the project can be efficiently completed within 2 semesters, it had been divided into 2 parts for the first semester. The first part involved in literature reviews related to the topic chosen and circuit designed and simulated using PSpice and Multisim Electronic Workbench (EWB) software.

3.2.1 Feasibility Study

The first studies cover only the theories of each fundamental that were related to the topic which are battery, piezoelectric, ultracapacitor, voltage regulator, rechargeable battery, inverter and solar cells. The studies were completed by doing research from the journals, text books, and websites. For these few topics, the concept behind them should be clearly understood and comprehensive enough since this will be helpful when preceding the project.

3.3 Tools

3.3.1 Hardware

The tools that will be used in designing the Solar Photovoltaic System are some hardware such as solar panel, voltage regulator, multimeter and DC load.

3.3.2 Software

The software required to implement this project involved:

- PSpice and Multisim Electronic Workbench (EWB)
- MATLAB and Maple
- Data Studio (Pasco, Data logger)

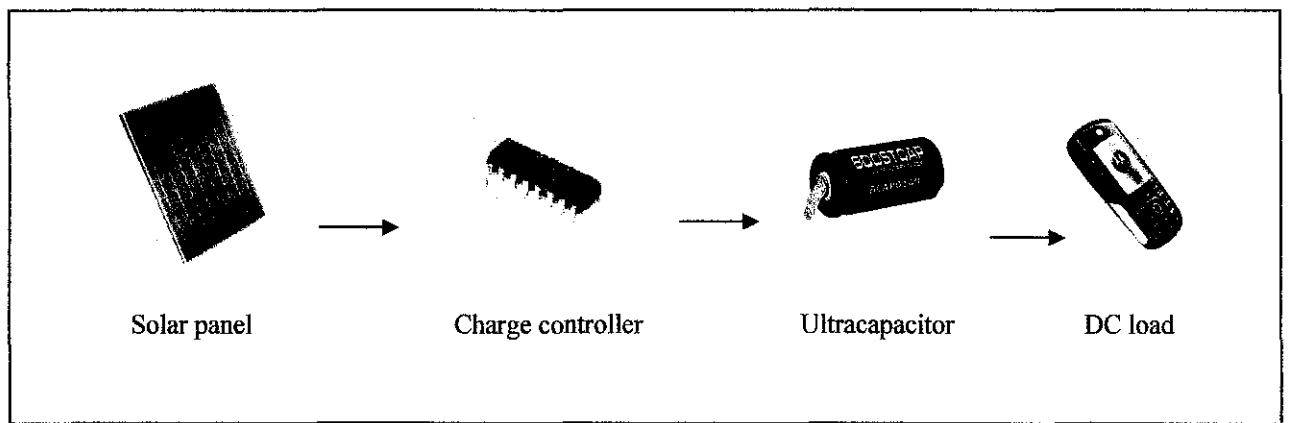


Figure 5: Overall design system

3.4 Solar Energy

At this stage, the main objective is to determine the solar cell configuration in term of size, capacity and efficiency. The main issue of solar energy is that it depends on the weather. Because of that, problem such as voltage drop and fluctuating voltage from solar energy must be taken into account when designing the charging circuit.

3.4.1 Research on PV cell

It is important to do research on PV in order to get better understanding of the system. The research will be covered on types of PV, the characteristics, the problems associated with it, the price and others.

3.4.2 PV cell size

Since the project focuses on making the prototype portable, the size of the PV is a major aspect in selecting the PV. After some research on the PV cell, the size of the PV cell will be determined based on its application. For the project, preferable size of PV cell would be the average size of pencil box.

When the sunlight falls on the cell area, the amount of energy that falls direct on the area is proportional to that area. The energy of full sunlight in Malaysia is approximately 1000 watts per square meter. Energy on the cell can be calculated by multiplying the constant with the area of the cell. For this project, it is assumed that full sunlight is coming straight on the cell. If the sun comes in at an angle, there is an additional constant of the cosine of the angle that must be multiplied in and other complications, such as optical effects that change the efficiency at different angles. [10]

$$\text{Energy out} = \text{width} * \text{height} * 1000 \text{ watts/m}^2 * \text{cell efficiency}$$

3.4.3 Testing

After the size and the rating for the PV is decided, a set of testing will be designed to get the data of the PV cell. The testing will be done using simple circuit during bright day. The main objective is to know the capability of the PV cell and how much voltage and current the PV can produce. The voltage from PV cell will be measured and recorded.

3.5 Energy Storage Unit (Ultracapacitor)

In this part, the focus will be more on designing the charging circuit for the prototype. During the early stage, a couple of circuit will be designed and tested for its function and suitability of the project. The testing will be done in PSpice simulation and the actual circuit analysis in the laboratory. The most suitable circuit will be chosen for the prototype. Other than testing the function of the circuit, other factors such as availability of the component also will be taken into account.

Early stage of the process shown that most of the electronic components in the circuits are easily found in the lab or electronics shop except for ultracapacitor. Since ultracapacitor is a new electronic components, it is hard to find one. The strategy is to find local distributor and order from them.

3.5.1 Design Process

The objective of the project is to design a prototype of power source that use ultracapacitor as energy storage component. As mention in the literature review part, ultracapacitor is still a new technology and still not widely use in the market. A comprehensive review on the ultracapacitor is essential in order to get a clear picture on its characteristic, function and behaviour. For example, an RC circuit will be very useful for the charging circuit since ultracapacitor have quick discharge rate compared to battery. Other than focusing on ultracapacitor, the designing process also involved in investigating and evaluating conventional way of storing energy which is battery. Comparison will be made and discuss later in the next chapter.

3.5.2 Testing

After the charging circuit is ready, a series of testing will be done in variety of condition and configuration. The test also included series and parallel connection of ultracapacitor and battery. Other factors such as weather also will be taken into account. Basically, the testing will be done using Pasco, Data Logger. By connecting the device to the computer, it can record and plot the voltage or current versus time graph. All the results will be discuss in detail in result and discussion part.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Results

4.1.1 Photovoltaic Cell

For the chosen solar panel in Figure 6, an experiment was done to test the capability of the device. Figure 7 shows the circuit that is used for the experiment. The results of the experiment are shown in Table 2. Based on the table, the maximum voltage produce from the solar panel is 7.11 and the minimum voltage generated is 5.28V at 4.48 pm.

Figure 8 shows the voltage spike from the solar panel. The figure clearly shows that voltage produced is varying with the weather conditions. As mentioned in the literature review part, this kind of voltage could potentially damaged or reduce the life cycle of batteries. Ultracapacitor on the other hand will not be affected by the unstable voltage since it is designed to be more robust compared to battery. Overall, the experiment shows that the solar panel that will be used for the prototype is capable of producing enough voltage to switch on the MAX712 and at the same time charge the 4.6V ultracapacitor..

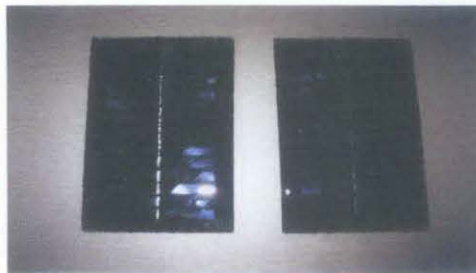


Figure 6: Polycrystalline Solar panel

Table 2: Polycrystalline Solar panel Characteristics

Attribute Type	Attribute Value
Load Voltage	7.2V
Output Power	1W
Open Circuit Voltage	10.3V
Temperature Coefficient	-37mV/°C
Dimensions	15 cm x 8cm
Type	Polycrystalline OEM Module

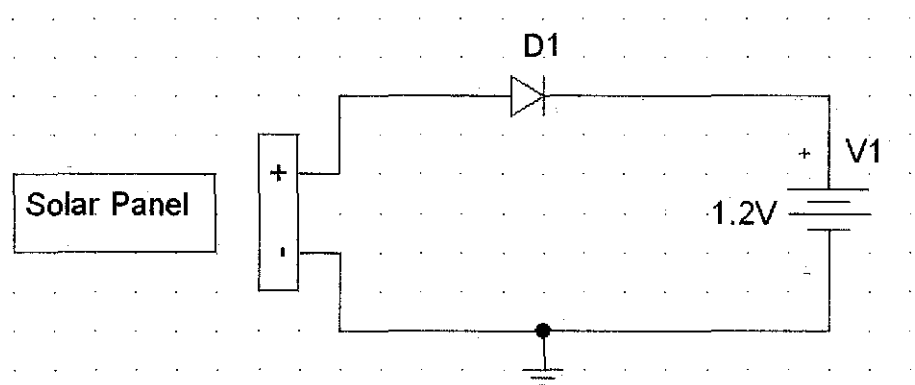


Figure 7: Simple Charging Circuit to test the Solar Panel Output

Table 3: Experiment Result

Time	Solar Panel Output Voltage	Solar Panel Output Current
11.27 a.m	7.11 V	102 mA
12.54 p.m	6.52 V	100 mA
2.06 p.m	6.27 V	95.4 mA
3.03 p.m	6.32 V	95.3 mA
4.03 p.m	5.86 V	70.1 mA
4.48 p.m	5.28 V	52.1 mA

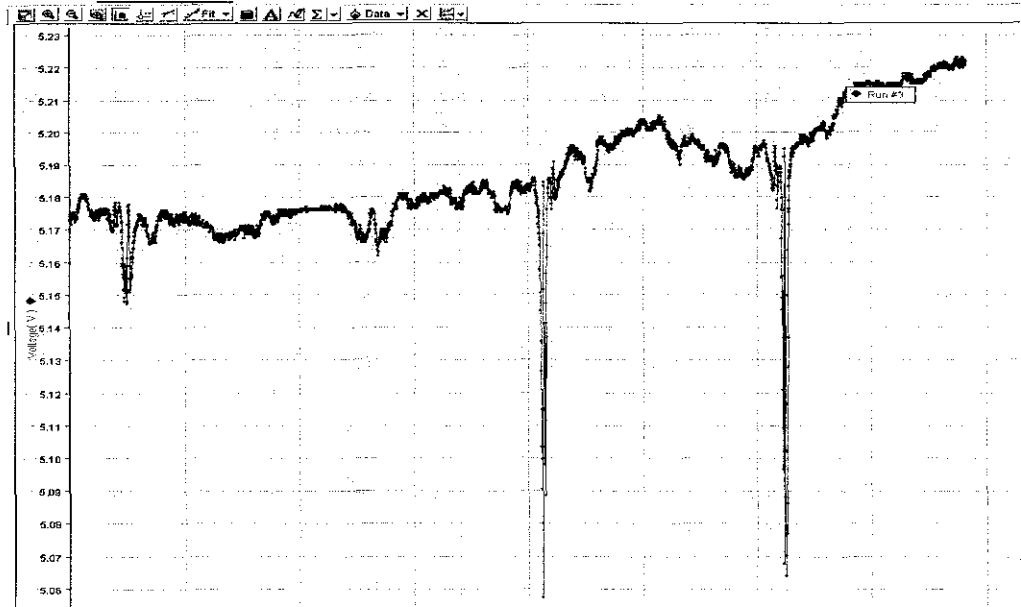


Figure 8: Voltage spike from PV

4.1.2 Ultracapacitor

After testing the solar panel, the next step is to test the ultracapacitor capability of charging and discharging voltage. The experiment was done by charging ultracapacitor using a constant 5V power supply. The main objective of the experiment is to determine the characteristics of ultracapacitor when it is charging and discharging. For this experiment, two ultracapacitors of 50F and 2.3V each are installed in series to get a total of 4.6V. In theory, the potential difference between 5.0V and 4.6V will ensure the ultracapacitor is in charging mode. The results are as shown in the Figures 9, 10 and 11.

Figure 9 shows the voltage of ultracapacitor when it is charging. From almost 0 voltage, the ultracapacitor only takes about 40 minutes to reach 4V. When it reaches 4V the charging rate becomes slower. As the voltage increases and reaches the maximum charging voltage (4.6V), the current decrease towards 0A. The next step is to investigate whether the ultracapacitor is capable of storing energy when it is fully charged.

As soon as the ultracapacitor is fully charged, the 5V power source is taken off and the ultracapacitor is left alone in the circuit without any load attached to it. Figure 11 shows the ultracapacitor voltage when it is in discharging mode. After 12 hours, the ultracapacitor voltage shows a reduction of only 0.2V.

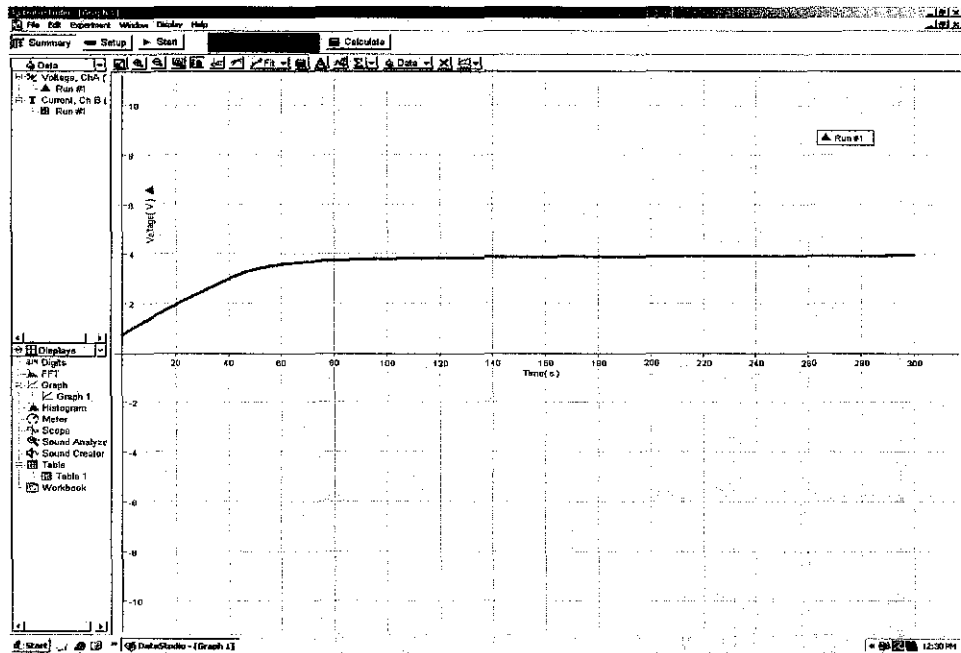


Figure 9: Graph of ultracapacitor voltage charged with constant 5V power source vs time

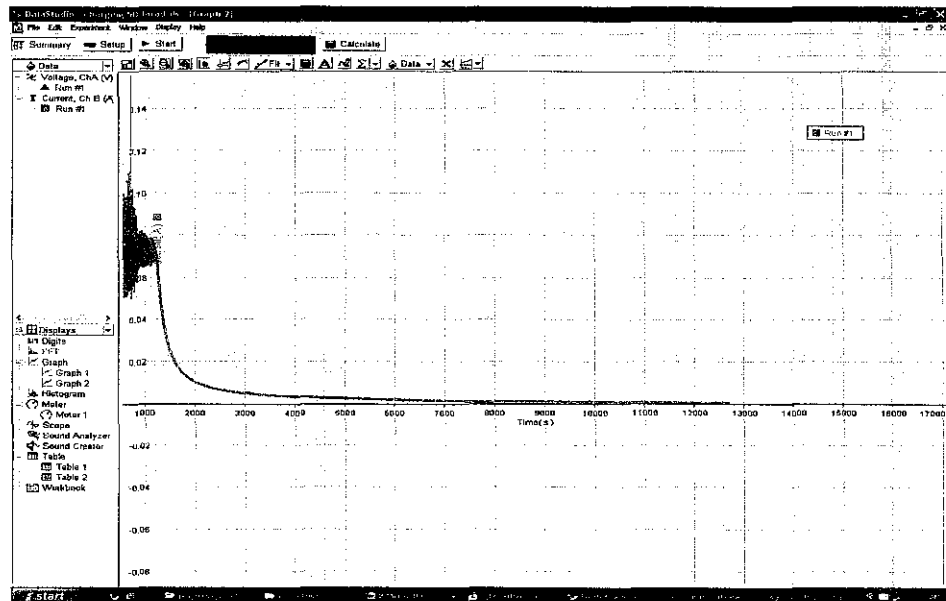


Figure 10: Graph of ultracapacitor current charged with constant 5V power source vs time

For the charge controller circuit, the design is as indicated in Figure 12. MAXIM (MAX712) fast-charge controllers will be used in the circuit. The key features for the IC are listed in the Appendix A.

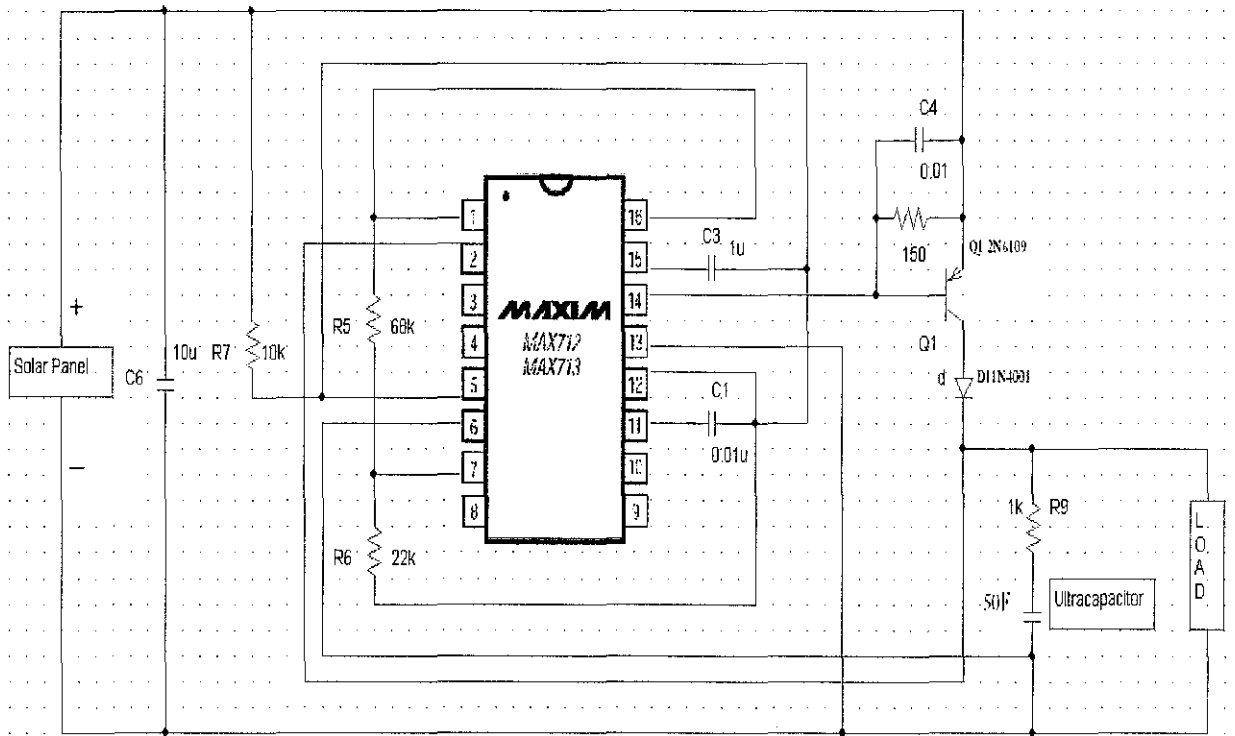


Figure 12: Charge Controller circuit

a) MAXIM (MAX712) fast-charge controllers

The MAX712 fast-charge controllers are used to charge from a DC source at least 1.5V higher than the maximum storage component. One of the features of the integrated circuit (IC) is a voltage-slope detecting analog-to-digital converter, timer, and temperature window comparator that determines charge completion. The MAX712 are powered by the DC source via an on-board +5V shunt regulator. The IC draws a maximum of 5μA from the storage component when it is not charging. A low-side current-sense resistor allows storage being charged and at the same time still supplying power to the batteries load. The MAX712 terminates fast charge by detecting zero voltage slopes.

b) Circuit Testing

Basically, the experiment is divided into 2 parts. The first one will be the circuit that tests the usage of ultracapacitor without battery and the second circuit is using battery and ultracapacitor in parallel. The main objective of the experiment is to determine either circuit constructed are working.

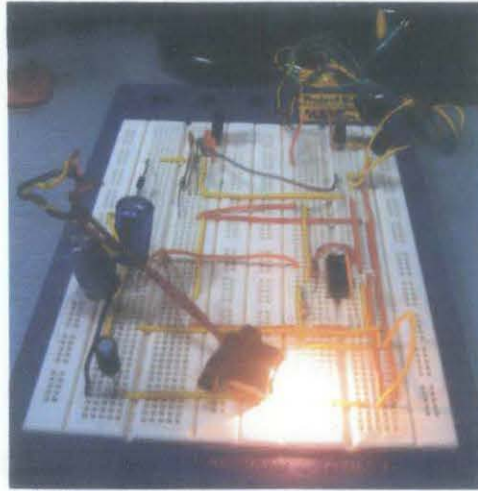


Figure 13: Experiment using 5V adapter to replace Solar Panel

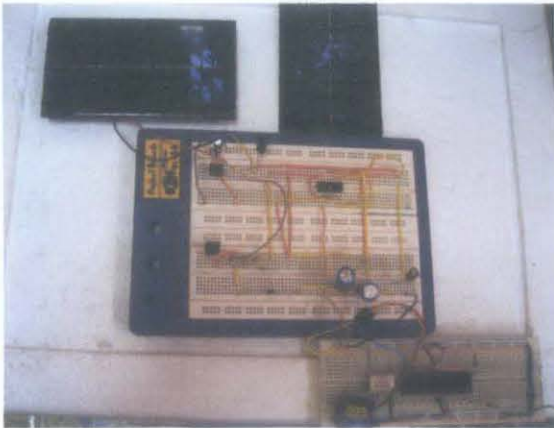


Figure 14: Experiment to power up
5V Server Motor



Figure 15: Experiment to power up
3.5V light bulb

After series of testing and adjustment, the circuit finally is functioning as desired. The first experiment shown in Figure 13 is done by using 5V adapter to power up the circuit. In this experiment, voltage regulator (KA 7805), is used to ensure constant 5V were delivered from the electrical plug to the circuit. The ultracapacitor used in this experiment (5F) only takes almost 5 minutes to fully charge. Since the value of the capacitance used is small, the energy stored in the ultracapacitor only lasted for 2 minutes maximum. In the second experiment, the circuit is powered up using a new solar panel.

Both experiments show that the circuits are functioning as they should be. The next step after this is to do more testing on the prototype.

4.1.4 Prototype

a) Experiment Setup

For the prototype experiment, it is carried out on a cloudy day. The experiment is done in such a manner to get the minimum value of voltage produced from the PV and observed if it is enough to charge the ultracapacitor. Figure 16 shows the setup of the experiment. The circuit is installed in a box to protect it from the heat from the sun. Both solar panels were installed at the top of the box. The experiment is carried out for almost full day, from 7 am until 7 pm. The highest voltage recorded is 5.2V and the minimum is 4.2V. The graph of voltage versus time for the experiment is shown in Figure 17.

Figure 18 shows the graph of voltage before and after the MAX712. The graph clearly shows that MAX712 is able to reduce the voltage spike from the solar panel. During the experiment, the reading from ultracapacitor is also monitored and data recorded. Figure 19 shows the graph of ultracapacitor voltage versus time.

b) Results:

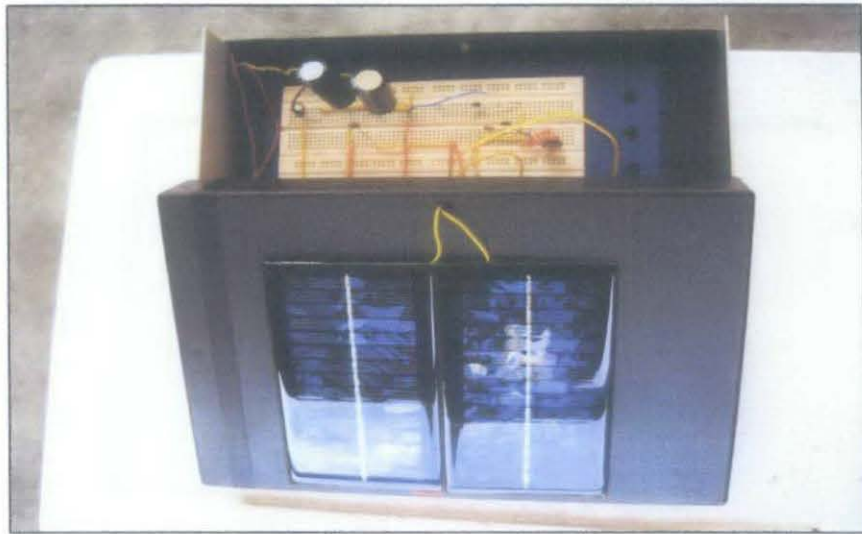


Figure 16: Experiment Setup

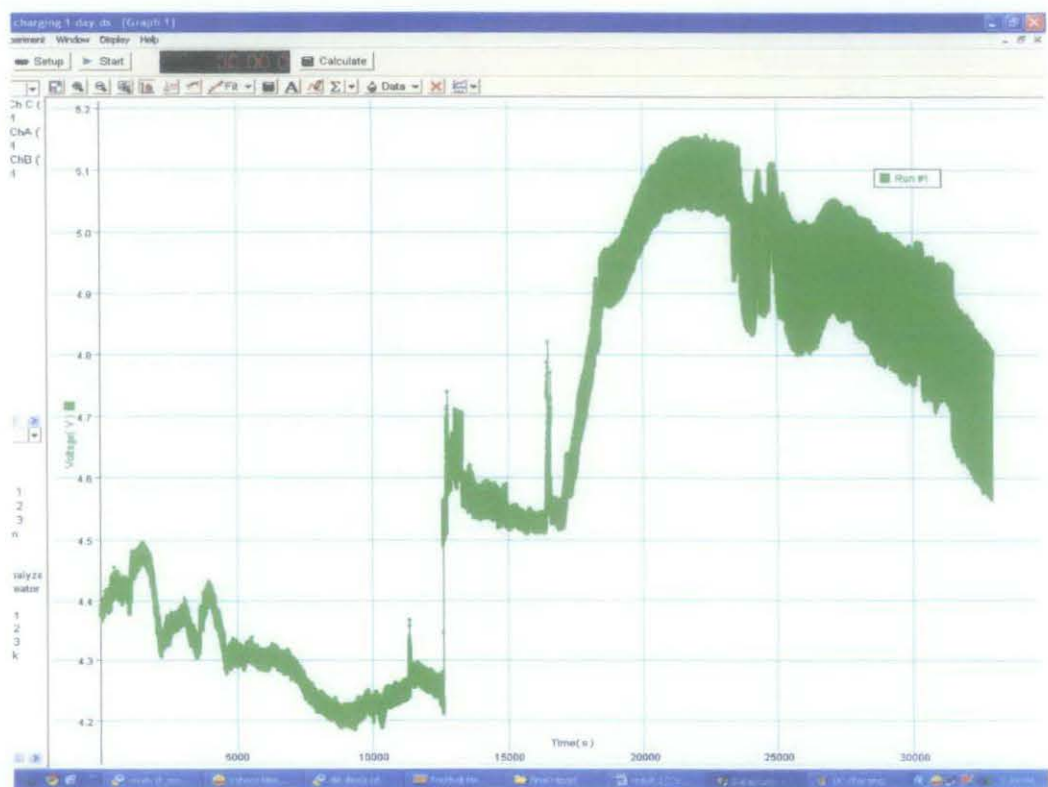


Figure 17: Graph of voltage from solar panel vs time



Figure 18: Graph of voltage from solar panel before and after MAX712 vs time



Figure 19: Graph of ultracapacitor voltage vs time

4.2 Discussions

4.2.1 Energy Storage Unit (ESU)

Energy storage unit is the main focus for this project. Storage medium is used to store energy generated by solar panel and to ensure the energy or power produced can be used for the load. Typical solar power source systems use battery as its storage medium. However, energy storage in battery is limited to alkaline or rechargeable batteries. In addition, these rechargeable batteries also are related to the problem of efficiency, availability and lifetime [15].

The problem with the efficiency, availability and lifetime of battery has moved people attention to another technology such as ultracapacitor. Ultracapacitors have found their way into many design engineers' product development strategies for portable devices. These strategies include using batteries and ultracapacitors in parallel or complete battery replacement with ultracapacitors. In both strategies, the main objective is to use ultracapacitor as energy storage. Based on the experiment done, it is proven that ultracapacitor is definitely capable of storing energy for future usage. However, to know how long the energy could last, a calculation can be made using the basic formula.

	$E = \frac{1}{2} q V = \frac{1}{2} C V^2$	C = Capacitance
		V = Voltage
		Q = coulomb
Rearrange	$q = C V$	
For 500F, 12V	$q = 500 * 12$ $= 6000$	
Convert to mAh	$1q = 0.2777777778mAh$ $6000q = 1666 mAh$	

From the calculation, it can be conclude that ultracapacitor with 500F and 12V can provide power up until two hours for the load that required around 800mAh.

Compared to battery, ultracapacitors contain no heavy metals and do not have the environmental concerns as some battery chemistries have. Another advantage of using ultracapacitor is the lightweight characteristic that it possesses. A single D-cell ultracapacitor at 2.5 V weighs approximately 60 g, whereas a D-size battery is significantly heavier and depends on the chemical elements. In addition, for alkaline cells, the voltage is only 1.5 V, requiring additional weight for equivalent voltage.

In ultracapacitors, the electrode is based on a carbon technology that allows for a very large surface area. The combination of this surface area along with a very small charge separation gives the ultracapacitors the high energy densities they possess. Most ultracapacitors are rated in farads and typically can be found in the 1 to 5,000-F range and rated in the 2.5 to 2.7- V ranges [12].

Ultracapacitors also can be charged and discharged at extremely high rates compared to batteries. Conventional rechargeable batteries can take several hours to recharge. Newer “rapid-charging” batteries still require several minutes to an hour to be fully charged. An ultracapacitor can be recharged within a matter of seconds or minutes depending on the amount of current available for recharge [16].

Table 4: Energy Storage Characteristics

Characteristics	Ultracapacitor	Battery (Lithium ion)
Charging/Discharging Duration	Quick	Slow
Charge Cycle	100000	1000
Temperature	-40°C -75°C	0°C-45°C
Operating Cost	No cost	Costly
Maintenance	No maintenance for over 10 years	Regular battery charges every 2-3 years
Equivalent Series Resistant	Low	High
Disposable Part	No	Yes
Explosive	No	Yes

From Table 4, ultracapacitor is better than lithium ion battery in term of charge cycle, temperature, operating cost, maintenance, disposable part, and explosive. Below is the example of ultracapacitor that will be using in this project.



Figure 20: The three different ratings of ultracapacitors

4.2.2 Loads

In order to design a power source, the capacity of the load or power consumption of the electrical loads must be known to ensure the reliability of power supply. Since the target group for the project is army and traveller equipment, the power consumption of the load can be considered as low voltage application. Table 5 below shows the list and rating of some of the equipment.

Table 5: List of the target loads for the power supply

Equipment	Volt	Current	Type
Walkie talkie Two-Way Radio	7.2	400mA	DC
Nokia 6300	5.0	350mA	DC
Sony Ericsson K550	4.9	450mA	DC

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

For this context of project, a prototype of a DC portable solar-powered electrical device using ultracapacitor as energy storage unit has been theoretically examined and experimentally validated. Currently, the power requirements of a number of applications have dramatically increased and some case have exceeded the capability of batteries of standard design. Therefore it is necessary to use other alternative strategies. Ultracapacitor has many advantages compared to battery despite the price of ultracapacitor that is still quite expensive due to their early stages of development and low production volumes.

5.2 Recommendations

The prototype proposed still can be improved in many ways. The modifications and improvements are:

- For high voltage and continuous power supply application, a higher value of ultracapacitor can be used.
- A device or method can be developed to reduce the discharging rate of the ultracapacitor.
- The design of the charger circuit can also be improved to better suit the usage of ultracapacitor.
- The result of the testing can be further improved by showing the rapid charging characteristic of the ultracapacitor.

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APPENDICES

APPENDIX A
DATASHEET FOR MAXIM 712

MAX712/MAX713

Features

For high-power charging requirements, the MAX712/MAX713 can be configured as a switch-mode battery charger that minimizes power dissipation. Two evaluation kits are available: Order the MAX712EVKIT-DIP for quick evaluation of the linear charger, and the MAX713EVKIT-SO to evaluate the switch-mode charger.

Battery-Powered Equipment
Laptop, Notebook, and Palmtop Computers
Handy-Terminals
Cellular Phones

Portable Consumer Products
Portable Stereos
Cordless Phones

TOP VIEW

VLIMIT	1	16	REF
BATT+	2	15	V+
PGM0	3	14	DRV
PGM1	4	13	GND
THI	5	12	BATT-
TLO	6	11	CC
TEMP	7	10	PGM3
FASTCHG	8	9	PGM2

MAXIM
MAX712
MAX713

DIP/SO

- ✦ Fast Charge NiMH or NiCd Batteries
- ✦ Voltage Slope, Temperature, and Timer Fast-Charge Cutoff
- ✦ Charge 1 to 16 Series Cells
- ✦ Supply Battery's Load while Charging (Linear Mode)
- ✦ Fast Charge from C/4 to 4C Rate
- ✦ C/16 Trickle-Charge Rate
- ✦ Automatically Switch from Fast to Trickle Charge
- ✦ Linear or Switch-Mode Power Control
- ✦ 5µA Max Drain on Battery when Not Charging
- ✦ 5V Shunt Regulator Powers External Logic

PART	TEMP. RANGE	PIN-PACKAGE
MAX712CPE	0°C to +70°C	16 Plastic DIP
MAX712CSE	0°C to +70°C	16 Narrow SO
MAX712C/D	0°C to +70°C	Dice*
MAX712EPE	-40°C to +85°C	16 Plastic DIP
MAX712ESE	-40°C to +85°C	16 Narrow SO
MAX712MJE	-55°C to +125°C	16 Cerdip**

****Contact factory for availability and processing to MIL-STD-883.**

SEE FIGURE 19 FOR SWITCH-MODE CHARGER CIRCUIT.

SEE FIGURE 19 FOR SWITCH-MODE CHARGER CIRCUIT

NiCd/NiMH Battery Fast-Charge Controllers

ABSOLUTE MAXIMUM RATINGS

V+ to BATT-	-0.3V, +7V	REF Current	10mA
BATT- to GND	±1V	Continuous Power Dissipation (T _A = +70°C)	
BATT+ to BATT-		Plastic DIP (derate 10.53mW/°C above +70°C	842mW
Power Not Applied	±20V	Narrow SO (derate 8.70mW/°C above +70°C	696mW
With Power Applied	The higher of ±20V or ±2V x (programmed cells)	CERDIP (derate 10.00mW/°C above +70°C	800mW
DRV to GND	-0.3V, +20V	Operating Temperature Ranges	
FASTCHG to BATT-	-0.3V, +12V	MAX71_C_E	0°C to +70°C
All Other Pins to GND	-0.3V, (V+ + 0.3V)	MAX71_E_E	-40°C to +85°C
V+ Current	100mA	MAX71_MJE	-55°C to +125°C
DRV Current	100mA	Storage Temperature Range	-65°C to +150°C
		Lead Temperature (soldering, 10sec)	+300°C

Stresses beyond those listed under "Absolute Maximum Ratings" may cause permanent damage to the device. These are stress ratings only, and functional operation of the device at these or any other conditions beyond those indicated in the operational sections of the specifications is not implied. Exposure to absolute maximum rating conditions for extended periods may affect device reliability.

ELECTRICAL CHARACTERISTICS

(I_{V+} = 10mA, T_A = T_{MIN} to T_{MAX}, unless otherwise noted. Refer to Typical Operating Circuit. All measurements are with respect to BATT-, not GND.)

PARAMETER	CONDITIONS	MIN	TYP	MAX	UNITS
V+ Voltage	5mA < I _{V+} < 20mA	4.5		5.5	V
I _{V+} (Note 1)		5			mA
BATT+ Leakage	V+ = 0V, BATT+ = 17V			5	µA
BATT+ Resistance with Power On	PGM0 = PGM1 = BATT-, BATT+ = 30V	30			kΩ
C1 Capacitance		0.5			µF
C2 Capacitance		5			nF
REF Voltage	0mA < I _{REF} < 1mA	1.96		2.04	V
Undervoltage Lockout	Per cell	0.35		0.50	V
External VLIMIT Input Range		1.25		2.50	V
THI, TLO, TEMP Input Range		0		2	V
THI, TLO Offset Voltage (Note 2)	0V < TEMP < 2V, TEMP voltage rising	-10		10	mV
THI, TLO, TEMP, VLIMIT Input Bias Current		-1		1	µA
VLIMIT Accuracy	1.2V < VLIMIT < 2.5V, 5mA < I _{DRV} < 20mA, PGM0 = PGM1 = V+	-30		30	mV
Internal Cell Voltage Limit	VLIMIT = V+	1.6	1.65	1.7	V
Fast-Charge VSENSE		225	250	275	mV
Trickle-Charge VSENSE	PGM3 = V+	1.5	3.9	7.0	mV
	PGM3 = open	4.5	7.8	12.0	
	PGM3 = REF	12.0	15.6	20.0	
	PGM3 = BATT-	26.0	31.3	38.0	
Voltage-Slope Sensitivity (Note 3)	MAX713		-2.5		mV/t _A per cell
	MAX712		0		
Timer Accuracy		-15		15	%
Battery-Voltage to Cell-Voltage Divider Accuracy		-1.5		1.5	%
DRV Sink Current	V _{DRV} = 10V	30			mA

NiCd/NiMH Battery Fast-Charge Controllers

ELECTRICAL CHARACTERISTICS (continued)

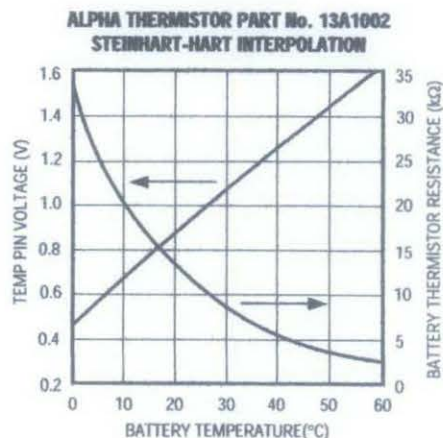
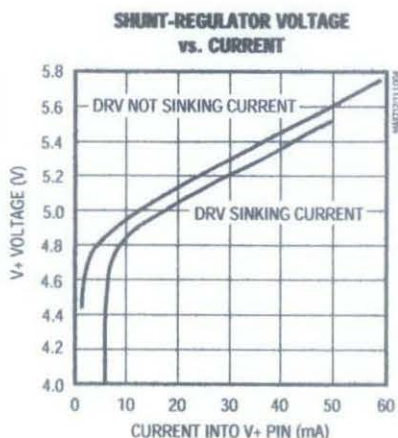
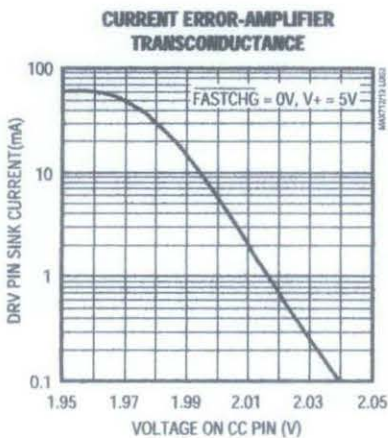
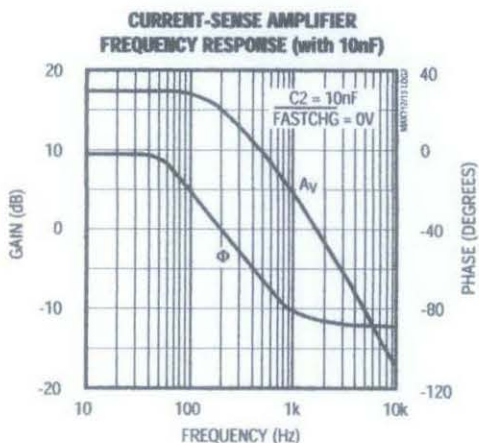
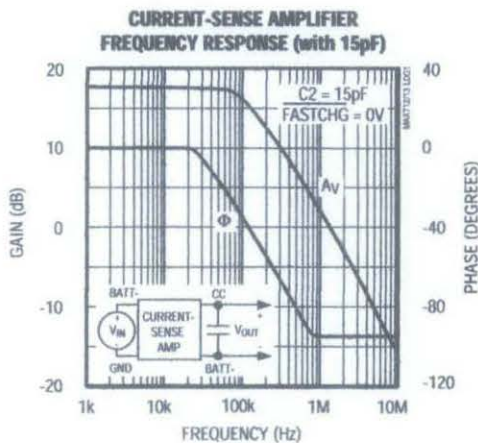
(I_{V+} = 10mA, T_A = T_{MIN} to T_{MAX}, unless otherwise noted. Refer to *Typical Operating Circuit*. All measurements are with respect to BATT-, not GND.)

PARAMETER	CONDITIONS	MIN	TYP	MAX	UNITS
FASTCHG Low Current	VFASTCHG = 0.4V	2			mA
FASTCHG High Current	VFASTCHG = 10V			10	μA
A/D Input Range (Note 4)	Battery voltage ÷ number of cells programmed	1.4		1.9	V

- Note 1:** The MAX712/MAX713 are powered from the V+ pin. Since V+ shunt regulates to +5V, R1 must be small enough to allow at least 5mA of current into the V+ pin.
- Note 2:** Offset voltage of TH1 and TLO comparators referred to TEMP.
- Note 3:** t_A is the A/D sampling interval (Table 3).
- Note 4:** This specification can be violated when attempting to charge more or fewer cells than the number programmed. To ensure proper voltage-slope fast-charge termination, the (maximum battery voltage) ÷ (number of cells programmed) must fall within the A/D input range.

Typical Operating Characteristics

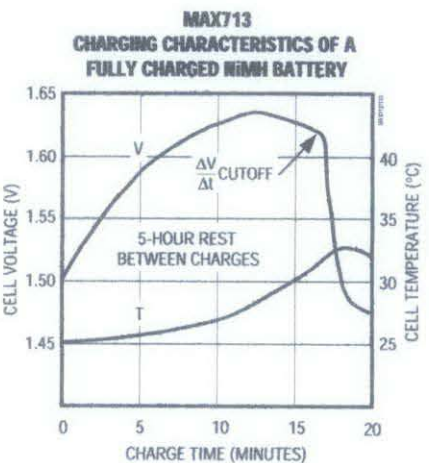
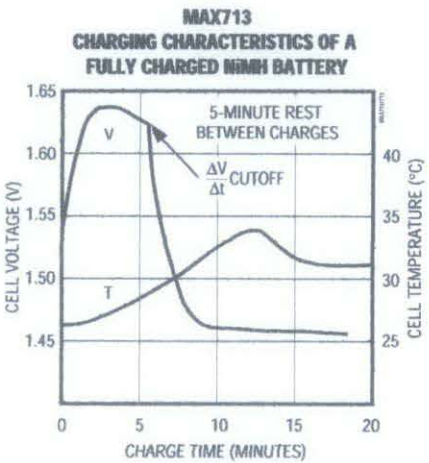
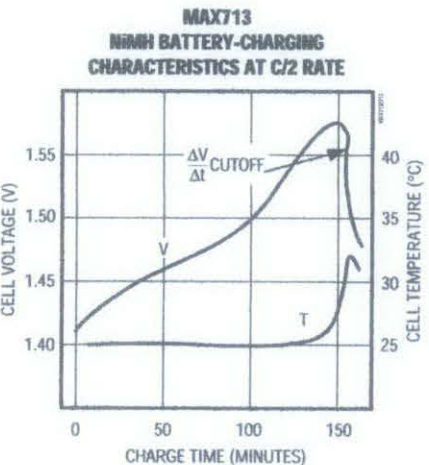
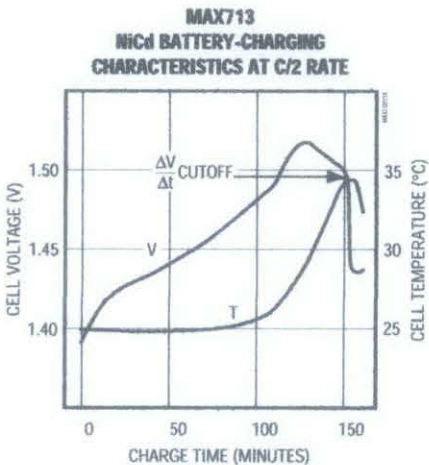
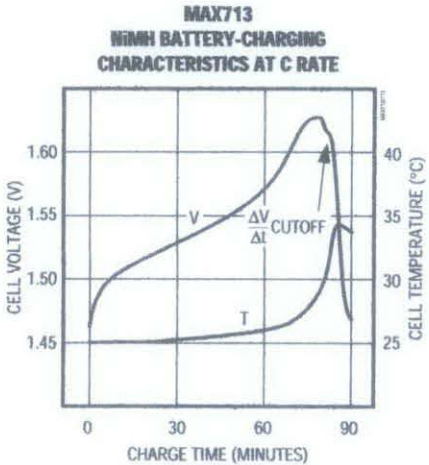
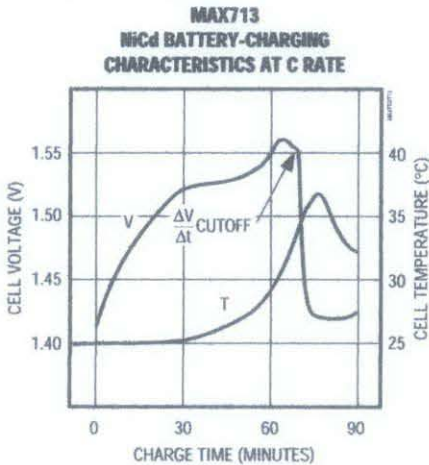
(T_A = +25°C, unless otherwise noted.)



NiCd/NiMH Battery Fast-Charge Controllers

Typical Operating Characteristics (continued)

(T_A = +25°C, unless otherwise noted.)



NiCd/NiMH Battery Fast-Charge Controllers

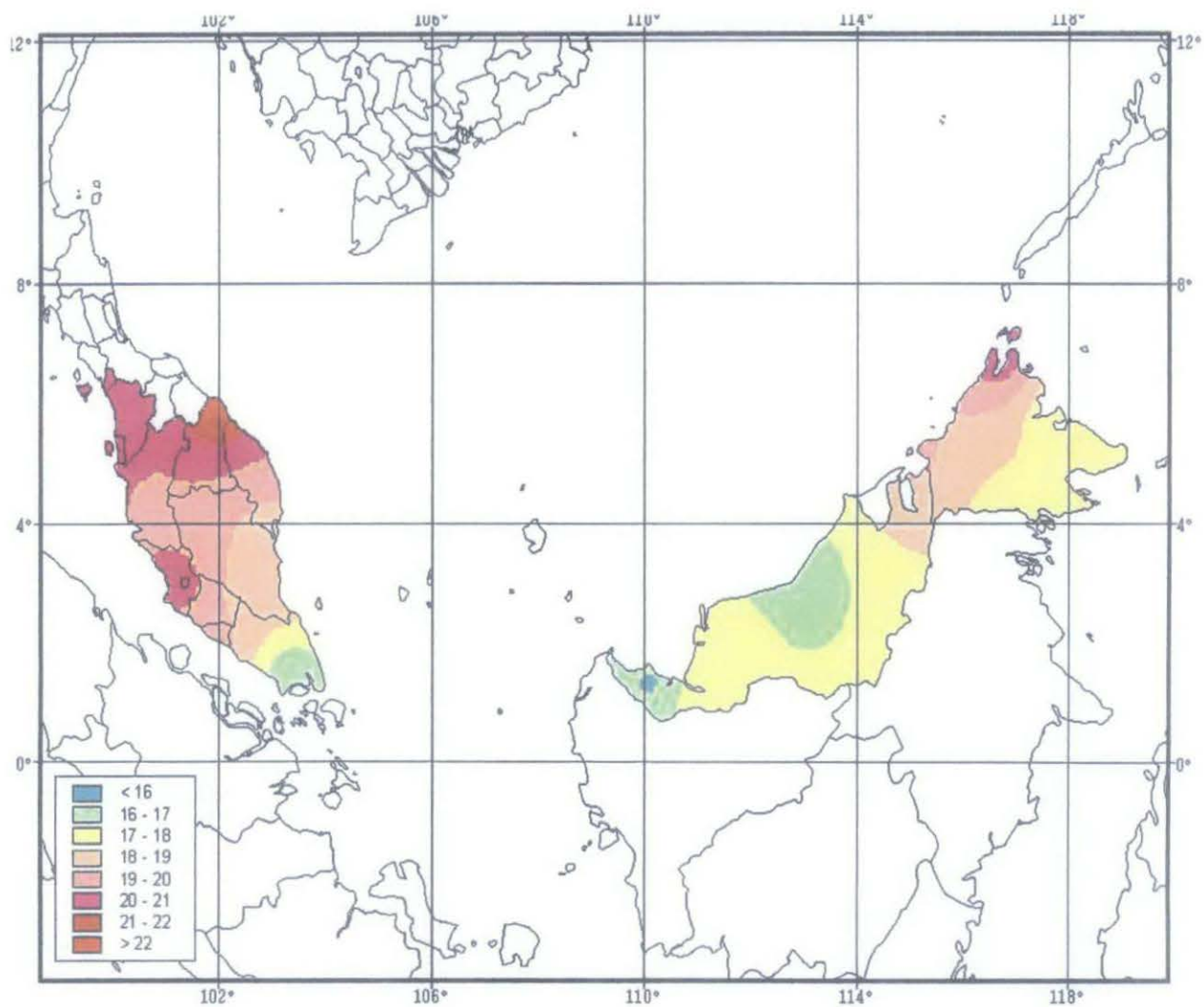
Pin Description

PIN	NAME	FUNCTION
1	VLIMIT	Sets the maximum cell voltage. The battery terminal voltage (BATT+ - BATT-) will not exceed VLIMIT x (number of cells). Do not allow VLIMIT to exceed 2.5V. Tie VLIMIT to VREF for normal operation.
2	BATT+	Positive terminal of battery
3, 4	PGM0, PGM1	PGM0 and PGM1 set the number of series cells to be charged. The number of cells can be set from 1 to 16 by connecting PGM0 and PGM1 to any of V+, REF, or BATT-, or by leaving the pin open (Table 2). For cell counts greater than 11, see the <i>Linear-Mode, High Series Cell Count</i> section. Charging more or fewer cells than the number programmed may inhibit ΔV fast-charge termination.
5	THI	Trip point for the over-temperature comparator. If the voltage-on TEMP rises above THI, fast charge ends.
6	TLO	Trip point for the under-temperature comparator. If the MAX712/MAX713 power on with the voltage-on TEMP less than TLO, fast charge is inhibited and will not start until TEMP rises above TLO.
7	TEMP	Sense input for temperature-dependent voltage from thermistors.
8	FASTCHG	Open-drain, fast-charge status output. While the MAX712/MAX713 fast charge the battery, FASTCHG sinks current. When charge ends and trickle charge begins, FASTCHG stops sinking current.
9, 10	PGM2, PGM3	PGM2 and PGM3 set the maximum time allowed for fast charging. Timeouts from 33 minutes to 264 minutes can be set by connecting to any of V+, REF, or BATT-, or by leaving the pin open (Table 3). PGM3 also sets the fast-charge to trickle-charge current ratio (Table 5).
11	CC	Compensation input for constant current regulation loop
12	BATT-	Negative terminal of battery
13	GND	System ground. The resistor placed between BATT- and GND monitors the current into the battery.
14	DRV	Current sink for driving the external PNP current source
15	V+	Shunt regulator. The voltage on V+ is regulated to +5V with respect to BATT-, and the shunt current powers the MAX712/MAX713.
16	REF	2V reference output

MAX712/MAX713

APPENDIX B

DAILY SOLAR RADIATION IN MALAYSIA



Mean Daily Solar Radiation (MJm⁻²)

APPENDIX C

PROTOTYPE

