Development of electrical power supply system for micro-satellite with maximum power point tracking

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Development of Electrical Power Supply System For Micro-Satellite With Maximum Power Point Tracking

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School of Electrical & Electronic Engineering

A thesis submitted to the Nanyang Technological University

In partial fulfillment of the requirement for the degree of

Master of Engineering

2005

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2005

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research and has not been submitted for a higher degree to any other University or Institution.

6 / 8 / 2005
Date

Tan Boon Liong

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SUMMARY

The development of intelligent power supply system for small satellite has always been a major challenge in satellite communication. Maximum Power Point Tracking approach offers numerous advantages, has become a main candidate for the power supply system for small satellite. This thesis presents the research and development work done on designing and developing a Maximum Power Point Tracking (MPPT) for micro-satellite system. The MPPT techniques that are analyzed in this research are the Open circuit solar voltage, Perturbation & Observation, Incremental Conductance and Hybrid MPPT. Through the study on the hostile effects in space on the Component-Off-The-Shelves, a Buck type switch mode power supply with variable duty cycle and microcontroller were designed and built by using space qualified components for conducting experiments in this research.

The Incremental Conductance technique was found to have the highest tracking efficiency compared to other techniques under all temperature and insolation variations of a typical orbit of a micro-satellite. Moreover, its ability to track the maximum solar power point under fast changing external environments makes it very suitable for micro-satellites with mission operations that require wide and fast changing angle of maneuver.

An improved version of MPPT technique was developed after studying the various terrestrial-based techniques employed to resolve issues faced when using actual solar cells. These realistic issues such as ageing and shading of the solar cells are taken into consideration when developing the algorithm of this improved MPPT, which is called the Hybrid MPPT. This Hybrid MPPT technique is promising for satellites with long designed life whereby the degradation of solar cells is inevitable.

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CHAPTER 1

INTRODUCTION

1.1 Motivation

Satellite industry has developed very fast since the early years, ranging from simple transmitter to very complicated communication payloads. In recent years, payloads have been developed for various applications such as communication, science, weather, navigation and surveillance purposes. To support and enable all the above operations, core modules such Electrical Power System (EPS), which converts solar energy to electrical energy for the entire mission period, form part of the satellite's backbone.

The design of satellite power supply system has become challenging due to the hostility of space environment such as radiation and temperature cycling from -105°C to $+110^{\circ}\text{C}$ [1]. Life degradation occurs because of thermal cycling in and out of eclipses, micrometeoroid strikes, plume impingement from thrusters and material outgassing. In general, for silicon solar cells and gallium arsenide solar cells in Low-Earth-Orbit (LEO) satellites, the power production can be reduced by 3.75% and 2.75% per year, respectively. More than half of this reduction is caused by photon and electron radiation. Most spacecrafts are using Silicon or Gallium Arsenide solar cells, with efficiencies of 14.8% and 18.5% respectively [1]. With all the above inefficiencies and degradation that are expected, it has put great demand on the EPS to extract maximum power from the panels. There exists one unique operating point, at which maximum power is extracted from the cell.

Figure 1.1 shows the two regions that the cell can operate: Current-Source region and Voltage-Source region that account for the non-linear characteristic. When the solar cell is operating at any voltages below the Maximum Power Point, the cell behaves like a current source. As this operating point shifts above the Maximum Power Point, the solar cell behaves like a voltage source. In between these two regions, there occurs a peak power point, which is termed as the Maximum Power Point. The highest power can be extracted when the solar array is controlled to operate at this unique point. When it is not operating at this unique point, less power is extracted from the solar array.

Figure 1.1 Operating Regions of a Solar Array

The Maximum Power Point is a variable that depends on environmental conditions such as the ambient temperature and sun insolation. Figure 1.2(a) shows the non-linear characteristic of solar cell during varying insolation from the Sun. The solar voltage at Maximum Power Point increases proportionally to the sun insolation. Figure 1.2(b) shows the non-linear characteristic of solar cell during varying temperature [2]. The solar voltage at Maximum Power Point increases proportionally to the ambient temperature. From Figure 1.2, it is observed clearly that the output characteristic of a typical solar cell is non-linear and depends on the temperature and insolation.

Figure 1.2 Variations of Maximum Power Point due to temperature and insolation changes [2]

Hence, it is of significant contribution to develop an EPS that is able to track and operate at this varying Maximum Power Point. In this research, this type of EPS is known as Maximum Power Point Tracking based EPS. A comparative study is done to observe the

performance of EPS with Maximum Power Point Tracking (MPPT) and without Maximum Power Tracking. It is observed that at least 65% of maximum power can be extracted with MPPT, whereas the non-Maximum Power Point Tracking achieves only 26-30% efficiency [2]. With MPPT, this means lesser cells are needed to generate the same amount of power.

Besides, the MPPT-based EPS is light and requires less volume compared to the commonly used power regulation topology known as the Direct Energy Transfer, which shunts away un-used energy. This method suffers from needing of heat sinks to dissipate this un-used energy. This translates to extra weight and volume in the spacecraft and more complicated thermal management within the satellite body.

In conclusion, the savings in terms of cost and size of solar panel have been the motivation to design and develop an effective EPS with Maximum Power Tracking capability.

1.2 Objectives

Objective 1: To develop a space qualified Buck Type Switch Mode Power Supply

Given the limited Components-Off-The-Shelves (COTS) that are space qualified, the first objective is to design and develop a space qualified Switch Mode Power Supply, which can step down the solar output voltage to nominal bus voltage. Unlike many commercial power supply systems that are highly efficient, they cannot be used in space, mainly because of their components being not able to tolerate the radiation environment in space.

Objective 2: To develop a microcontroller-based Maximum Power Point Tracker (MPPT)

The second objective is to design and develop a MPPT using a micro controller, which performs the required computation of the Maximum Power Point of the satellite solar panels. Intelligent algorithms, which monitor the Maximum Power Point using various methodologies, are downloaded into this controller. Micro controller with space heritage is used, to ensure high reliability in a highly hostile environment.

Objective 3: To develop an intelligent algorithm for multiple power maxima tracking

It is known that a solar array can have multiple power maximum points with a single global power maximum point. Due to the multiple maxima points, conventional MPPT methods would be 'trapped' at the wrong maxima point and not extracting the maximum power from the solar array. This objective is to develop an intelligent algorithm that could identify the global maximum point without compromising the overall power efficiency.

1.3 Major Contributions

1. Development and experimental implementation of a space qualified Buck Type Switch Mode Power Supply.

The efficiency of this converter is about 90-95% of the input power. The major and critical components are carefully selected so to withstand the hostility such as the Total Irradiation Dosage and Single Event Upset in the orbit. The superiority of this converter lies on its ability to withstand the 3 years of operation in the hostile space environment. Besides, its simple design with low component count ensures low possibility of power supply failure for the satellite.

2. Development and experimental implementation of a Microcontroller-based Maximum Power Point Tracking.

Two MPPT algorithms known as 'Perturbation & Observation' and 'Incremental Conductance' methods were successfully implemented and were able to track the Maximum Power Point to an accuracy of 98.66% and 99.91%, respectively. The experimental results have validated the advantages of these algorithms in monitoring environmental changes such as temperature and sun insolation. Due to the high efficiency by operating at the maximum power point, it eases the thermal management of the satellite due to less heat dissipated at the solar array.

3. Development of a Hybrid Maximum Power Point Tracking Algorithm.

A new Hybrid MPPT algorithm has been developed and its functionality tested and verified. This Hybrid MPPT scheme has successfully sampled and tracked the global power maximum point. This new algorithm enables the power supply system to extract 99.72% of the total available solar power under hostile conditions such as ageing, shading and cell damage.

1.4 ORGANIZATION OF THE THESIS

The rest of this thesis is organized as follows:

Chapter 2 gives the literature review of the entire power supply system of a spacecraft. The main aspects of the power supply such as solar energy, chemical storages and power management & distribution are presented here. The space environmental factors that determine the design of the power supply system are also reviewed here.

Chapter 3 gives the literature review of Maximum Power Point Tracking methods for terrestrial applications. The author then presents the study of adapting the terrestrial MPPT for space applications. Subsequently, this chapter reviews different methods in tracking multiple power maxima points, which are also known as the Global Maxima Tracking. These methods, based on terrestrial applications, are being adapted for space applications. Critical consideration factors in the adaptation are presented here.

Chapter 4 focuses on the development of the power management sub-system of a micro satellite, which is the Buck Type Switch Mode Power Supply (SMPS). It presents the design and setup of the SMPS. It also presents the development of MPPT using a micro controller. This chapter then looks into the setup of the Solar Array Simulator. The accuracy of this simulator in emulating the characteristic of a typical space solar cell is also presented here.

Chapter 5 presents the performance of the implementation of MPPT and Global Maximum Power Tracking under different conditions of the solar array. A typical satellite orbit path with varying electrical characteristics of the solar array is used in this measurement.

Chapter 6 gives the conclusions of this thesis and recommendations for future research.

CHAPTER TWO

REVIEW OF SPACECRAFT POWER TECHNOLOGIES

2.1 Introduction

The design of spacecraft power supply system is a multi-disciplinary engineering development, which requires knowledge of electrical, mechanical, thermal and material disciplines. In this chapter, an overview of these disciplines of the spacecraft power supply system will be presented. The orbital parameters such as altitude and inclination, which establish the level of space radiation and orbit period, determine the size of solar array and battery. The spacecraft external environment factors such as the neutral atmosphere, radiation, plasma and meteoroids determine the type of materials used for protection from corrosion of solar panels. Various types of sources such as solar energy and nuclear power will be reviewed. Another major module in a spacecraft power supply system is the energy storage system. The choice of storage system depends on factors such as mission lifespan, operations and many more. All these issues would be examined here.

The chapter continues to present the power supply management and distribution systems, which comprise of several main areas: bus management and control; battery management and power conversion.

2.2 Environmental Factors

Design theories of power supply and its related disciplines that have been commonly established for applications on Earth cannot be transferred directly into spacecraft power supply design. The development of a spacecraft power supply is subjected completely to its external environment factors in space.

The environmental factors such as neutral atmosphere, radiation, plasmas and meteoroids (Figure 2.1) impact the design of spacecraft. These factors, mainly radiation related issues that determine component choice, circuitry design and many more, are dominated by the Sun that radiates about 10^{27} W and emits 10^6 kg/ sec of protons and electrons. Its radiated field extends from wavelengths of 0.2 μ m to about 4 μ m with different intensity [3]. All these four environmental factors produce synergetic interactions that alter the chemical, mechanical, thermal and electrical aspects of the spacecraft material [7,8]. Each element is further described below.

Figure 2.1 The Space Environmental Factors [3]

2.2.1 Neutral Atmosphere

The neutral atmosphere is caused by factors such as the atomic flux, pressure and temperature. With a spacecraft orbital speed of 8 km/sec, the flux of atomic oxygen atoms is of the order 10^{14} atoms/cm²-sec, corresponds to mean energy of 5 eV. Hence the solar array needs to be built using strong material to withstand the erosion caused by this flux. Table 2.1 shows the erosion yield for selected materials that describes the volume of material lost per incident atomic oxygen atom. KaptonTM with erosion yield factor of 0.1-0.9 is normally used as solar array protection layer. The choice of material depends on the

cost and hardness of protection layer needed. Diamond coating, which has the lowest erosion yield, has been used on radiation-hardened components. The second cause of neutral atmosphere is pressure. The ambient pressure outside the spacecraft is typically different from the pressure inside the body of satellite. This is due to outgassing phenomena, which describes loss of material when exposed to vacuum conditions. The loss of material is caused by escape of volatiles, often water vapor from the surface of the material. This again limits the choice of Components-Off-The-Shelves (COTS) that are commonly used in LEO spacecraft project [5, 6, 8]. COTS are components designed and built for terrestrial application and have no radiation-hardened feature. Components are chosen for its fast rate to outgass and drop to zero in a very short time. A final cause of the neutral atmosphere is temperature, which rises sharply at altitude greater than 250 km. The temperature influences the solar array design and spacecraft thermal management. The thermal design attempts to maintain each module in the spacecraft at different temperature range in order to ensure proper functionality.

Table 2.1 Erosion Yields for Selected Materials [3]

Erosion Yield (10^{-24} cm ³ /atom)				
0.01-0.09	0.1-0.9	1.0-1.9	2.0-4.0	>4.0
Diamond	Polysiloxane/ Kapton TM	Epoxies	Graphite/ Epoxy	Silver
Al ₂ O ₃	Siloxane. Polyimide	Polystyrene	Kevlar TM / Epoxy	
Al coated Teflon TM FEP	401-C10 Flat Black	Most forms of Carbon	Polyethylene	
Molybdenum	Z-306 Flat Black		Mylar TM	

2.2.2 Plasmas

Plasma is a state in which at least one electron has enough energy to escape the coulomb attraction of the atomic nucleus resulting in the independent motions of the free electrons and the atomic ions. More than 99% of all matter across the universe is found in this fourth state of matter. The plasmas environment exists in all orbits and pose problems such as spacecraft charging, arcing, electrical breakdown of dielectrics, parasitic currents and shifts in electrical potential.

2.2.3 Radiations

Radiation comprises of firstly the Electro-Magnetic (EM) radiation from the Sun and secondly the ionizing radiation created by energetic particles impinging on the spacecraft. The Sun generates its energy through a thermonuclear fusion of hydrogen into helium, which releases about 4×10^{26} joules of energy in a second. This EM radiation is in the radio frequency range, hence may interrupt the communications system. If needed, the power supply unit system has to be designed with certain intelligence in its power management during this period of inactive communication with the ground station.

The ionizing radiation is caused by charged particles origins from Van Allen belts, solar proton flares and galactic cosmic rays. Van Allen belts contain energetic protons and electrons that are trapped by the Earth's magnetic field in two distinct zones: inner zone ($1.5 R_e$ to $2 R_e$) and outer zone ($4 R_e$ to $5 R_e$). R_e is the distance of the Earth's radius. Solar flares produce very energetic proton fluxes (greater than tens of keV to 1 GeV) on the Earth's magnetosphere. The ionizing radiation is distinct from plasmas effects since the energies observed in this case is quite large and capable of initiating radiation effects within the spacecraft. It disrupts components such as microprocessors and sensors. Galactic cosmic rays are extremely high-energy particles, typically greater than 100 MeV and as great as 10^{28} eV that originates outside the solar system. Radiation causes two types of failure on spacecraft components: Total Irradiation Dosage (TID) and Single Event Upset (SEU). The TID damage is a cumulative of trapped charges that cause components malfunction such as leakage currents of PN junction [13], change in current gain (BJT) and carrier mobility (MOSFET). Based on Figure 2.2, radiation hardened BJT component is able to withstand the highest radiation before showing symptoms of failure at above 10^6 rad (Si) and only experiencing severe operational problems above 10^7 rad (Si). The dose rate is given in rad (Si) per unit time, where 'rad' is a measure of absorbed ionizing energy.

Figure 2.2 Total Irradiation Dosage failure levels [6]

SEU is an event that a high-energy photon/ electron bombards the device causing it to pass current large enough to cause failure. This SEU event is random and worsens for small feature size components. As the fabrication technology attempts to reduce component size, it increases the circuit vulnerability towards SEU event. To mitigate this, radiation hardened devices and redundant circuitry are used in power supply unit for certain satellites. In most of the small satellites, COTS that could withstand the nominal TID and SEU are becoming more favored because of its cheap cost and short lead-time. Table 2.2 shows TID and SEU level for both COTS and Radiation Hardened components. It illustrates that it is safe to use COTS in orbit that has lower TID and SEU levels as indicated.

Table 2.2 TID and SEU levels for COTS and Radiation Hardened Components [1]

Characteristics	COTS	Radiation Hardened
Total Irradiation Dosage	10 ³ -10 ⁴ rads (Si)	10 ⁵ -10 ⁶ rads (Si)
Single-Event Upset	10 ⁻³ -10 ⁻⁷ errors/ bit-day	10 ⁻⁸ -10 ⁻¹⁰ errors/ bit-day
Single-Event Latchup/ Burnout	<20 MeV-cm ² / mg	37-80 MeV-cm ² / mg

2.2.4 Meteoroids

Lastly, the particulate environment is composed of natural meteoroids and man-made debris, which can pit or penetrate the satellite's surface. Man-made debris is created from previous space operations, purposeful or accidental fragmentation of rocket bodies, deterioration of spacecraft surfaces and aluminum oxide released from firing solid rocket

motors, is more detrimental than the natural meteoroids. Solar panels naturally have greater probability of impact; hence protection layers are engineered to give extra protection against the particulate environment.

2.3 Solar Energy Conversion

2.3.1 Fundamental of Solar Cell Operation

Solar cell is formed by semiconductor material that transforms solar power into electrical energy when being exposed to photons in the sunlight. Photons are particles of light, which energize electrons inside the semiconductor of the solar cell. Electrical energy is produced only when the photon energy is higher than the semiconductor band gap energy, which refers to the amount of energy needed to free an electron from its semiconductor. When the solar cell is connected to a load, the free electrons travel and form current flow.

The early solar cells were p on n devices, but it was later realized that implanting n on p devices is more superior when the high-energy electrons and protons irradiate the cells. Figure 2.3 shows a modern day schematic of a silicon solar cell. The emitter (doped Si) layer is very thin compared to the base (doped Si) layer thickness, so that the thick base can absorb the incident light effectively. To increase light absorption, antireflective coating is used on the top surface, while the conducting grid is designed to produce minimal shadowing of the underlying semiconductor.

Figure 2.3 Schematic Diagram of a Typical Silicon Solar Cell [3]

In the early development of solar cell, its efficiencies were typically about 10%. State-of-the-art space silicon solar cell can produce from 90 to 110W/m-sq at Beginning-Of-Life (BOL) using mounted rigid panels. There are a few environmental factors that affect the BOL and End-Of-Life (EOL) power: electron and proton bombardment, mechanical and

electrical degradation of cell interconnection, thermal cycling and many others. BOL and EOL are defined as spacecraft condition at the beginning of its mission and end of its mission, respectively.

After the launch of Sputnik 1, which had a short lifespan because of its sole dependence on non-irreversible (non-rechargeable) battery power, solar energy had been studied and applied in the subsequent launches. Solar cell efficiencies on the earliest array were about 10% and they had low survivability in space environment.

The power requirement for commercial spacecraft has increased tremendously. Over the years, more complicated instruments are mounted unto the spacecraft to perform special tasks such as satellite communications, Earth observations and interplanetary missions. The power requirement for such spacecraft has been increasing exponentially as illustrated in Figure 2.4. Hence it is important to develop high performance solar array system.

Figure 2.4 Spacecraft Power Demand [3]

First solar array used in space was on Vanguard I, providing the spacecraft about 1W of power for more than 6 years. The power requirement continues to increase to the extent that small paddles of solar cells were mounted on the hinged arms that swung out from the body of the spacecraft. This paddle array system allows larger panel area than the spacecraft main body, was firstly used in Explorer 6. The paddles were oriented to provide continuous power as the spacecraft rotated. This system later developed into more efficient way of mounting the solar cells. One common method is to use the rigid panel planar solar arrays, known also as honeycomb panel. This consists of 2 thin-aluminum face sheets glued to a honeycomb like core. The automatic deployment of rigid

panel arrays is accomplished by using springs to actuate motion around a series of hinges between the panels. Once deployed, the panels are locked in place and not re-foldable.

Besides the improvement in the mounting technology, a lot of development effort has been channeled into increasing the solar array performance. To measure the performance of space solar array, 2 figures of merit are used, namely the power per unit mass (W/kg) and power per unit area (W/m^2) also known as specific power and area power density, respectively. The subsequent segment looks at the some recent developments to increase the specific power and area power density.

2.3.2 Solar array development for space applications

There are many efforts to increase the solar cell performance to meet the higher power demand of advanced systems in space. The development of Back Surface Reflector, shown in Figure 2.3 has increased the maximum short circuit current. The Back Surface Field, which is formed by a narrow region of high doping density at the back surface of the cell, has successfully improved cell resistance to radiation. With other improvements, the state-of-art silicon solar cell has now matured and reached efficiency of 14.3%.

One inherent bottleneck in Silicon cell is its 1.1 eV band gap energy; hence one alternative is to increase the band gap energy using 'band gap engineering'. By increasing the band gap energy, it means to alter the cell to have electrons of higher energy band. The band gap energy is proportional to the amount of solar power being generated by the cell. Materials such as III-V compound are used by designers because of their high band gap energy.

In recent years, Gallium Arsenide (GaAs) has been widely used because of its high band gap energy compared to Silicon. Using the efficiency versus temperature curve shown in Figure 2.5, it can be shown that GaAs solar cells are more efficient and its efficiency is less temperature dependent than the Silicon cells.

Figure 2.5 Efficiency versus temperature for GaAs and silicon solar cells

GaAs cells are more superior to Silicon cells in terms of its high efficiency (as observed in Figure 2.5), high operating temperature, potential to achieve high specific power and high radiation resistance. Figure 2.5 illustrates the relative radiation damage of Silicon and GaAs cells by measuring the End-Of-Life Power Density of solar cells with varying thickness of cover glass (3, 6, 12, 20, 30, 60 mils). The curves display consistently a positive gradient across time, which means the ratio of GaAs EOL and Si EOL is increasing with higher accumulated radiation. In another words, the GaAs cells are less affected by radiation as compared to Si cells.

Figure 2.6 End-Of-Life Power ratio of GaAs to Si Solar cells [3]

In addition, multiple junction cells have further increased power generation, by extending the wavelength spectrum of which incident light is absorbed. Table 2.3 compares the single junction (Silicon, Thin Sheet Amorphous Silicon, Gallium Arsenide, Indium

Phosphide) and the multi-junction solar cells in terms of their power efficiency and life span. Multi-junction cell such as Gallium Indium Phosphide/ Gallium Arsenide (GaInP/GaAs) that achieved 22% efficiency (production) is a candidate for high power spacecraft.

Cell Type	Silicon	Thin Sheet Amorphous Si	Gallium Arsenide	Indium Phosphide	Multijunction GaInP/GaAs
Planar cell theoretical efficiency	20.8%	12.0%	23.5%	22.8%	25.8%
Achieved efficiency: Production	14.8%	5.0%	18.5%	18%	22.0%
Best laboratory	20.8%	10%	21.6%	19.9%	25.7%
Equivalent time in geosynchronous orbit for 15% degradation					
– 1 MeV electrons	10 yr	10 yr	33 yr	155 yr	33 yr
– 10 MeV protons	4 yr	4 yr	6 yr	89 yr	6 yr

Table 2.3 Comparisons of Various Solar Cells

Table 2.4 shows the power conversion efficiency and band gap energy of various thin film solar cells for space application. AM0 (Air Mass 0) refers to atmospheric conditions in space with sun illumination of 1360 W/m². AM1.5 (Air Mass 1.5) defines terrestrial standard spectrum and intensity of sunlight. There are two primary reasons for interest in thin film solar cells for space application: the potential low cost and the apparent radiation resistance.

Cell Type	Bandgap	Predicted AM0 Efficiency	Reported Efficiency
CuInSe ₂	1.0	17%	10%(AM0)
CuIn _x Ga _{1-x} Se ₂	1.0 - 1.2eV	17% - 20%	17% (AM1.5)
α-Si	1.72eV	25%	10% (AM0)
CdTe	1.44	24%	16% (AM1.5)

Table 2.4 Thin Film Solar Cell Types and Efficiencies [3]

Another alternative in increasing solar power generation is by using concentrator arrays, which provides better focus of Sunlight on the solar array. The concentrator reduces the active semiconductor area by a factor 1/X, where X is the concentration ratio of the optical element. The reduced area allows the use of advanced, high efficiency solar cells at considerably lower cost than for the same output planar array. The reduced cell also means additional shielding against radiation damage can be provided without a major impact on total array mass. The drawback in using concentrator array is its stringent

alignment to $\pm 3^\circ$ along the axis normal to lens surface. The application of concentrator array requires more stringent altitude control; otherwise the array receives almost zero insolation when out of alignment.

In addition to the development in increasing the area power density (Watt/ m^2) of solar cells, many developments have been channeled to improve the glass protection layer on the solar cells. The cells have special cover glass glued to them, which does not become darkened under radiation, like normal glass. It protects against micrometeorites, and against radiation damage in the cells. It also has special coating, to aid the absorption of the light. This coating by itself increases the efficiency of the cells by some 5%. This glass must be glued with space-qualified glue, which does not evaporate under vacuum, and does not fall apart under radiation. The glass is expensive, and the assembly of each piece is also expensive. The cells are stronger than terrestrial cells, to avoid breaking under launch vibration and shock. Space cells are radiation tolerant compared to terrestrial cells that would not last long in the space radiation environment.

2.4 Chemical Storage and Generation Systems

As the name implied, chemical storage and generation system stores energy when it is being charged by other source and supplies energy to load during discharge. During eclipse, the operations of spacecraft's sub-systems rely on its energy storage capacity. The energy storage is also used as power booster. During peak power operation, the total power to supply all the loads comes from the solar power and the energy storage. By using the energy storage as a power booster, the solar array area can be reduced by sizing it to meet average operation need rather than peak operations. Both primary (non-rechargeable) and secondary (rechargeable) batteries have been used in space applications. In general, there are two types of chemical storage for spacecraft, namely battery cells and fuel cells.

Date (m/d/y)	Satellite	Duration	Type	Comments
10/4/56	SPUTNIK 1	3 months	Ag/Zn	1W for 3 weeks
12/6/56	VANGUARD	Failed	Zn/HgO	First U.S. launch
2/1/58	EXPLORER 1	3.8 months	Zn/HgO	Van Allen Radiation Belt
8/6/59	EXPLORER 6	2 years	Cyl Ni/Cd	First earth photos
3/13/61	IMP 1	3.5 years	Ag/Cd	Non-magnetic
1/26/62	RANGER 3	Solar orbit	Ag/Zn	Moon photos
4/26/62	ARIEL 1	14 years	Pris Ni/Cd	First LEO mission
8/27/62	MARINER 2	Venus probe	Ag/Zn	Venus mission
6/23/63	SYNCOM-2	Communications	Cyl Ni/Cd	First GEO
5/20/65	APOLLO CM	Short	Ag/Zn	LTD cycle life
6/23/66	NTS-2	5 years	Ni/H ₂	12 hour polar
9/23/66	USAF	Classified	Ni/H ₂	LEO
2/14/80	SOLAR MAX	8 years	Ni/Cd	Standard battery
4/4/83	STS-3	Days	Li-BCX	Astronaut use
5/19/83	INTELSAT V	14 years	Ni/H ₂	GEO
4/6/84	LDEF	6 years	LITHIUM	Exposure to space
10/18/89	GALILEO	Hours	Li-SO ₂	Jupiter probe
4/25/90	HST	In orbit	Ni/H ₂	NASA LEO
6/10/90	LEASAT	Orbiting	Super Ni/Cd	GEO
1/25/94	CLEMENTINE	5 months	SPV Ni/H ₂	Lunar mapping
1/25/94	TUBSAT-B	4 years	2 Cell CPV	Store messages
5/19/95	CENTAUR	1st mission	Li-SOCl ₂	28V, 250AH battery
5/5/96	IRIDIUM-1	Commercial	50Ah SPV	34 to date-LEO
12/4/96	Mars Lander	JPL mission	Ag/Zn	40AH rechargeable
12/4/96	Mars Rover	JPL mission	Li-SOCl ₂	3 'D' cell batteries
11/19/97	FLIGHT EXP	USAF experiment	Na/S	Wakeshield platform

Table 2.5 Chronological list of first used batteries in space [3]

The fuel cell system differs from a battery cell system in its reactants that are stored outside the cell in cylinders. This arrangement allows more fuel and oxidant to generate more energy. The selection of storage systems depends on a few major criteria such as payload operations, mission lifespan, weight and cost.

A chronological history of first uses of batteries in space applications appears in Table 2.5. Silver-zinc was the battery of mostly used in the early missions because of its high specific power (W/ kg). Silver-zinc was used in Sputnik 1, which lasted for 3 months. Due to the short lifespan of Silver-zinc, it was replaced by the Nickel Cadmium battery (used in SOLAR MAX spacecraft that lasted for 8 years) which has longer battery life span as shown in Table 2.6. Nickel Cadmium and Silver Zinc are identified as Ni-Cd and Ag-Zn, respectively.

Table 2.6 Charge-Discharge Cycles of Various Battery Cells [10, 11]

Type of cells	Nominal Voltage/ Cell (Volts)	Energy Density (WHr/kg)	Temperature (°C)	Cycles Life at Different Depth of Discharge Levels		Whether Space Qualified
				25 %	75 %	
Ni-Cd	1.25	25~30	-10~40	21000	800	Yes
Ni-H ₂	1.30	50~80	-10~40	> 15000	> 4000	Yes
Ag-Cd	1.10	60~70	0~40	3500	100	Yes
Ag-Zn	1.50	120~130	10~40	2000	75	Yes
Pb-Acid	2.10	30~35	10~40	1000	250	-
Li-Ion	3.60	90	-40~50	40000	1000	Yes

In 1970s, Nickel Cadmium was replaced by Nickel hydrogen because its high specific energy (Wh/ kg). This means more battery packs could now be placed on board without increasing the weight. INTELSAT V (launched 1983) had operated for 14 years with the Nickel Hydrogen battery on board. Hence, the development of high specific energy secondary storage has allowed longer operational years and high power consuming operations during the eclipse period.

In recent years, Lithium Ion battery that has almost double the specific energy of Nickel Hydrogen battery is being used for Jet Propulsion’s Laboratory planetary missions. Table 2.6 shows that the Lithium Ion battery has the highest specific energy compared to the Nickel Cadmium battery and Nickel Hydrogen battery.

As seen in Table 2.5, the choice of battery cell is different for each spacecraft. The selection of type of battery cell depends on many factors such as [4]:

- Capability of accepting and delivering unscheduled power at high rates
- Large number of charge-discharge cycles or long charge-discharge cycle life under a wide range of conditions
- High recharge efficiency
- Good hermetic seal to prevent loss of electrolyte and corrosion throughout thousands of electrical cycles involving pressure and thermal changes
- Possibility of operation in all positions
- Availability of cells with well matched characteristics
- Capability to withstand launch and space environments
- Stable long-term overcharge characteristics
- Maximum usable energy per unit weight or low weight
- Low volume
- Low cost
- High and proven reliability

Two common terms used in gauging the capacity of the battery is the Depth-Of-Discharge (DOD) and State-Of-Charge (SOC). DOD is the percent or fraction of the battery capacity being removed during a discharge. SOC is the percent or fraction of battery capacity within the cell during charging. Charge rate is usually indicated by the capacity of the battery(C) i.e. the charge rate of 1C for a 7 Ampere-Hour battery is 7 Amp.

2.5 Power Management and Distribution (PMAD)

The functions of PMAD can be divided into several main areas: bus management and control, battery management and power conversion.

2.5.1 Bus Management and Control

A spacecraft bus voltage is defined as the common voltage that is converted from the solar array output voltage that usually has wide voltage swing. This conversion reduces the voltage swing to a manageable limit, hence allows all electronic devices to operate. There are a few processes that perturb the equilibrium of the bus voltage such as the solar power generation process that varies according to temperature and sun illumination, the battery charging/ discharging process and loading process. There are two systems used to regulate the bus voltage, the dissipative systems and the non-dissipative system. The dissipative system also known as Direct Energy Transfer (DET), maintains the bus voltage by shunting the excess solar array power, whereas the non-dissipative system extracts only the required power from the solar array.

The dissipative systems can be implemented using the linear or switching shunts as shown in Figure 2.7. In the linear system, the bus voltage is compared to a reference voltage and error signal is generated. The amount of power shunted depends on the level of error signal. However in the switching shunt system, this error signal is compared with a ramp signal and resulting output is used to modulate the shunt transistor. Since the transistors are operated as switches, power dissipation is drastically reduced and lower-power transistors can be utilized. In practice, both these systems are used in a multistage sequential topology shown in Figure 2.8. In a sequential shunt system, several transistors are used as a switch in series with a shunt resistor. These transistors are turned on one at a time, depending on the level of error signal. As the error voltage increases, more transistors are turned on to shunt more solar array circuits. The same principle applies to sequential switching shunt regulators, whereby each solar string is connected to a Pulse Width Modulator shunt regulator.

Figure 2.7 Dissipative System Topologies [3]

Figure 2.8 Sequential Shunt Systems [3a]

The non-dissipative systems take advantage of the non-linearity of solar output voltage and current. Figure 2.9 shows the voltage-current curve of a typical solar array. This system is also known as Maximum Power Point Tracking system, tracks the Maximum Power Point of the solar voltage-current to extract the maximum power available from the cell. This operation will be elaborated more in subsequent chapter of the thesis.

Figure 2.9 Solar Array IV Characteristics

Table 2.7 summarizes the characteristics of both the Maximum Power Tracking (MPPT) and Direct Energy Transfer (DET). The MPPT only extracts the amount of power that is needed from the solar array, hence reducing the heat dissipation very minimal within the power supply unit. In DET, especially during standby operation that only a few sub-systems are operating, the extra power that is extracted from the solar array is dissipated in the shunt regulator and hence requires more heat sinks. This is because the DET has no ability to reduce the power extraction from the solar array. The DET system also has no capability to extract the additional power during the BOL of the satellite because the DET has a fixed solar array operating point. Unlike the MPPT system, the solar array operating point is a variable and shifted to the point that produces the maximum power. This feature is useful during the BOL that higher than average power can be extracted from the solar array. One drawback of the MPPT system is more components including micro-controller or processor are needed in the design, which could increase failure rate.

Table 2.7 Comparisons between MPPT and DET Systems [1]

<i>Parameter</i>	MPPT Approach	DET Approach
Thermal & Mass Constraints	Heat dissipation is limited to a low and nearly constant value	In periods of excess power, heat is usually dissipated in the shunt regulator which therefore requires heavy heat sinks
Power Utilization	More power is available at the BOL to operate additional equipment or increase its operating time	Additional power at the BOL is not properly utilized
Control Design	More sensors and micro-controller needed. More complicated circuitry, which increase risk of failure. High component counts	Only need simple components. Simple circuitry and hence more reliable. Low component counts.

2.5.2 Battery Management

The battery charging, discharging and reconditioning are important process to ensure safe operation of the battery until EOL. Cell Charge and Discharge voltage level deviation are determined by several factors. The deviation of cell voltage from its equilibrium is termed as ‘polarization’, which is caused by the current flowing through the cell and its chemical constituents. The greater the energy removed during discharge (high DOD), the greater the effect of the polarization factors. In another words, greater DOD refers to higher risk of cell failure because the cell has less active chemical constituents to convert, the electrolyte may become depleted and some active chemical constituents may become passive, thus increasing the resistance of current flow. The greater the DOD on a regular basis, the sooner the battery will fail to deliver the required voltage for the time period required. Figure 2.10 illustrates that higher DOD results in shorted life cycles. At the same number of cycles, the DOD is higher when the battery temperature is higher. This means higher energy storage capacity when the battery temperature is higher ($T_1 > T_2 > T_3$) because the chemical constituents are more active compared to low temperature situation.

Figure 2.10 Depth Of Discharge Curve [3]

At high discharge rates, the cell will appear to have an unusually low voltage and will exhaust one of the electrodes. As the curve in Figure 2.11(a) shifts towards right side that represents high discharge rate, it is shown to have lower capacity. During high discharge rate, there is greater voltage drops due to internal and external circuitry in the cell.

Figure 2.11(a) General Trends for the Effect of Rate on Capacity

The battery appears to have lower capacity at lower temperature due to the chemical constituents become inactive, as shown in Figure 2.11(b).

Figure 2.11(b) General Trends for the Effect of Temperature on Capacity

Hence, the charging mechanism is the key to sustain the lifespan of cell. Commonly used charging methods are constant current, constant voltage and maximum current with temperature compensated voltage limit followed by current taper (V_T method). These three methods are elaborated in the following paragraphs.

The primary advantage of constant current charging is its simple and low cost design, which is relatively more reliable because of its low component counts. Figure 2.12 shows the typical charging voltage profile at different charging rate. The charging rate is always referring to the charging current. At higher charging rate, the battery cell reaches higher voltage at full charge compared to low charging rate. Hence, the cut-off voltage to stop the charging process has to be shifted higher in this case. This cut-off method is sometimes known as the voltage-sensing control [9]. The cut-off voltage depends on both the charge rate and battery temperature. Figure 2.13 shows the effect of battery temperature on charging voltage profile. All the four charging curves at 15 °C, 23 °C, 30 °C and 40 °C have the same charging rate. This information would be later used to describe the V_T charging method.

Figure 2.12 Constant Charging Method: Effect of Charge Rate on Voltage Profile [12]

Figure 2.13 Constant Charging Method: Effect of Battery Temperature on Voltage Profile [12]

A Constant Voltage Charging implies that the charger maintains a constant voltage independent of the charge rate [12]. These chargers normally incorporate some sort of series regulation or shunt regulation between the charging power source and the battery to hold the voltage across the battery terminals relatively constant. Figure 2.14 illustrates a typical Constant Voltage charging characteristic. In practice, the constant voltage is not perfectly constant throughout the range of charging currents, as shown by the dotted line in Figure 2.14. The charger will interact with the dynamics of battery voltage during the charging process. The solid line in Figure 2.15 shows the actually battery voltage profile during the Constant Voltage Charging, while the dotted lines represent a typical battery

response to charging at various charge rates (using the Constant Current Charging method). The battery first behaves like it is receiving a constant-current charge until the charging voltage reaches the set point voltage of the charger. At that point, the battery voltage remains almost constant as the battery continues to charge i.e. the battery moves to the right in Figure 2.15, cutting the charge current profiles.

Figure 2.14 Constant Voltage Method: Voltage-Current Profile [12]

Figure 2.15 Constant Voltage Method: Voltage-Capacity Profile [12]

The V_T method is a combination of both the Constant Current and Constant Voltage Methods, which were described earlier. It is commonly used in Nickel Cadmium cell, in which a maximum current initially charges the cell until a voltage reaches a preset value. Then, the charging continues with Constant Voltage Charging. This preset value is determined from the V_T curve in Figure 2.16. For instance, it is safe to operate a Nickel Cadmium battery at 10 °C with 25% DOD. From Figure 2.16, it is observed the cut-off voltage is 1.435V. This means that the battery should be charged until 1.435V using maximum current before switching to Constant Voltage Method to allow the charging current to taper off.

Figure 2.16 V_T curve for Nickel Cadmium battery [12]

These preset levels are a function of charging voltage and temperature. Extra care must be taken when excessive heating or battery becomes short-circuited that cause the batteries string voltage to drop. If the charging mechanism fails to detect these causes, the charging operation will continue until the battery voltage reaches a higher level. As a result, more energy will flow through the battery and result in battery overcharge.

As described earlier that the battery cut-off voltage depends on the charge rate (Figure 2.12), hence there are parallel lines in Figure 2.16 that corresponds to different charge rates. This is illustrated in Figure 2.17. Charge rate is such that $V_{T4} > V_{T3} > V_{T2} > V_{T1}$. By using this method, the additional solar power (when the array is cold), can be optimized by charging the battery using maximum current at the initial charging phase.

Figure 2.17 V_T curve for Nickel Cadmium battery at different charge rates [12]

Figure 2.18 is a typical charging curve of Nickel Cadmium cell using the V_T method. It is observed that the battery voltage gradually increased during the Constant Current Charging until it reached the cut-off voltage at 31.62V. At this point, the charger began to operate in Constant Voltage Charging mode by maintaining the battery voltage while allowing the charging current to taper off. With this method, the battery can reach its full charge safely without encountering issue such as over-voltage charging.

Figure 2.18 Nickel-Cadmium V_T Charging Profile [3]

Batteries require periodic reconditioning for long life, which can be done by a depleting the battery to a full discharge state through a resistor. Although this is required for Nickel Cadmium batteries, most power sub-system designs do include this feature to allow for system flexibility. The management of battery will be elaborated more in subsequent chapter of the thesis.

2.5.3 Power Conditioning

The power conditioning basically comprises of DC-DC converters for low power spacecraft. The function of a DC-DC converter is to regulate the bus voltage to one or few other voltages and to supply to various loads of different input voltages. Figure 2.19 shows the classification of various types of converters. Linear regulators are used when milli-volts output ripples are required. However, linear regulators are of limited use for high-power, high-efficiency power processing systems.

Figure 2.19 Classifications of DC-DC Converters [3]

In such high power and high efficiency applications, switching regulators such as Buck Regulators are used to step down the output voltage of solar array and Boost regulators are used to step up the voltages. A combination of both regulators is known, as Buck-Boost Regulator is able to produce output voltage that is lower, higher or equal to the input voltage. The design of the Buck Regulator is elaborated in Chapter 4. Based on Figure 2.19, these switching regulators are categorized as hard-switched converters because of the voltage and current waveforms in these converters are generally square wave. Figure 2.20 shows the typical waveforms of a Buck-Boost PWM converter and

demonstrates the switching losses at turn-on and turn-off of the transistor. The finite rise time and fall time for these waveforms caused a period of overlapping voltage (V_Q) and current (I_Q) across the switch. This overlapping results in power dissipation in the power switch.

Figure 2.20 Waveforms of Buck-Boost Converter [3]

Resonant converters are used to eliminate the constraints and power loss in hard switching converters. The advantages of resonant converters are reduction in components ratings and reduction in switching losses compared to hard switching converters. The voltage-current profile of the power switch can be observed in Figure 2.21.

Figure 2.21 Waveforms of Resonant Converter [3]

Switching loss is reduced greatly because there is nearly zero overlapping of voltage and current during both transitions of turn-on and turn-off of the power switch. However, there are a few inherent disadvantages of resonant converters such as higher gate drive losses and faster drop-off in efficiency at lighter loads. There are 2 basic modes of resonant operation, the series resonant converters places the load in series with the resonant tank and the parallel resonant converter places the load in parallel with the resonant tank capacitor, as shown in Figure 2.22. The series and parallel resonant converters are also known as the zero-current and zero-voltage switching, respectively.

Figure 2.22 Zero-Current and Zero-Voltage Switching Converters [3]

Table 2.8. Voltage Conversion Topologies [14]

Topology	Power Rating (W)	$V_{in(DC)}$ Range	In/Out Isolation
Buck	0-1000	5-1000	No
Boost	0-150	5-600	No
Buck-Boost	0-150	5-600	No
Half-forward	0-150	5-500	Yes
Flyback	0-150	5-500	Yes
Push-pull	100-1000	50-1000	Yes
Half-bridge	100-500	50-1000	Yes
Full-bridge	400-2000+	50-1000	Yes

Table 2.8 illustrates the various options based on the power requirement. A high power spacecraft that requires higher than 1 kW normally operate at higher bus voltage to reduce ohmic losses, hence would call for the full-bridge topology.

2.6 Chapter Summary

An overall and complete description of the spacecraft power supply system has been presented. The functionality and development of various choices of secondary storage capacity and primary energy sources were elaborated. A variety of power management and control methods, battery management approaches and voltage conversion using DC-DC converters have also been discussed.

One conclusion can be made about the solar power demand in future spacecraft missions. The future spacecraft would carry higher computation power on-board to perform sophisticated operations; hence it is worthwhile to develop high performance power management and control. Maximum Power Point Tracking capability is becoming a stringent requirement to achieve high performance power management and control as presented in Chapter 1 and this chapter. In addition, the MPPT is able to extract the maximum solar power despite solar cell degradation issues that cannot be eliminated.

Chapter 3 reviews the different algorithms used to implement the MPPT. These algorithms and implementations are based on terrestrial applications that allow usage of electronic components and processors of high computation speed. Due to the limited components that can be used in space, the performance of the MPPT in spacecraft could not match those of terrestrial applications. This chapter would also examine the issue of shading and ageing of solar cell.

CHAPTER THREE

MAXIMUM POWER POINT TRACKING AND GLOBAL MAXIMA TRACKING APPROACHES

3.1 Introduction

Chapter 2 concluded that there is a need for developing a high performance MPPT for spacecraft applications due to the increasing payload power demand. Chapter 3 presents various MPPT schemes that are implemented in terrestrial as well as space applications. The effectiveness of existing MPPT schemes in spacecraft are lower compared to those on Earth. With intention to improve the existing MPPT in space, the author has adapted some high performance terrestrial MPPTs for space applications. The issues related to implementing terrestrial MPPT in space would be presented.

3.2 Global vs Local Maxima

An important intrinsic characteristic of solar array is known as the ‘multiple power maxima points’ phenomenon. The highest power point among all the multiple power maxima points is known as the global power maximum point or global maxima. The rest of the power maxima points that indicate lower solar power than the global maxima are known as local power maximum point or local maxima. The current literature on various terrestrial and space based MPPT have largely neglected this phenomenon, which implies that a typical solar array has more than one Peak Power Point. Most reviewed MPPT schemes are developed based on the assumption that all the solar cells on the panel have the same Peak Power Point (also known as the optimum point). Hence, the collective solar power of the panel is the summation of these individual cells operating at its optimum point. Under the condition that all solar cells have same optimum point, the ‘multiple power maxima points’ would not exist. This condition is valid under two conditions, firstly is when all the solar cells are receiving the same level of insolation from the Sun and secondly when they are operating at the same level of cell temperature. These two conditions are valid for small panel satellite (nano satellites) with a well-designed thermal management. With active thermal management system, it is able to regulate temperature of all solar cells to be in an acceptable narrow range.

However, these two conditions are usually invalidated by many factors. One factor that cause unequal cell insolation is shading of solar cells that is due to protruding element such as antennas, boom, sensors and satellite body [15]. Other factors are the satellite's maneuver that cause different angle of solar incidence and cell damage that is due to meteorite/ particles collision. This phenomenon is illustrated in Figure 3.1 that shows partial insolation (shaded) and full insolation (un-shaded) unto the solar cells connected in series. The 5 cells marked with single arrows are partially shaded to receive half as much insolation as the rest.

Figure 3.1 Partial and full insolation on solar cells [15]

Figure 3.2 Solar Current Curves for shaded and un-shaded cells

In Figure 3.1, the solar cells exposed to partial insolation, produce solar current indicated by the red curve in Figure 3.2. The full insolation solar cells produce solar cell current indicated by the blue curve in Figure 3.2. Current level A and level B are solar cell currents at peak power of the shaded and un-shaded cells, respectively.

Figure 3.3 shows the solar output current when the shaded and un-shaded solar cells are connected in series. At the global maxima point, the solar output current is limited to the output of the half-shaded cells (Point II in Figure 3.2). The half shaded cells are producing near their maximum power output (Point I in Figure 3.2), but the un-shaded cells are producing only about half of their maximum power output.

At the local maxima point, the un-shaded cells produce near their full current (Point III in Figure 3.2). When the solar cell is exposed to sun, electron is generated and flows from the anode to cathode of the solar cell. So, the current (positive charges) flows from the cathode to anode of the solar cell. The shaded cells are bypassed by the Diode B. In this situation, Diode B becomes forward biased and current flows from terminal Y to terminal X. The un-shaded cells, however, do not produce any power.

Figure 3.3 Local and global maxima points

Due to the multiple maxima points, a typical MPPT scheme would be 'trapped' at any local maxima point and not extracting the maximum power from the solar array. In summary, an improved MPPT method is needed when the satellite is in the conditions as listed below:

1. Long number of satellite operational years, under which the current-voltage characteristic of solar cell would vary. All the solar cells are not matched in terms of their current-voltage profile after a few years of operation.
2. Big protruding elements that cover the solar panel
3. Bypass high radiation orbit, which vary the current-voltage characteristic of solar cell. This variation is a random process; hence all the solar cells are not matched in terms of their current-voltage profile under high radiation.

A few improved MPPT methods that track these multiple maxima power points are reviewed and presented subsequently. The author has simply named these improved MPPT as Global Maxima Tracking (GMT) for to distinguish them from the conventional MPPT methods. The final segment of this chapter would look into the adaptation issues of terrestrial based GMT for space applications.

3.3 Review of MPPT methodologies

3.3.1 Maximum Power Point Tracking (MPPT)

Previous researchers have analyzed various tracking methods known generally as Maximum Power Point Tracker (MPPT), which maximize the power efficiency. In general, there are 2 categories of MPPT methods, which are the true MPPT and non-true MPPT that are further explained below. The Figure 3.4 below, though is not totally complete, but can provide us an overview of classification of various tracking methods.

Figure 3.4 Maximum Tracking Methods Classification

Perturbation & Observation Method

For any operating condition, the solar cell has its peak power operating point where the ratio of differential power to differential current, $dP/dI = 0$. Through this design, the MPPT operates by incrementing and decrementing the solar voltage periodically [15,16,17]. When the difference of the 2-power level is positive, the operating voltage will be increased. If the difference of the 2-power level is negative, then its operating voltage will be decremented. By doing so, the optimized operating voltage of the solar

panel is tracked. In some analysis, this is also known as the ‘hill-climbing method’ because of its searching method. Analog and discrete components have been used to calculate its instantaneous power at 2 instants, hence detecting the difference in power [67]. Advanced microprocessor such as RISC PIC16C74 has also been used to track the peak power more accurately [67]. This is also known as the Power Feedback Method.

Figure 3.5 Dynamics of Perturbation & Observation on Solar Power

Figure 3.5 summarizes the dynamics of Perturbation & Observation algorithm into 4 principles shown in the 4 small rectangular boxes. The Blue and Red curves refer to the solar power of 2 arrays. The working basis of these 4 principles are based on perturbing the V_{REF} in the same and opposite direction as the preceding cycle when there is an increase and decrease in solar power, respectively. Some variables being used are V_{REF} (Reference Voltage), ΔV (Step change in V_{REF}) and P (Solar power). V_{REF} is used to control the solar operating voltage. This Reference Voltage is proportional to solar voltage e.g. the solar voltage increases when V_{REF} is increased. Subscript refers to time instants e.g. P_1 is solar array power at time = t_1 .

Figure 3.6 shows the detail of Perturbation & Observation algorithm that is based on those 4 principles. Some new variables being used are such as V (solar array voltage) and I (solar array current).

Figure 3.6 Perturbation & Observation algorithm [22]

This algorithm begins by measuring the V_2 and I_2 and calculates P_2 . P_1 stores the solar output power of the preceding cycle. If an increase of solar power is detected, V_{REF} will be updated similar to its preceding cycle. For instance, if V_{REF} was increased during the preceding cycle, V_{REF} will be increased at this current cycle. If a decrease of solar power is detected, V_{REF} will be updated opposite to its preceding cycle. For instance, if V_{REF} was increased during the preceding cycle, V_{REF} will be decreased at this current cycle. After the V_{REF} was being updated, the algorithm proceeds to update P_1 with the current measurement of solar power (P_2). This process is attempting to locate the solar voltage point that produces the highest solar power. By repeating the cycle, the Peak Power Point is located.

Incremental Conductance Method

Being one of the most efficient ways to track the peak power point, the Incremental Conductance Method offers short response time to track the solar panel operating point, hence has usually been used in large satellite systems [2, 35].

This method attempts to match the input impedance of the switching converter to the impedance of the PV array. Hence, maximum power transfer can be achieved when both sides of impedances are matched [21].

Figure 3.7 summarizes the dynamics of Incremental Conductance into 2 working principles as shown in the 2 small rectangular boxes. The dP measures the change in solar power and dV measures the change in solar voltage. The V_{REF} is the same control signal described in Figure 3.5 and Figure 3.6. The algorithm of this method tracks the peak power point, which occurs at $dP/dV=0$ as shown in the figure. At this instant, there is no change in the control signal V_{REF} . When the solar array is at the $dP/dV>0$ region, a control signal (V_{REF}) is used to increase the solar voltage. When the solar array is at the $dP/dV<0$ region, a control signal (V_{REF}) is used to decrease the solar voltage. With such process, the solar array would operate at its optimum point to produce maximum power.

Figure 3.7 Dynamics of Incremental Conductance on Solar IV

Figure 3.8 shows the algorithm for Incremental Conductance Method. Some variables that used are V (solar array voltage), I (solar array current), dV (change of solar voltage), dI (change of solar current) and ΔV (Step change in V_{REF}). The Reference Voltage, V_{REF} is

used to control the solar operating voltage. This Reference Voltage is proportional to solar voltage e.g. the solar voltage increases when V_{REF} is increased. Subscript refers to time instants e.g. I_1 is solar array current at time = t_1 . This algorithm has been experimented and verified that it is able to track fast changing insolation level [21].

Figure 3.8 Algorithm based on Incremental Conductance Method [21]

The algorithm in Figure 3.8 starts its cycle by obtaining the present values of I_2 and V_2 . This followed by computing dI and dV by using the stored I_1 and V_1 from the preceding cycle. The main check is carried out by comparing dI/dV against $-I/V$, and according to the result of this check, the Reference Voltage V_{REF} will be adjusted in order to move the

solar array voltage towards the Maximum Power Point voltage. At the Maximum Power Point, $dI/dV = -I/V$, no control action is needed, therefore the adjustment stage is bypassed and the algorithm will update the stored parameters at the end of the cycle as usual. Two other checks are included in the algorithm to detect whether a control action is required when the array is operating at the MPP ($dV=0$); in this case the change in the atmospheric conditions is detected using dI . Now the Reference Voltage, V_{REF} adjustment depends on whether dI is positive or negative, as shown in the figure.

From Figure 3.8, it was observed that $dI/dV = -I/V$ is used as the main check instead of dP/dV . This is because current sensors and voltage sensors are used in a practical MPPT hardware module to perform the MPPT operation. The solar current and voltage are easier to measure using simple hardware implementation.

$$\frac{dI}{dV} = \frac{-I}{V} \quad Eq3.1$$

Below shows the mathematical derivation of Equation 3.1. Some variables that used in this derivation are V (solar array voltage), I (solar array current), dV (change of solar voltage) and dI (change of solar current). Subscript refers to time instants for e.g. I_1 is solar array current at time = t_1 .

At Peak Power Point,

$$\begin{aligned} 0 &= \frac{dP}{dV} \quad (\text{Substitute } P = I * V) \\ 0 &= \frac{d(I * V)}{dV} \\ 0 &= I * \left(\frac{dV}{dV} \right) + V * \left(\frac{dI}{dV} \right) \\ 0 &= I_1 + V_2 * \frac{(I_2 - I_1)}{(V_2 - V_1)} \\ -\frac{I_1}{V_2} &= \frac{(I_2 - I_1)}{(V_2 - V_1)} \end{aligned} \quad Eq3.2$$

From Equation 3.2, it is observed that the implementation of this method requires more complicated devices to measure the additional parameters such as the panel voltage (V),

current (I), change of voltage (dV) and change of current (dI), are used to compute the incremental (dI/dV) and instantaneous (I/V) array conductance.

Open Circuit Voltage

In this Open Circuit Voltage algorithm, the solar array voltage is clamped close to the peak power point by regulating the array's voltage. This is also known as the Voltage Feedback Method. Based on analysis of photovoltaic cell, its optimal operating voltage during peak power point is estimated to be about 78% of its open circuit voltage, V_{OC} . As the name implies, this algorithm perform voltage sampling of the solar array by periodically measure the array in open circuit. When the closed circuit solar voltage is larger than $0.78 * V_{OC}$, this algorithm would decrease the control signal, V_{REF} . Likewise, when the close circuit solar voltage is smaller than $0.78 * V_{OC}$, this algorithm would increase the control signal, V_{REF} . There is no correction action on V_{REF} when the closed circuit solar voltage equals $0.78 * V_{OC}$ because the solar array is operating on the Peak Power Point.

Close matching between the reference solar cell and the array may be difficult to achieve due to severe degradation by shadowing, radiation or damage to the array/ reference cell. This early design of voltage regulation does not consider the effects of insolation and temperature effect on V_{OC} [2, 20, 35]. However, an improved Voltage Feedback design has taken into consideration the temperature effect on V_{OC} . Additional components such as temperature compensation diodes are mounted in the solar panel to measure the change in array temperature that varies in the orbit [23].

Recently, the neural network control enables monitoring of more factors that alter the open-circuit voltage such as insolation and loading. It can also monitor the ageing factor and hence gives quite an accurate identification of the open-circuit voltage in the long term. The additional configuration of a neural network usually comprises of processor and memory. Input parameters such as time and open circuit voltage are weighted to form a lookup table to determine the final optimal photovoltaic operating voltage. This process is also known as the 'training of the neural network' [19].

Curve Fitting

This approach is considered a 'non-true maximum power point tracking'. The VI characteristic of the photovoltaic cell is analyzed to locate the loci of peak power operation point, so that an explicit mathematical function describing the output characteristics can be predetermined. Any change in the load current is detected and compared to a reference level that is predetermined from its VI plot. The difference between the 2 levels is used to shift the array operating voltage [24]. Although this technique attempts to track the Maximum Power Point without computing the solar power, it cannot adjust to aging, temperature change and breakdown of cells.

Load Matching

This method is one of the few early developments of MPPT, which utilizes direct coupling from PV array to loads without complicated controller. The load matching factor, u is used as a measure for the quality of the matching. Optimization method is used to solve the load-matching problem with the objective of maximizing the load-matching factor. It was shown that optimum matching could be achieved by carefully selecting the array parameters with respect to the load parameters [25].

The application of solar energy has been growing fast for the last decade; hence many research efforts have been put to increase the tracking efficiency of Maximum Power Point. It must be noted that the methods elaborated in Section 3.3.1 are not exhaustive; there are other techniques to perform the Maximum Power Point Tracking. Due to time constraint, the author has limited the research to Open Circuit Voltage, Perturbation & Observation and Incremental Conductance methods. These methods are selected because they are more established and widely tested. Hence, more research papers and other references are available as references.

The following segment compares the performance of each method in terms of tracking efficiency, ability to track under insolation and temperature variation and hardware requirements.

Performance Analysis

Table 3.1 compares the effectiveness of each tracking method, at different rates of insolation variation [2]. Since the solar flux that impress upon the photovoltaic cell varies according to time and location of the orbit (in situation of a satellite), this rate analysis showed the performance of each method in locating the changes in solar flux.

Table 3.1. Comparison of tracking methods efficiency under Insolation Variation [2]

Tracking Method	Insolation	Tracking efficiency, η
Incremental Conductance	Slowly ($65 \text{ mW/cm}^2 \sim 85 \text{ mW/cm}^2$)	0.88
	Rapidly ($42 \text{ mW/cm}^2 \sim 88 \text{ mW/cm}^2$)	0.86
Perturbation & Observation	Slowly ($60 \text{ mW/cm}^2 \sim 84 \text{ mW/cm}^2$)	0.85
	Rapidly ($35 \text{ mW/cm}^2 \sim 87 \text{ mW/cm}^2$)	0.82
Open Circuit Voltage	Slowly ($68 \text{ mW/cm}^2 \sim 86 \text{ mW/cm}^2$)	0.73
	Rapidly ($55 \text{ mW/cm}^2 \sim 90 \text{ mW/cm}^2$)	0.65
Direct Method	Slowly ($65 \text{ mW/cm}^2 \sim 86 \text{ mW/cm}^2$)	0.30
	Rapidly ($44 \text{ mW/cm}^2 \sim 85 \text{ mW/cm}^2$)	0.26

The tracking efficiency here refers to the ratio of extracted solar power to the total available power from the array. The higher the tracking efficiency means more solar energy that is generated by the solar array is transformed into useful electrical energy. The Direct Method is one without any MPPT control; the photovoltaic array is connected directly to the DC-DC converters. Hence, during slow and rapid changing environment, this design suffers a great deal of power loss because most solar energy is transformed into heat on the solar array. The Incremental Conductance MPPT method offers best performance under slow and rapid variation in insolation, followed by Perturbation & Observation and Open Circuit Voltage MPPT. The results in Table 3.1 are consistent with another research finding [35]. The finding shows that the Incremental Conductance has the highest tracking efficiency of 98.2%, followed by Perturbation & Observation (96.5%) and Open Circuit Voltage (88.1%).

Table 3.2. Summary of MPPT Analysis

Methods of MPPT	Temperature Variation	Insolation Variation	Design Complexity	Tracking Efficiency (%)
Incremental Conductance	Yes	Good control	Average	98.2
Perturbation & Observation	Yes	Average control	Average	96.5
Open Circuit Voltage	Yes	No control	Simple	88.1
Curve fitting	No control	Good control	Simple	
Load Matching	No control	No control	Simplest	
Direct Method	No control	No control	Simplest	

Table 3.2 summarizes the design requirements for the MPPT in this research, which is based on factors below.

a. Temperature Variation

It was shown that the solar array generates higher solar energy when cold than when hot. This phenomenon is described in Section 1.1. The MPPT should be able to track the IV curve shift caused by changes in solar array temperature. By doing so, the additional energy during low temperature can be fully utilized. From Table 3.2, Incremental Conductance, Perturbation & Observation and Open Circuit Voltage methods are able to track the peak power point under temperature variation.

b. Insolation Variation

The variation of insolation is caused by the varying flux of Sunlight that is normal to the solar array panel, as described in earlier segment. For Sun-synchronous orbit, this factor is not dominant because the solar flux that is impressed on the photovoltaic array is almost constant. However, the solar flux still fluctuates during satellite maneuvering. Hence, during such mission operations, the MPPT should be able to adjust the solar operating point to extract the maximum power from the solar array. From Table 3.2, Incremental Conductance and Perturbation & Observation methods are able to track the peak power point under insolation variation.

c. Design Complexity

In satellite development, the simplest design methodology is used, to avoid any components failure. Power supply system is the heart of the satellite in providing energy to all the sub-systems; hence a simple design that requires minimum component count is preferred to ensure high reliability.

d. Tracking Efficiency

Based on the reference [35], the results of tracking efficiency are based on varying the insolation to a 250W solar array. An 8-bit microcontroller, HC11 was used in the experiment.

Based on the Table 3.2, two main methods, which are the Incremental Conductance and Perturbation & Observation Methods, are identified for experimental testing and verification. They are adopted because of their capabilities such as tracking temperature, insolation changes and high tracking efficiency. For a typical mission of the LEO satellite, the maximum temperature difference of the solar cells in a single and independent solar array is about 30 °C to 35 °C [27]. A satellite that performs imaging operation would need to maneuver its body that would also alter the insolation level.

With reference to Table 3.3, it is observed that the V_{OC} method was favored in micro-satellites power supply. Hence, the V_{OC} algorithm will also be tested and used as a frame of reference. The power consumption of the extra components required to perform the MPPT have not been considered so far, but they must not exceed the amount of power saved from using MPPT. This aspect of power consumption is critical in determining the type of MPPT design and would be presented in subsequent Section 3.4. The availability of space qualified COTS to support the MPPT algorithm is another critical aspect that will be examined there.

3.4 Adaptations of terrestrial MPPT methodologies for space implementation

As concluded in the previous Section 3.3 that the Perturbation & Observation and Incremental Conductance methods are of interest in this research, however the various implementations that are documented in Section 3.3 for both methods have made use of COTS that are not space qualified. As a result, such designs and components that bear risk to the power supply system could not be used in this research. The hardware and software implementations must be adapted to space environments to ensure reliability, which is of concern in this research.

Table 3.3 summarizes different MPPT algorithms implemented in small satellites using COTS. Due to the confidentiality of satellite project development, not all information on the power supply system is published and shared. Hence, Table 3.3 only reflects those satellite projects that provide more complete information pertaining MPPT. Many other small satellites developments were shared through the World Wide Web, but not reflected in Table 3.3 due to incomplete information.

Table 3.3 Key Component & MPPT Algorithm in small satellites

Satellites	Algorithm	Key Component	Intended Lifetime
NavGold [26]	No Info	Micro processor	1 year
CubeSat [13]	Perturbation & Observation	Micro processor (PIC16C774)	1 year
Quest [28]	Open Circuit Voltage	Micro controller	3 years
TsingHua-1 [29]	Open Circuit Voltage	Pulse Width Modulator (PWM) chip	3 years

In Table 3.3, it shows the Open Circuit Voltage based MPPT was favored for missions of long design lifetime (3 years). This algorithm is a good candidate because of its key component is less susceptible to TID. The CubeSat design also confirmed that the more advanced algorithm such as Perturbation & Observation required key component with computational power of a microprocessor and only suitable for short intended lifetime (1 year) missions. With such a microprocessor on-board, the intended lifetime has to be shorter (1 year) in view of possible component failure due to TID. As compared to PWM IC, microprocessors are more susceptible to TID hence only used in short intended lifetime missions.

Within the family of small satellites, this research focuses on a specific type, called the micro satellite because of its interest in Singapore in recent years. The family of small satellites is categorized based on the power consumption, lifespan and satellite weight, as listed in Table 3.4.

Table 3.4 Categorization of small satellites [30,31,32]

Spacecraft Types	Peak Solar Power (W)	Design Life Time (years)	Weight (kg)	Examples
Pico-satellite	<1	<1	< 1	CubeSat
Nano-satellite	10	1	1-10	SNAP-1, NavGold
Micro-satellite	50	3	10-100	UoSAT-5, KITSAT-1, TsingHua-1, Quest
Mini-satellite	175	3	100-500	UoSAT-12

Based on Table 3.4, micro-satellites (TsingHua-1 and Quest) with high peak solar power and long design lifetime utilized the Open Circuit Voltage MPPT. This Open Circuit Voltage MPPT method that requires only a simple Pulse Width Modulator, has proven to be reliable for micro satellites space mission of 3 years. Whereas pico-satellites (CubeSat) with low peak solar power and short design lifetime used the Perturbation & Observation MPPT that requires a powerful microprocessor.

Many other micro-satellites have also employed the Open Circuit Voltage MPPT algorithm although with a compromise of performance. Hence, it is the aim of this research to demonstrate that micro satellites with long design-lifetime could also be equipped with high performance MPPT without compromising reliability.

One of the major constraints is that the implementations of Incremental Conductance and Perturbation & Observation methods require extra processing power to compute its algorithm. The amount of power saved through these new algorithms must exceed the power consumption of its additional circuitry to justify its implementation in micro-satellites. Based on the literature review in Section 3.3, all the references that implemented the Incremental Conductance and Perturbation & Observation algorithms used either a microprocessor or microcontroller to compute the Peak Power Point. The choice of microprocessor/ microcontroller in this research depends on a few aspects such

as space heritage, power consumption, and processing power, cost, mass and market lifetime. Here, the author attempts to search for a suitable microcontroller/microprocessor to be used in space. Table 3.5 shows the space heritage of small satellites' microcontroller/ microprocessor used as the core processors that manage the operations such as the satellite attitude control, power supply monitoring and payload operations. This core processor is also known as the On-Board Computer.

Table 3.5. Small Satellites Status Report by AMSAT & GSFC [33,34]

Satellites	Date of launch	Last known date of operation	Design lifespan	Microcontoller/ Microprocessor	Current condition (as on June 2003)
Snap-1	28 June 2000	Not Applicable	1 year	80C515	Still Operational
UoSat-12	21 Apr 1999	Not Applicable	5 years	ARM60B, 80C515, 80C186, 80C386, ERC-32	Still Operational
BilSat-1	28 Nov 2002	Not Applicable	15 years	80C186, 80C386, 80C515	Still Operational
PanSat	30 Oct 1998	Not Applicable	2 years	80C186	Telemetry downloads only
UoSat-3	21 Jan 1990	Oct 1996	3 years	80C31, 80C186	Possible battery failure
CubeSat (AAU)	30 June 2003	22 Sept 2003	1 year	PIC16C774	Battery failure
SunSat	23 Feb 1999	1 Feb 2001	5 years	80C31	Physical failure

The first 4 small satellites (SNAP-1, UoSat-12, BilSat-1 and PanSat) are still functioning up to June 2003 and SNAP-1 is still operational and has exceeded its mission lifetime. This shows that the microcontrollers/ microprocessors in these 4 small satellites have successfully withstood the hostile space environment within their mission design lifetime. These components would provide a degree of reliability if being used in similar space radiation environment. UoSat-3 has also completed its 3 years mission successfully, whereas CubeSat and SunSat were reported to have failures before the end of their design lifetime. CubeSat's design that comprised of the PIC16C774 was reported to experience battery failure only 3 months after launched as shown in Table 3.5. The actual cause of failure was not available at the point of this review is done but this microcontroller would be disregarded for the author's research to ensure high system reliability. The 80C31 also would not be considered for this research because of its failure in SunSat although its exact cause is unknown.

Table 3.6 compares the power consumption and processing power of microcontrollers/ microprocessors used in small satellite within the LEO orbit. Based on a research conducted by Hohm D.P. and Ropp M.E. [35], an 8-bit microcontroller (2-4 MHz) achieved good MPPT tracking accuracy of 96.5% (Perturbation & Observation method) and 98.2% (Incremental Conductance method). This tracking accuracy is the ratio of power extracted from solar array over total available solar power. To prevent over-designing the MPPT circuitry, a space-qualified microcontroller of 8-bit resolution and 2-4 MHz processing frequency would be used. From Table 3.6, it is observed that the 8-bit microcontrollers (>10 MHz) such as 80C515, 80C31 and PIC16C774 have the lowest power consumption. This power saving feature is important to be observed in a small satellite development because of its limited solar power. As a result, 80C515 an 8-bit microcontroller is a good candidate because of its good space qualification as proven by 4 satellites (UoSat-12, SNAP-1, SunSat and UoSat-3). Based on the availability of 80C515 in the market, the author eventually opted for this microcontroller in the implementation of MPPT.

Table 3.6. Comparisons of Microcontroller/ Microprocessor

Types	Average Power Consumption (W)	Processing Power
80C515 [36]	0.1 W	10 MHz, 8 bit
80C186 [37]	0.3- 0.5 W	12-25 MHz, 16 bit
80C386EX [38]	1.6 W	25-33 MHz, 32 bit
80C31 [39]	0.1 W	16 MHz, 8 bit
PIC16C774 [40]	0.1 W	20 MHz, 8 bit
ARM60B [41]	2.0 W	40 MHz, 32 bit
ERC-32 [42]	1.0 W	10-25 MHz, 32 bit

3.5 Review of Global Maxima Tracking (GMT) methodologies

The failure of a basic MPPT in tracking the global maxima is because of their operating principles and limitations. For instance the Perturbation & Observation searches the peak power point by comparing the solar power around a predefined solar voltage range, which is usually a small range to attain fast tracking time response. Within this predefined solar voltage range, as the algorithm performs the ‘hill-climbing’ operation, it would gradually shift the solar operating to the point that extracts highest power. Figure 3.9 illustrates within the solar voltage of 0V-6V, the highest power is 7.0W and it occurs at 5.7V. If the Perturbation & Observation algorithm starts its tracking operation within this voltage range, the algorithm would detect and lock the solar operating voltage at this local maxima point at 5.7V since 7.0W is the highest solar power that can be extracted from the solar voltage range of 0V-6V. At this solar operating point, the tracking efficiency is only 63.9% of the total available solar power that is 10.9W at 12.3V. This low tracking efficiency is extracted from Table 5.19 in Chapter 5 that is based on real experimental results. Previous research [66] indicates that by having the GMT technique, the output solar power is 1450W, almost 20% more than the non-GMT technique. The success of a basic MPPT depends on the predefined solar voltage range. The limitation of a basic MPPT lies in its inability to identify the true global maximum power point that is outside the given predefined solar voltage range.

Figure 3.9 Local and global maxima points

From the above, it is observed that the basic MPPT could not identify the true global maxima from the local maxima point. This Section 3.5 will review and compare the existing GMT methods. This literature review presents only the terrestrial GMT schemes because there is no information on space-based GMT currently. Subsequently, the author

has adapted the terrestrial GMT for space applications. In general, there are two terrestrial based GMT algorithms, namely the Hybrid MPPT and the Short Circuit Current Pulse.

Hybrid MPPT Algorithm

A Hybrid MPPT method combined the advantage of traditional Perturbation and Observation (P&O) and Incremental Conductance (IncCond). The Perturbation & Observation Method and Incremental Conductance are implemented based on Figure 3.5 and Figure 3.7, respectively.

This Hybrid MPPT method operates by periodically interrupting the normal IncCond MPPT operation with P&O MPPT operation, as shown in Figure 3.10. Based on Figure 3.10, the duration of the IncCond MPPT operation is 12s as compared to mere 40ms operation of the P&O MPPT. In such an arrangement, a higher efficiency could be expected since the solar arrays primarily operate in IncCond MPPT mode. Multiple maxima problems could be overcome by finding the global maximum through scanning a wide control range using P&O MPPT. Since the percentage of P&O method is much smaller, the overall system efficiency will be almost the same as IncCond method [15].

Figure 3.10 Modified MPPT scheme [43]

Short Circuit Current Pulse Algorithm

The Hybrid MPPT method has desirable adaptability in slow changing insolation, but has a drawback concerning response time. Another method that instantaneously determines the optimum operating point is by using a short circuit current pulse. One reference [44] reported that the optimum operation current for maximum output power is proportional to the short circuit current under various conditions of insolation as follows:

$$I_{OP} = k * I_{SC}$$

However this reference does not examine temperature effect on the proportional factor k. A subsequent study is conducted with temperature and insolation effects on the proportional constant, k. This research [18] shows that the k factor is not always constant and should rather be regarded as a variable because it is sensitively affected by surface conditions of the PV panel, especially by shades partially covering the panel. It shows a non-linear relationship between factor k and short circuit current during low insolation (short circuit current < 0.4A).

The drawback of this method is extra circuitry needed to measure the solar short circuit current. During the sampling, the solar panel would be connected in short circuit, which incur a high risk. Components failure that result in permanent shorting of the solar panel would fail the entire satellite mission. Protection measure such as designing two switches in series in this circuitry can only reduce its failure risk.

In summary, the Hybrid MPPT comprises of the Perturbation & Observation and Incremental Conductance methods has highest reliability factor, which is a main design criterion in satellite development. The slow response time can be countered by reducing the frequency of scanning operation. Since the satellite mission operations are predetermined, hence the pattern of solar array shading can be predicted. A look-up table of global maximum data can be formed for each mission operation hence reduce the need of frequent scanning of solar array power. This method is suitable for any micro controller based MPPT or DSP based MPPT.

3.6 Adaptations of terrestrial GMT methodologies for space implementation

The Hybrid MPPT algorithm required a Digital Signal Processor (DSP) to perform the computation. A research group [43] implemented the Hybrid MPPT by using TMS320C24X from Texas Instruments and claimed that the overall efficiency is very close to efficiency of the Incremental Conductance due to negligibly short period of Perturbation & Observation.

Here, there are two alternatives in the choice of key components to implement the Hybrid MPPT, which performs both the basic MPPT and GMT. The alternatives are either the microcontroller (80C515) or a space qualified DSP. The author has opted to use the 80C515 microcontroller because time can be reduced in spending to source for a space qualified DSP. Most importantly, the reason that the 80C515 is chosen over a DSP is detailed in Section 3.4.

3.7 Chapter Summary

Arising from the literature review, this project focused on developing and testing a microcontroller-based MPPT. The MPPT algorithms of interest are both the Incremental Conductance and Perturbation & Observation, together with the Open Circuit Voltage algorithm that is used as frame of reference.

Within this research, it is decided to adopt the Hybrid MPPT with its algorithm to be defined after the analysis of all MPPT methods. The final choice of Hybrid MPPT algorithm depends on the most effective MPPT method that could be implemented by using a micro-controller. This Hybrid MPPT would be able to identify the global power maxima point, as well as performing the Maximum Power Point Tracking.

Chapter 4 elaborates the simulation, experimental setup and test results of MPPT. It also presents the development of the power regulation of a micro satellite, which is the Buck Type Switch Mode Power Supply (SMPS). It explains the design, simulation and experimental implementation of the Buck Regulator.

CHAPTER FOUR

EXPERIMENTAL DESIGN & SETUP

4.1 Introduction

Chapter 4 presents the development and testing of a microcontroller-based MPPT, which is implemented in a Buck type Switch Mode Power Supply. This chapter would elaborate the hardware design, software program as well as the integration into the required test equipment. Figure 4.1 shows the integrated system of the final SMPS with MPPT, as indicated in checked box.

Figure 4.1 Functional Diagram of SMPS with MPPT

As seen, the complete SMPS with MPPT comprises of the Buck type Switch Mode Power Supply, Voltage & Current Sensor, Digital-To-Analog Converter and a microcontroller. The microcontroller measures the solar voltage (V_s) and solar current (I_s) through the Voltage & Current sensor that performs signal conditioning. By running the MPPT algorithm that is embedded in the microcontroller, a digital control signal (V_{REF}) is sent to

the Digital-To-Analog converter before passing to the SMPS. This control signal would shift the operating solar voltage according to the MPPT algorithm. The hardware design of the 3 modules that are the SMPS, the Voltage & Current sensor and the Digital-To-Analog Converter is included in this chapter. Subsequently, the 80C51 microcontroller from Siemens is embedded with the MPPT algorithm and is used to control the SMPS. The key features of the 80C51 microcontroller that is used in this research would also be highlighted here. The complete test environment that includes the other test equipment, simulators and data loggers, which would be explained subsequently.

The key performance indicator of the MPPT is the tracking efficiency. As defined in earlier segment, the tracking efficiency is the ratio of extracted solar power over the total available power from the solar array. The process of determining the total available power from the solar array involves the careful integration of a Solar Array Simulator and an Electronic Programmable Load. This process identifies the total available solar power (also known as the Peak Power Point) under 6 different predefined environmental conditions, would be explained here.

The HP VEE language is adopted to integrate most of the test equipment such as the Solar Array Simulator, Electronic Load and Data Acquisition Card that is used to log electrical parameters. This software is elaborated more in the subsequent segment.

4.2 Experimental Design & Setup

4.2.1 Programming with ‘General Purpose Interface Bus’

The ‘General Purpose Interface Bus’ (GPIB) was originally developed by Hewlett Packard Corporation in the 1970's. The standard was set by the Institute of Electrical and Electronic Engineers (IEEE) in October 1974, and accepted as an international standard in 1980 (IEEE-488). The bus is primarily designed for connecting instruments to a central controller, for the purposes of creating automated test and measurement systems. It is used in the following application areas such as medical instruments, plotters, test instruments and Automated Test Equipment.

The basic structure of the bus is shown in the Figure 4.2 below. A number of devices (maximum of 15) may be connected to the bus, and are a controller, a talker, or a listener. Figure 4.3 shows the connector pin layout.

Figure 4.2. Basic structure of GPIB

Figure 4.3. GPIB Connector Pin Layout

HP VEE Lab works with all Computer Boards® I/O boards as well as boards from Data Translation and GPIB boards from most vendors. A powerful Instrument Manager greatly simplifies setting up IEEE-488 systems. HP VEE Lab also includes a comprehensive instrument library. HP VEE Lab provides over 200 math and analysis functions, ranging from elementary math to calculus to DSP and statistical functions. A large number of data display functions including meters, thermometers, X-Y plots, and strip charts are provided, as well as user interface objects ranging from simple push buttons to variable slide and rotary virtual instrument panels.

The suitability of HP VEE in developing the Maximum Power Tracking system is compared to another graphical programming language, LabVIEW. LabVIEW is a graphical implementation of a standard textual programming language. Conceptually, the LabVIEW implementation simply replaces each command of a text-based language with an icon. Though this strategy is more visually oriented than a standard textual programming language, it shares many of the disadvantages of a standard programming language. In particular, these low-level programming languages are difficult to learn, requiring the programmer to remember not only a huge number of small bits and pieces, but also exactly how they can be put together without generating errors. Low-level programming languages are also slow to program, requiring a large number of lines of code (or icons) for even a relatively simple function.

HP VEE Lab uses a different and unique strategy. The developers of HP VEE Lab recognized that most people who program measurement applications use a variety of similar programming blocks or objects (whether in subroutine or in-line form). HP VEE

Lab provides these objects as easy-to-use, high-level graphical objects to simplify and expedite the programming process. What may take 20 to 30 lines of code in MS C++, would typically take a corresponding 20 to 30 LabVIEW icons, but might take only 3 or 4 objects in HP VEE Lab. Hence, HP VEE is adopted in the author's research. The HP VEE application programs such as Solar IV Curve Test and MPPT Test are included in the individual hardware setup in the following.

4.2.2 Setup of Solar Array Simulator (HP 4350B) and Electronic Load (HP 6050)

The purpose of this setup is to identify the non-linear characteristic of a typical solar array, which eventually provide important data such as the solar power and solar voltage at Peak Power Point. With this information, the tracking efficiency of each MPPT schemes could be determined.

In this research, a DC Electronic Load is used to facilitate easy control of load when necessary. In order to obtain the solar array's current-voltage characteristic, a variable DC load is required to draw solar power in small steps. HP 6050 by Agilent, an 1800W power is a configurable system that operates on GPIB connection. It can be setup to operate in 3 different modes; Constant Current load, Constant Voltage load and Constant Resistance load.

A solar array simulator is being used here instead of an actual array due to a several reasons. The advantage of using a simulator lies in its ease in generating any solar curves within the capacity of the simulator without being constrained by the external factors during test such as ambient temperature and available insolation. Any tests can be repeated to gather more data because it does not depend on those external factors. Another reason for not using an actual solar array is due to the different sun insolation that is up in space compared to that on Earth. In addition, the heat from the solar array is dissipated through air conduction whereas this is impossible in the space vacuum. Due to the different heat dissipation mechanism, the performance of the solar array in space is very different and difficult to be emulated accurately on Earth. Using an actual solar array is more complicated because it requires the integration of a pyranometer that measures solar radiation and Compact Source Iodide (CSI) lamps that simulate the sun insolation. After such considerations, the Agilent E4350B Solar Array Simulator was chosen to expedite the testing process in this research. This simulator is primarily a current source with very low output capacitance. It is capable of simulating a solar array up to 480W under different conditions such as temperature, isolation and age. The IV curve is programmable over the IEEE-488.2 bus and is automatically generated within the simulator. It has three operating modes [45]:

1. *Fixed Mode:* The IV output has a rectangular characteristic of a standard power supply.
2. *Simulator Mode:* The IV output has a non-linear characteristic of a typical solar array. An internal algorithm is used to simulate the IV curve based on 4 input parameters such as the open circuit voltage (V_{OC}), short circuit current (I_{SC}), current at peak power point (I_{MP}) and voltage at peak power point (V_{MP}).
3. *Table Mode:* The IV output is determined from a programmed lookup table. It provides up to 60 tables with a total of 33,500 IV points of storage and a maximum of 4,000 IV points per table. The solar array manufacturer normally provides the information to form the lookup tables.

In the author's research, the simulator mode is used to simulate a space solar array that was one of the candidates for micro-satellite development in Nanyang Technological University. The simulated solar array is based on the 'TEC3i Cascade' solar cells manufactured by TECSTAR (California). These 20 mm x 20 mm triple-junction solar cells are made up of Germanium (Ge), Gallium Arsenide (GaAs) and Gallium Indium Phosphide (GaInP) substrate. An intensive qualification test of the cell has provided key parameters used in programming the Agilent Solar Array Simulator. The following paragraphs explain (a) construction of a 25W array, (b) solar array's profile in relation to temperature and (c) solar array's profile in relation to sun incidence angle.

(a) Construction of a 25W solar array

Multiples of 20 mm x 20 mm unit solar cells are connected together to produce an array of 25W. Two of these 25W solar arrays would be required to operate a typical micro-satellite mission that demands about 50W, as indicated in Table 3.4. Based on the specification from the manufacturer, there are 5 cells in series and 38 strings in parallel, respectively to produce a 25W array. The advantage of using 2 separate solar arrays of 25W each lies on its independent power management. With this independent topology, higher system reliability is achieved because failure in one of the power management would not fail the entire satellite mission. Moreover, the independent topology offers higher power conversion efficiency because each solar array are likely to have different peak power points for reasons explained in Section 3.2.

The solar array is sized based on its expected degradation due to 3 years of space radiation. This means that it is sized to ensure 50W of solar power to be generated at the end of 3 years of hostile radiation. Equations 4.1 to 4.4 describe the relation of radiation, temperature to its electrical characteristic of a unit solar cell. [3]

$$v_{MP} = \psi_{MP} * \left(v_{MPO} + \frac{dv_{MP}}{dT} * \Delta T \right) \quad \text{Eq 4.1}$$

$$v_{OC} = \psi_{OC} * \left(v_{OCO} + \frac{dv_{OC}}{dT} * \Delta T \right) \quad \text{Eq 4.2}$$

$$i_{MP} = \zeta_{MP} * A * \left(j_{MP} + \frac{di_{MP}}{dT} * \Delta T \right) \quad \text{Eq 4.3}$$

$$i_{SC} = \zeta_{SC} * A * \left(j_{SC} + \frac{di_{SC}}{dT} * \Delta T \right) \quad \text{Eq 4.4}$$

These non-capital letter coefficients indicate the unit solar cell characteristics. In subsequent segment, capital letter coefficients are used to indicate the complete solar array parameters.

ψ_{MP}	v_{MP} radiation impact factor, 0.887	$\frac{di_{SC}}{dT}$	i_{SC} temperature coefficient, 11.25uA/cm ² /°C
ψ_{OC}	v_{OC} radiation impact factor, 0.886	v_{MPO}	v_{MP} at 28°C before any radiation, 2.27V
ζ_{MP}	i_{MP} radiation impact factor, 0.868	v_{OCO}	v_{OC} at 28°C before any radiation, 2.55V
ζ_{SC}	i_{SC} radiation impact factor, 0.926	j_{MP}	Peak current density at 28°C before any radiation, 15.5mA/ cm ²
$\frac{dv_{MP}}{dT}$	v_{MP} temperature coefficient, -7.2mV/°C	j_{SC}	Short current density at 28°C before any radiation, 16.1mA/ cm ²
$\frac{dv_{OC}}{dT}$	v_{OC} temperature coefficient, -6.86mV/°C	ΔT	Temperature deviation from 28°C
$\frac{di_{MP}}{dT}$	i_{MP} temperature coefficient, 14.7uA/cm ² /°C	A	Area of unit solar cell, 4cm ²

All the above coefficients are based on 1.0 MeV of electron radiation with fluence of 3×10^{15} e/cm². With Equation 4.1 to 4.4, the following parameters describe the complete electrical characteristic of a unit solar cell at end of 3 years (-75°C) [46].

V_{MP}	2.67V	i_{MP}	0.0496A
V_{OC}	2.89V	i_{SC}	0.0553A

Quoting from the manufacturer, there are 5 and 38 cells connected in series and parallel, respectively to produce a 25W array. As multiple of these unit solar cells are connected in series, the overall solar string voltage increases proportionally based on Equation 4.5 and 4.6 [24]. The overall solar current is also proportional to the number of parallel strings connected together, with reference of Equation 4.7 and 4.8 [21, 35].

Solar string voltage at peak power point, V_{MP}
$$= n_S * v_{MP}$$
Eq 4.5

Solar string open circuit voltage, V_{OC}
$$= n_S * v_{OC}$$
Eq 4.6

Solar string current at peak power point, I_{MP}
$$= n_P * i_{MP}$$
Eq 4.7

Solar string short circuit current, I_{SC}
$$= n_P * i_{SC}$$
Eq 4.8

The following parameters as shown in Table 4.1 are derived from Equations 4.5 to 4.8, describe the complete electrical characteristic of a solar array at end of 3 years with temperature of -75°C and aspect angle of 0°.

Table 4.1 Complete electrical characteristic of a solar array at end of 3 years with temperature of -75°C and aspect angle of 0°

Parameter	Unit	Value
Solar Voltage at peak power point, V_{MP}	Volt	13.4
Solar Open Circuit voltage, V_{OC}	Volt	14.5
Solar Short Circuit Current, I_{SC}	Amp	2.10
Solar Current at peak power point, I_{MP}	Amp	1.88
Aspect angle, β	Degree	0
Solar array temperature, T	°C	-75
Parameter	Unit	Value
Number of cells in series, n_S	NA	5
Number of cells in parallel, n_P	NA	38

(b) Solar Array's electrical parameters caused by temperature variation

As the satellite is nearing the end of its eclipse and approaching sunlight, its array's temperature is at its lowest. Its array temperature begins to increase gradually when the satellite moves in the orbit due to the increasing sunlight exposure. Due to this temperature increment, the solar IV curve changes and the solar cell output power reduces because of its negative power-temperature coefficient as seen in Figure 1.2(b) from Chapter 2. The effect of temperature are captured by Equation 4.9 to 4.12 [3, 21, 24, 35], which are dependent on 3 new variables, n_s , n_p and temperature coefficients. (Temperature, T is measured in Celsius)

At T, $V_{MP}(T) = V_{MP(-75C)} + (T - (-75\text{ }^{\circ}\text{C})) * (n_s * \frac{dv_{MP}}{dT})$ Eq 4.9

At T, $V_{OC}(T) = V_{OC(-75C)} + (T - (-75\text{ }^{\circ}\text{C})) * (n_s * \frac{dv_{OC}}{dT})$ Eq 4.10

At T, $I_{MP}(T) = I_{MP(-75C)} + (T - (-75\text{ }^{\circ}\text{C})) * A * (n_p * \frac{di_{MP}}{dT})$ Eq 4.11

At T, $I_{SC}(T) = I_{SC(-75C)} + (T - (-75\text{ }^{\circ}\text{C})) * A * (n_p * \frac{di_{SC}}{dT})$ Eq 4.12

Table 4.2 below summarizes the array's electrical parameters that reflect the impact of temperature variation by using Equation 4.9 to 4.12.

Table 4.2 Impact of temperature variation on array's electrical parameters

Conditions	Temperature (°C)	Voltage at Peak Power Point, V_{MP} (V)	Current at Peak Power Point, I_{MP} (A)	Peak Power, P_{MP} (W)	Short Circuit Current, I_{SC} (A)	Open Circuit Voltage, V_{OC} (V)
Maximum Temperature	75	8.0	2.22	17.8	2.36	9.4
Medium Temperature	0	10.7	2.05	22.0	2.23	11.9
Low Temperature	-75	13.4	1.88	25.2	2.10	14.5

Equation 4.9- 4.12 are generally used in other literatures [3, 21, 24, 35] to represent the characteristics of a solar array. The author is unable to conduct any experimental verification on Equation 4.9 to Equation 4.12 in this research due to the high cost and long lead time to acquire the ‘TEC3i Cascade’ solar arrays.

(c) Solar Array's electrical parameters caused by insolation variation

Apart from the temperature variation of the solar array, a few other conditions are programmed to simulate satellite maneuvering. For certain mission operations such as Earth imaging and transmission to Earth's ground station, the satellite would maneuver its camera axis and transmission antenna to a specific location on Earth, respectively. Under such operations, the sun insolation would vary because of changes in aspect angle. This eventually changes the available solar power that can be extracted from the array. For a receiving ground-station near Equator, the satellite maneuvering operations typically occur when it nears the Equator. When the satellite is near Equator, the solar array's temperature has reached its peak, which is taken as +75°C [64]. Based on the preliminary analysis of a LEO satellite, it is observed that the aspect angle varies from 0° to 40° [65]. In the author's research, maximum aspect angle taken is 45° to include margin.

The electrical parameters of the array at different aspect angles (β) are estimated using Equation 4.13 to 4.16. $V_{MP(\beta=0)}$, $V_{OC(\beta=0)}$, $I_{MP(\beta=0)}$ and $I_{SC(\beta=0)}$ are extracted from Table 4.2, where the aspect angle is zero and the temperature is at +75 °C.

$$\text{At } \beta, V_{MP} = V_{MP(\beta=0)} * \phi_{\beta} \quad \text{Eq 4.13}$$

$$\text{At } \beta, V_{OC} = V_{OC(\beta=0)} * \gamma_{\beta} \quad \text{Eq 4.14}$$

$$\text{At } \beta, I_{MP} = I_{MP(\beta=0)} * \lambda_{\beta} \quad \text{Eq 4.15}$$

$$\text{At } \beta, I_{SC} = I_{SC(\beta=0)} * \alpha_{\beta} \quad \text{Eq 4.16}$$

ϕ_{β}	Sun insolation factor on V_{MP} at β	λ_{β}	Sun insolation factor on I_{MP} at β
γ_{β}	Sun insolation factor on V_{OC} at β	α_{β}	Sun insolation factor on I_{SC} at β

The change in the available solar power is mainly contributed by the change in the solar short circuit current, I_{SC} and solar current at peak power point, I_{MP} . A few step-changes in aspect angle (15°, 30° and 45°) are simulated. The Table 4.3 indicates the Sun insolation

factors at different aspect angles, which are extracted from data specification of Tec3iQual. These factors are ratio of its electrical parameters measured at any β to its electrical parameters measured at β equals to zero.

Table 4.3 Sun insolation factors for different aspect angles [46]

	$\beta=15^\circ$	$\beta=30^\circ$	$\beta=45^\circ$
ϕ	0.999	0.996	0.987
γ	0.999	0.996	0.987
λ	0.969	0.880	0.716
α	0.971	0.885	0.723

Table 4.4 below summarizes the array’s electrical parameters that reflect the impact of insolation variation.

Table 4.4 Impact of insolation variation on array’s electrical parameters

Conditions	Aspect angle β (Degree)	Peak Power, P_{MP} (W)	Short Circuit Current, I_{SC} (A)	Current at Peak Power Point, I_{MP} (A)	Open Circuit Voltage, V_{OC} (V)	Voltage at Peak Power Point, V_{MP} (V)
Low Insolation	45	12.6	1.71	1.59	9.3	7.9
Medium Insolation	30	15.6	2.09	1.95	9.4	8.0
Maximum Insolation	15	17.2	2.29	2.15	9.4	8.0

This subsequent segment would look into the accuracy aspect in measuring the solar voltage and current of the Solar Array Simulator at Peak Power Point. The accuracy depends on the equipment’s accuracy and user-defined current (step) drawn from the Solar Array Simulator. The simulator generates the voltage and current relation by using an exponential model in the Simulator Mode. This model is illustrated in the ‘Specifications and Application Information’ section of the manual. This exponential model inherits a marginal error that is dependent on the rectangularity of the solar IV curve. As the rectangularity factor $((V_{OC}/ V_{MP})*(I_{SC}/I_{MP}))$ moves closer to 1, the error reduces from 20% to 0% of its peak power, as shown in Figure 4.4.

Figure 4.4 Range of P_{MP} error due to modeling equation [45]

Based on the electrical characteristics of Tec3iQual solar array, the rectangularity factor ranges from 1.21 to 1.27 for all the temperature and insolation variations. This is shown in Table 4.5 and 4.6 below.

Table 4.5 Rectangularity factor under temperature variation

Temperature (Celsius)	V_{MP} (V)	I_{MP} (A)	V_{OC} (V)	I_{SC} (A)	P_{MP} (W)	Rectangularity factor
-75	13.4	1.88	14.5	2.1	25.2	1.21
0	10.7	2.05	11.9	2.23	22	1.21
75	8	2.22	9.4	2.36	17.8	1.25

Table 4.6 Rectangularity factor under aspect angle variation

Aspect Angle (degree)	V_{MP} (V)	I_{MP} (A)	V_{OC} (V)	I_{SC} (A)	P_{MP} (W)	Rectangularity factor
15	8	2.15	9.4	2.29	17.2	1.25
30	8	1.95	9.4	2.09	15.6	1.26
45	7.9	1.59	9.3	1.71	12.6	1.27

With reference to Figure 4.4, the maximum error that is due to exponential modeling is 5% of its peak power. This error is the maximum acceptable error. This implies that the magnitude of the solar current step should be chosen not to produce error in power measurement beyond 5%.

Based on the manual, this simulator inherits a current resolution of 2.5mA (Programming Resolution). This means the smallest solar current step that can be programmed is 2.5mA.

Subsequently, the simulated peak power level is compared to the programmed value to by using a solar current step of 2.5mA.

Figure 4.5 shows the electrical and GPIB connections to obtain the solar array current-voltage profile. The Solar Array Simulator (E4350B) is connected in series to the DC Electronic Load (HP 6050). By using the GPIB bus, specific control settings (V_{MP} , V_{OC} , I_{MP} , I_{SC} to E4350B and I_{LOAD} to HP 6050) are sent to these instruments and data (V_S , I_S from E4350B) are collected from the Solar Array Simulators.

Figure 4.5. Setup of Solar Array Simulators and DC Electronic Load

Figure 4.6 shows the program flow used to characterize the electrical parameters (solar voltage and solar current) of a solar array. The program starts by initiating the Data Acquisition Board by using the 'Direct I/O' Object. This object calls a few instructions such as to setup the polling/ sampling method, range and gain of analogue inputs. This is followed by programming the Solar Array Simulator with the 4 parameters, namely the V_{OC} , V_{MP} , I_{SC} and I_{MP} , using the 'Direct I/O' Object provided in HP VEE language.

The Electronic Load is programmed to the Constant Current Mode after the Solar Array Simulator is turned ON. When the Electronic Load is turned ON using the 'Direct I/O' Object, it starts to draw current from the Solar Array Simulator. During this process, the electrical parameters such as solar voltage, solar current, load voltage and load current are measured and stored in an Excel file.

The 'Build Record' Object is used in creating this data logging operation. The data logging continues to measure and store all the specified values until the solar voltage reaches almost zero. At this point, the solar array is known to be in a short circuit condition and the solar current level is at its maximum. This identifies the end of test operation.

Panel Views (also called panels) are the user interface to your program. The Detail View (the development area that contains all Objects used in program) and the Panel View are two views of the same program that appear in the Main Window; just like heads and tails are the two sides of the same coin. The Detail View of this program can be found (in text format) in Appendix A.

Figure 4.6. Program Flow to characterize Solar Array

Table 4.7 and Table 4.8 record the performance of the Solar Array Simulator. It is observed that the highest percentage error in power is 1.41% under both temperature and aspect angle variations. Since the measured error of 1.41% is below the maximum limit of 5%, it is concluded that the performance of the Solar Array Simulator is acceptable.

Table 4.7 Percentage error of solar power under temperature variation

Temperature (Celsius)	P _{MP} Programmed, P1 (W)	P _{MP} Measured, P2 (W)	%Error (P1-P2/P2*100%)
-75	25.20	25.46	1.03
0	22.00	21.98	0.09
75	17.80	17.81	0.06

Table 4.8 Percentage error of solar power under aspect angle variation

Aspect angle (degree)	P _{MP} Programmed, P1 (W)	P _{MP} Measured, P2 (W)	%Error (P1-P2 /P2*100%)
15	17.20	17.24	1.41
30	15.60	15.62	0.13
45	12.60	12.59	0.08

4.2.3 Sub modules setup

With reference to Figure 4.1, the sub modules include the Buck type Switch Mode Power Supply, Voltage & Current Sensor, Digital-To-Analog Converter and a microcontroller. This section looks into the design of the Voltage and Current Sensor. This is followed by the Digital-To-Analog Converter, Buck type Switch Mode Power Supply and finally the microcontroller.

(a) Design of Voltage Divider & Current Sensor

The functions of this sub module are to measure the solar voltage & solar current and to condition these measurements. The input to the Voltage & Current Sensor comes from directly from the solar array, as shown in Figure 4.1. During the coldest ambient temperature, the solar array reaches its peak voltage of 14.5V (V_{OC}). This peak voltage would be conditioned to a lower acceptable level based on the microcontroller that receive this measurement. The conditioned solar voltage, with peak level of +5V, is implemented using potential divider method through series of high tolerance resistors. This conditioned solar voltage would be used together with the solar current measurement in the MPPT algorithm that is embedded in the microcontroller. The solar current would be measured using a Current Sensing IC (MAX471) that has been proven reliable by Nasa [51].

The MAX471 featured in Figure 4.7 has an internal 35m Ω current-sense resistors and measures currents up to $\pm 3A$. This device operates from 3V to 36V and draw less than 100 μA over temperature fits into the operating conditions of the solar voltage. This IC is favored in other space missions because of its wide operating temperature from $-40^{\circ}C$ to $+85^{\circ}C$, which is beyond the normal temperature within the satellite. The temperature of the power control unit is found to vary from $-20^{\circ}C$ to $+55^{\circ}C$ [1].

The current-gain ratio has been preset to 500 $\mu A/A$ so that an output resistor (R_{OUT1}) of 2k Ω yields 1V/A for a full-scale value of +3V at $\pm 3A$.

$$R_{OUT1} = \frac{V_{out}}{(I_{load} * 500\mu A / A)} \quad \text{Eq 4.17}$$

Iload is defined as the maximum current to be measured and Vout is the preferred voltage level to be measured at the point of maximum current. In the author’s research, it is designed to measure a maximum Iload of 2.5A (where the maximum solar current is 2.29A during maximum sun insolation based on Table 4.4). Vout of +5V is designed based on the acceptable range of +5.05V input voltage at the analog ports of the microcontroller. ROUT1 is calculated to be 4kΩ. However, 3.9kΩ is the single piece resistor closest available value to 4kΩ. Hence, ROUT1 of 3.9kΩ is used with a slight modification in the current gain. Capacitor C3 (1uF) is added to reduce the noise at OUT (Pin 8), which is identified as Iread (in Figure 4.7) and directly connected to the analog pin of the microcontroller.

At the RS- terminals of the IC, two high tolerance (1%) resistors are used as voltage divider to scale down the maximum solar voltage to +5.05V, as specified in the specification of 80C515 IC. The highest solar voltage is 14.5V during the lowest temperature (Table 4.2). A maximum voltage of +20V (at the RS- terminals) is used to size R1 and R2.

$$\frac{5V}{15V} = \frac{R_1}{(R_1 + R_2)}$$

Eq 4.18

With Equation 4.18, R1 and R2 are designed with 1kΩ and 3kΩ, respectively. Large capacitors C1 and C2 decouple the load and thereby reduce the current transients, which is quite significant in switching power supply. The RS- terminals are connected to the input stage of Buck type Switch Mode Power Supply.

Figure 4.7 shows the schematic design of this sub module.

Figure 4.7. Schematic Design of Voltage & Current Sensor

Table 4.9 shows the current measurement results using MAX471 has error below 0.5%. The corrected solar current I_2 is calculated by multiplying I_1 with the ‘Multiplication Factor’. Based on the specification of MAX471, the maximum error in measuring 0.3A to 3.0A is below 3%; hence the IC performance is within its specification.

Table 4.9. Solar current measurement using MAX471

Solar Current I_1 (A)	Solar Current (measured)	Multiplication Factor	Solar Current I_2 (corrected)	Error $((I_2-I_1) / I_1$ $*100\%)$
1.96	3.79	1.93	1.964	0.19%
1.69	3.27	1.93	1.694	0.25
1.05	2.03	1.93	1.052	0.17
0.55	1.06	1.93	0.549	0.14
1.96	3.79	1.93	1.964	0.19

The maximum acceptable error in measuring the solar voltage is estimated using Equation 4.19 This error amounts to 2% since each resistor’s tolerance is 1% each. The solar voltage measurements show maximum error of 1.9% in Table 4.10, which is within the acceptable range. The corrected solar voltage V_2 is calculated by multiplying V_1 with the ‘Multiplication Factor’.

Percentage in Voltage Error (max)= Tolerance of R1 + Tolerance of R2 Eq 4.19

Table 4.10. Solar voltage measurement using resistors divider

Solar Voltage V_1 (V)	Solar Voltage (measured)	Multiplication Factor	Solar Voltage V_2 (corrected)	Error $((V_2-V_1) /$ $V_1 *100\%)$
8.31	1.93	4.23	8.16	1.90
10.90	2.58	4.23	10.91	0.08
13.90	3.27	4.23	13.83	0.49
14.20	3.39	4.23	14.34	0.97
14.50	3.48	4.23	14.72	1.50

(b) Design of Digital-To-Analog Converter (DAC)

Based on Figure 4.1, the DAC IC converts the output digital signal ($V_{REF(8 \text{ DIGITAL LINES})}$) to analog control signal ($V_{REF(Analog)}$). The $V_{REF(Analog)}$ is used as control signal in adjusting the duty cycle of the Switch Mode Power Supply. This is implemented by connecting the $V_{REF(Analog)}$ to error amplifier 1 of the Pulse Width Modulator IC (TL494). The error amplifier directly determines the ON time of the SMPS power MOSFET.

AD 7302 is a dual (DAC-A and DAC-B), 8-bit voltage out DAC that operates from a single +2.7V to +5.5V supply and consumes about 15.5mW at +5.5V. Its on-chip precision output buffers allow the DAC outputs voltage to swing rail to rail. Its wide operating temperature from -40°C to $+105^{\circ}\text{C}$ allowed it to be used in LEO satellite. The Reference Voltage used in converting the digital input bits to an analog level can be either an internal reference derived from the power supply input (VDD) or an external reference applied at the REFIN pin.

$$V_{OUTA} = 2 * V_{REF} * N / 256 \tag{Eq 4.20}$$

In Equation 4.20, N is the decimal equivalent of the 8-bit code loaded on the DAC register that ranges from 0 to 255. V_{OUTA} is the analog output equivalent (from DAC-A) of the 8-bit code. V_{REF} here is $VDD/2$. Without compromising the performance of the DAC operation, the internal reference is selected for simplicity and it reduces the need for extra components. The Load DAC Logic Input (LDAC) is a control pin used to update the content of their DC registers. When this logic input is taken low, both DAC outputs are simultaneously updated with the new values of the 8 bit digital input. The LDAC pin is permanently tied to zero voltage in the author’s research; hence the DAC is updated on the rising edge of Write Input (WR), which is controlled by the microcontroller.

Figure 4.8. Schematic Design of AD7302

Table 4.11 shows the measurement results based on the schematic design in Figure 4.8 above. With an average error of 1%, the performance of the DAC circuitry is acceptable.

Table 4.11 Measurement results using AD7302

Input V ₁	Voltage, V ₂	Measured Voltage, V ₂	Percentage Error, abs (V ₁ - V ₂)/ V ₁ *100%
0.98		0.97	1.02
1.96		1.96	0.00
2.94		2.96	0.68
3.92		3.96	1.02
4.90		4.94	0.82

(c) Design Of Buck Type Switch Mode Power Supply

Here, the first segment describes the design of Buck Voltage converter, followed by the design of the Pulse Width Modulator circuitry. The Buck Voltage converter and the Pulse Width Modulator circuitry formed the Switch Mode Power Supply, as indicated in Figure 4.1. The most common and simplest step-down power stage topology is the Buck topology. The Buck topology is chosen for this research because the solar output voltage is always higher than common (bus) voltage within a micro-satellite. It is a non-isolated, that is, the input and output voltages share a common ground.

Figure 4.9 Simplified schematic of Buck topology [47]

Figure 4.9 shows the basic component of a Buck regulator. The power switch, Q_1 is an n-channel MOSFET. However, a p-channel MOSFET is preferred in space environment because the radiation impact on its gate threshold voltage is negligible. The diode, CR_1 is usually called the catch diode, or freewheeling diode. The inductor, L and capacitor, C constitute to the output filter. The capacitor equivalent series resistance (ESR), R_C and inductor DC resistance, R_L are also shown. The resistor, R represents the load. During a normal operation, Q_1 repetitively switches ON and OFF with the ON and OFF duration governed by a control circuit. This switching causes a train of pulses at the cathode of CR_1 that is filtered by the L/C output filter to produce a DC output voltage, V_0 .

Figure 4.10 Power MOSFET Dual Operational States in Buck Regulator [47]

In continuous conduction mode, the Buck power stage assumes two states per switching cycle. The ON state is when Q_1 is ON and CR1 is OFF. The OFF state is when Q_1 is OFF and CR1 is ON. The equivalent circuits in Figure 4.10 show these two states that refer to the condition of the power switch. The duration of the ON state is $D \cdot T_s = T_{ON}$ where D is the duty cycle, set by the control circuit. The duty cycle is defined as the ratio of the switch ON time to the complete switching duration T_s . The duration of the OFF state is called T_{OFF} . Since there are only two states in one switching cycle, T_{OFF} is equal to $(1-D) \cdot T_s$ [47].

The load current must be identified in order to design the output inductor of the Buck Voltage converter. The following segment describes the dynamic of the load. A resistive load is connected at the output stage of this SMPS. In the author's research, this resistive load is chosen so to match the output impedance of the Solar Array Simulator under all preset solar conditions. The Buck Regulator can be seen as a black box that performs impedance matching using Equation 4.21 [48].

$$R_{OPT} = n \cdot R_{MP} \cdot [1/D]^2 \quad \text{Eq 4.21}$$

$$R_{MP} = V_{MP} / I_{MP} \quad \text{Eq 4.22}$$

- R_{OPT} Optimum load resistance
 R_{MP} Impedance of solar array at Peak Power Point
 n Efficiency of SMPS (0.85)
 D Maximum duty cycle of power MOSFET of SMPS (0.9)

With Equation 4.21 and 4.22, the various R_{OPT} for different solar condition are listed in Table 4.12.

Table 4.12 Dynamics of R_{OPT} at different solar condition

	Aspect angle (degree)	I_{MP} (A)	V_{MP} (V)	R_{MP} (Ω)	R_{OPT} (Ω)	V_{LOAD} (V)	I_{LOAD} (A)	Duty Cycle
Low Insolation	45	1.59	7.9	4.97	3.42	4.85	2.20	0.61
Medium Insolation	30	1.95	8.0	4.10	2.82	5.40	2.46	0.68
Maximum Insolation	15	2.15	8.0	3.72	2.56	5.67	2.58	0.71
	Temperature ($^{\circ}$ C)	I_{MP} (A)	V_{MP} (V)	R_{MP} (Ω)	R_{OPT} (Ω)	V_{LOAD} (V)	I_{LOAD} (A)	Duty Cycle
Maximum Temperature	75	2.22	8.0	3.60	2.48	5.76	2.62	0.72
Medium Temperature	0	2.05	10.7	5.22	3.59	6.40	2.91	0.60
Low Temperature	-75	1.88	13.4	7.13	4.91	6.86	3.12	0.51

The lowest R_{OPT} (2.48 Ω) determines the maximum load resistance to be used under all solar conditions and ensures the solar array to be operating at its peak power point. When 2.48 Ω is used, the PWM would adjust its duty cycle based on Equation 4.21 to shift the solar operating point to its peak under all kind of solar conditions. The nearest value of wire wound resistor available is 2.2 Ω and is used in the actual hardware implementation.

Equation 4.23 to Equation 4.25 is used to calculate the V_{LOAD} , R_{LOAD} and Duty Cycle in Table 4.12. The $R_{OPT(MIN)}$ used here is 2.2 Ω . The Duty Cycle here refers to duty cycle of the power MOSFET of the SMPS. Equation 4.23 is based on energy conservation that the solar power equals to load power and power losses.

$$V_{LOAD} = \sqrt{n * V_{MP} * I_{MP} * R_{OPT(MIN)}} \tag{Eq 4.23}$$

$$I_{LOAD} = V_{LOAD} / R_{OPT(MIN)} \tag{Eq 4.24}$$

$$DutyCycle = V_{LOAD} / V_{MP} \tag{Eq 4.25}$$

Equations 4.23 to Equation 4.25 summarize the key equations in designing of a Buck Regulator [48]. In a typical micro-satellite, the SMPS switching frequency is above 100kHz to ensure all Buck components to be of small volume and mass. Hence, 100kHz is used as the oscillation frequency of the SMPS design, which is indicated as ‘OscFreq’ in Equation 4.26. From Table 4.12, DutyCycle_{MAX} equals to 0.72. With this, the calculated T_{ON(MAX)} is 7.2 us based on Equation 4.26.

$$T_{ON(MAX)} = \text{DutyCycle}_{MAX} / \text{OscFreq} \quad \text{Eq 4.26}$$

$$\begin{aligned} \Delta I_{MIN} &= 2 * 1\% * I_{LOAD(MAX)} \\ &= 2 * 0.01 * 3.12A \\ &= 0.62A \end{aligned} \quad \text{Eq 4.27}$$

$$\begin{aligned} L_{MIN} &\geq \frac{(V_{MP} - V_{LOAD}) * T_{ON(MAX)}}{\Delta I_{MIN}} \\ &\geq (13.4 - 6.86) * 7.2e^{-6} / 0.62 \\ &\geq 75\mu H \end{aligned} \quad \text{Eq 4.28}$$

Designing the inductor

The inductance is chosen to be sufficiently large to ensure that the regulator operates continuously over the required range of load current. The $\Delta I_{(MIN)}$ is the minimum load ripple current, which is taken as 1% of maximum load current, I_{LOAD(MAX)} as seen in Equation 4.27. The V_{MP} and V_{LOAD} during –75°C (as shown in Table 4.2) are used to obtain the minimum inductance in Equation 4.28.

Three different types of core materials are commonly used for the inductor in a switching regulator—Bobbin cores, Powder-ironed cores and Ferrite cores. Each material type has advantages, hence a few major factors are considered in selecting the most suitable material as shown in Table 4.13.

Table 4.13 Major consideration factors for inductor core material

Core Types	Operating Frequency range [60]	Maximum Operating Temperature [60]	Flux density, H [61]	Core Cost [61]	Core Loss [61]	EMI
Bobbin	< 1 MHz	200°C	7000-15000	High	Low-Medium	Average
Powdered-iron	< 1 MHz	200°C	9000	High	High	Average
Ferrite	< 2 MHz	125°C	5000	High	Low	Good

Powder core structure gives a soft saturation characteristic that has many design benefits, including an overall smaller core size, and over current protection. It also alleviates the fringing flux difficulties, which occur if a discrete gap design is used. Toroidal powder core is suitable where EMI is concern and where the components are densely packed. Due to the nature of the toroidal geometry, the majority of the flux is conducted through the core, leaving only a small amount of leakage outside the winding [59].

Ferrite core offers the advantages of decreased EMI and low cores losses at high frequencies. For switching regulators, power ferrite materials (F, P, R, and K) are recommended because of their core loss and DC bias characteristics. By adding discrete air gaps to these ferrite shapes, the cores can be used efficiently while avoiding saturation.

Bobbin core gives the smallest core size due to its high flux density among the other material. The bobbin inductors are suitable in continuous current mode of a switching power supply because of its low EMI [59].

From the Table 4.13, different core materials are compared and selected for satellite application. In the author’s research, the inductor is chosen mainly to have low EMI that does not interfere the critical section of the power electronics such as the inputs of the PWM error amplifiers or other sub-systems. Ferrite core is a good candidate among all the materials. However, it requires deeper knowledge and skill to assemble the coils. So, a

bobbin core is adopted because it is easily available, comes with short lead and design time. To mitigate the EMI issue, a toroidal bobbin inductor (1400 series) from C&D Technologies is used. This inductor claims to exhibit low EMI due to shape of the core that the magnetic path flows only within the inductor and hence stray field is virtually eliminated [62]. However, this inductor would be replaced if its EMI disturbs critical section of the power electronics.

Designing the filter capacitor

The ripple voltage (V_{RIPPLE}) at the output of the Buck Regulator is usually within 1% of the load voltage (V_{LOAD}) as seen in Equation 4.29. The ripple voltage is reduced by using a filtering capacitor, C that is calculated using Equation 4.30. The capacitor that is chosen from the manufacturer must have small ESR, as shown in Equation 4.31. In normal practice, the capacitor is chosen to have at least 10 times of its required capacitance with at least double or triple of the voltage rating [48]. Hence, a 100 μ F, 35V rated capacitor with ESR of 48m Ω is used. This capacitor has a maximum permissible ripple current of 1.65A, which exceeds the requirement of 0.62A.

$$\begin{aligned} V_{\text{RIPPLE}} &= 1\% * V_{\text{LOAD}} \\ &= 0.01 * 6.86V \\ &= 68.6mV \end{aligned} \quad \text{Eq 4.29}$$

$$\begin{aligned} C &\geq \frac{\Delta I_{\text{MIN}}}{8 * \text{OscFreq} * V_{\text{RIPPLE}}} \\ &\geq 0.62 / (8 * 100e^3 * 0.0686) \\ &\geq 11.3\mu F \end{aligned} \quad \text{Eq 4.30}$$

$$\begin{aligned} \text{ESR}(C) &\leq \frac{V_{\text{RIPPLE}}}{\Delta I_{\text{MIN}}} \\ &\leq 68.6mV / 0.62A \\ &\leq 111m\Omega \end{aligned} \quad \text{Eq 4.31}$$

Designing freewheeling diode

The freewheeling diode conducts when the power switch turns off and provides a path for the inductor current. Important criteria for selecting the rectifier include: fast switching, breakdown voltage, current rating, low-forward voltage drop to minimize power dissipation, and appropriate packaging. Unless the application justifies the expense and complexity of a synchronous rectifier (which is not the case in the author’s project), the best solution for low-voltage outputs is usually an Schottky rectifier. The breakdown voltage is chosen to be at least 3 times of the maximum input voltage (~13.4V based on Table 4.2) in consideration of transients and spikes. The current rating should be at least two times the maximum power stage output current [47] that is 3.12A (with reference to Table 4.12).

Table 4.14 shows 2 potential ultra-fast switching diodes (approved by NASA [51]) that meet the requirement of the author’s research. The 1N5814 is found to be better than 1N3891 due to its low forward voltage drop and short recovery time, which is proportional to the junction capacitance. However, the procurement of both diodes would take 2-3 months. Hence, other diodes with shorter lead-time are considered, even without the approval of NASA. The replacement diode is chosen to have close electrical parameters to 1N5814, in order to minimize modifications on the circuitry design (when the 1N5814 is being used).

Table 4.14 Ultra-fast switching diodes from NASA

Part Number	Forward Voltage Drop, V	Junction Capacitance, nF	Current rating, A	Breakdown Voltage, V
1N5814 [54]	0.86	7	20	100
1N3891[55]	1.50	40	12	200

Two defining criteria in choosing the replacement diode are the forward voltage drop and junction capacitance. The forward voltage drop defines the main power loss within the diode, whereas the junction capacitance determines the diode switching duration. These 2 criteria are closely matched by BYV79E, hence it was chosen to replace 1N5814.

Part Number	Forward Voltage Drop, V	Junction Capacitance, nF	Current rating, A	Breakdown Voltage, Vs
BYV79E [58]	0.9	3.0	14	100

Designing the power switch

The choice of the power switch depends on ability to operate under high switching frequency and simple driving circuit. In the author’s research, MOSFET switch is chosen over BJT switch due to its switching speed up to 300 kHz. Furthermore, the MOSFET switch especially the P-type can be driven simply by using a single IC. By having only a single component in the driving circuitry, this can minimize risk of component failure that occurs in the more complicated driving circuitry for BJT switches. An N-type MOSFET is less preferred due to its slightly more complicated driving circuitry and its gate-threshold voltage. Under the radiation environment, its gate-threshold voltage would gradually become more positive. Its increase in the gate-threshold voltage would reach a point that the driver could not turn ON the MOSFET. However, this scenario does not occur in a P-type switch. Hence, a P-type MOSFET, IRF9540 is selected from the list of components approved by the NASA [51]. Based on the list, a few potential P-type channel MOSFET are reviewed and compared, as shown in Table 4.15. Due to the short Turn-OFF time and low $R_{DS(ON)}$, IRF 9540 is chosen.

Table 4.15 Compares these MOSFETs in terms of the key parameters.

Part Number	$R_{DS(ON)}$, Ω	Turn-ON time (max), ns	Turn-OFF time (max), ns	Current rating, A
IRF 9540 [49]	0.2	120	140	19
IRF M9140 [52]	0.2	120	150	18
IRF M9240 [53]	0.51	120	150	11

Designing the driving circuitry for IRF 9540 switch

Unlike bipolar transistors, power MOSFETs have a considerable gate capacitance that must be charged beyond the threshold voltage $V_{GS(TH)}$, to achieve turn-on. The gate driver must provide a high enough output current to charge the equivalent gate

capacitance, C_{EI} , within the time required by the system design. The curve of Figure 4.11 is typical of those supplied by MOSFET manufacturers. Notice that in order to achieve strong turn-on, a V_{GS} well above that required to charge C_{EI} (and well above $V_{GS(TH)}$) is required. The equivalent gate capacitance is determined by dividing a given V_{GS} into the corresponding total gate charge. The required gate drive current (for a transition within a specified time) is determined by dividing the total gate charge by the desired transition time. The following Equation 4.32 to Equation 4.34 that are derived from Reference 56 and Reference 57, are used to select the appropriate MOSFET driver.

Figure 4.11. Gate Charge Characteristics [56]

$$Q_G = Q_{GS} + Q_{GD} + Q_{OD} \tag{Eq 4.32}$$

where:

Q_G is the total gate charge

Q_{GS} is the gate-to-source charge

Q_{GD} is the gate-to-drain Miller charge

Q_{OD} is the “overdrive charge” after charging the Miller capacitance

In equation form:

$$Q_G = C_{EI} \cdot V_{GS} \tag{Eq 4.33}$$

$$I_G = Q_G / T_{(TRANSITION)} \tag{Eq 4.34}$$

where:

Q_G is the total gate charge, as defined above

C_{EI} is the equivalent gate capacitance

V_{GS} is the gate-to-source voltage

I_G is the gate current required to turn the MOSFET on in time period $T_{(TRANSITION)}$
 $T_{(TRANSITION)}$ is the desired transition time

From the IRF9540 manufacturer’s specifications, maximum Q_G is 65nC at V_{GS} of 10V. The desired $T_{(TRANSITION)}$ is 50 ns. With Equation 4.34, the required I_G is 1.3A and the appropriate MOSFET driver is TC4427 [56]. The TC4427 can easily switch 1000 pF gate capacitances in under 30 ns, and provide low enough impedances in both the ON and OFF states to ensure the MOSFET’s intended state will not be affected, even by large transients. It will not latch up under any conditions within their power and voltage ratings.

The following Figure 4.12 shows the schematic diagram of the Buck Regulator and its driver circuitry.

Figure 4.12 Schematic diagram of Buck Regulator & driver circuitry

Figure 4.13. Efficiency of Buck Regulator under different input power levels

Figure 4.13 captures the efficiency of the Buck Regulator when the solar array simulator is operating under different settings. Three settings are used, namely when the solar array is at Low Temperature (-75°C), Maximum Temperature ($+75^{\circ}\text{C}$) and Maximum Insolation ($\beta=15^{\circ}$) as shown by the dark blue, red and light blue curves, respectively. When the Buck Voltage converter is operated near its full load, the efficiency is in the range of 90%-95%.

4.2.4 Setup of 80C515C Microcontroller

This segment explains the C compiler and the Analog-To-Digital operation of the microcontroller. The 80C515C is an 8-bit microcontroller that allows a maximum clock rate of 10MHz. It is equipped with 64kByte on-chip Read-Only-Memory (ROM) and 256Byte on-chip Random-Access-Memory (RAM). The C Compiler from Keil development, which is provided together in the microcontroller developmental kit, is used in the author’s research.

Analog-To-Digital Operation

Figure 4.14 shows the block diagram of the 80C515 microcontroller [50]. One of its 6 Input/Output ports is the analog input port (Port 6), which is used to read in external analog signals. Port 6 in this block diagram is used to read in 2 independent analog signals in the author’s research; the solar voltage (V_s) and solar current (I_s).

Figure 4.14 Block Diagram of 80C515 microcontroller

Port 6 contains 8 multiplexed input channels with 10 bits resolution that are identified as P6.0 to P6.7. These input channels are selected by programming the control register of the microcontroller, ADCON1 to the integer of the channel number. For instance, the command $ADCON1 = 1$ and $ADCON1 = 2$ select and measure the analog signal from

Port 6.1 and Port 6.2, respectively (Port 1 and Port 2 are also used in the author's research). To initiate the analog-to-digital conversion, any value is written to the control register of the microcontroller, ADDATL. The register ADDATH and ADDATL hold the 10 bits conversion result in left justified format. The most significant bit (MSB) result is bit 7th of ADDATH. The least significant bit (LSB) is bit 6th of ADDATL. To get a 10-bit conversion result, both ADDATH and ADDATL register must be read. Figure 4.15 below shows the bit format of ADDATH and ADDATL.

Figure 4.15 Control Register of microcontroller

The content of ADDATH have to be bit-shifted by 2 positions to the left, while the content of ADDATL have to be bit-shifted by 6 positions to the right. After bit-shifting, these 2 registers are bit-added to form the 10 bit value by using a OR-ing operation as shown in Equation 4.35.

$$X = \text{ADDATH} \ll 2 \mid \text{ADDATL} \gg 6; \tag{Eq 4.35}$$

Subsequently, 'x' (Equation 4.35) that is in 10 bit binary format is converted to analog value by dividing with 2^{10} using Equation 4.36 below. V_{AREF} in the default configuration is tied to 5V.

$$Y = X * V_{\text{AREF}} / 2^{10}; \tag{Eq 4.36}$$

All the commands mentioned here are included in the C code that is embedded into the microcontroller. Figure 4.16 shows the codes that perform the analog-to-digital conversion.

```
ADCON1 |= 1;      //select analog input pins
        ADDATL = 1;    //start conversion process
        while (BSY);    //wait command

Vsolar=ADDATH<<2 | ADDATL>>6;
```

Figure 4.16 C-Code for analog-to-digital conversion

Figure 4.17. Photo of experimental setup for MPPT testing

Figure 4.18. Photo of experimental setup for IV curve test

Both Figure 4.17 and Figure 4.18 show the physical instrument and circuitry that were built during this research.

4.3 Chapter Summary

All hardware circuit designs of the SMPS (with MPPT capability) is successfully developed and tested to be within the acceptable performance. With all the required test equipment configured as shown in Figure 4.1, the final MPPT and LMT test could now be performed. The subsequent chapter details the test of the various MPPT schemes.

CHAPTER FIVE

EXPERIMENTAL RESULTS

5.1 Introduction

This chapter presents the solar IV profiles as simulated by the HP 4350B. These solar profiles under different temperature and insolation conditions established the solar peak power points, which later would be referenced in determining the tracking efficiency of each MPPT methods. The experimental results of each MPPT systems are presented and compared here. The 2 critical parameters in each MPPT algorithms (unit threshold voltage, V_T and sampling size) are explained here.

5.2 Solar IV Curves

This section presents the results from the Solar Array Simulator (HP 4350B) that is used to simulate the solar IV profiles under varying temperature and insolation levels. The Solar Array Simulator (HP 4350B), being the power source is connected to an Electronic Load (HP 6050) as shown in Figure 4.5. Section 4.2.2 in Chapter 4 explains the setup of the Solar Array Simulator (HP 4350B) and Electronic Load (HP 6050) in details. These settings such as V_{MP} , I_{MP} , V_{OC} and I_{SC} are coded using HP VEE language (Refer to Appendix A for program codes).

5.2.1 Temperature Variation

In order to simulate temperature variation in space, the HP 4350B is programmed according to the settings shown in Table 4.2.

Figure 5.1, Figure 5.2 and Figure 5.3 show the solar power plotted against solar voltage (PV) when the solar array's ambient temperature is at $-75\text{ }^{\circ}\text{C}$, $0\text{ }^{\circ}\text{C}$ and $+75\text{ }^{\circ}\text{C}$, respectively. The non-linearity characteristic of the solar array is observed from these figures. The solar power increases as the solar voltage rises until it reaches the peak power point. From the peak power point onwards, the solar power begins to decrease as the solar voltage continues to increase. With an MPPT system, the user is always operating the solar array at this peak power point, drawing highest solar power from the array.

Figure 5.1. PV plot at -75 °C

Figure 5.2. PV plot at 0 °C

Figure 5.3. PV plot at +75 °C

The main parameters, V_{MP} and P_{MP} were recorded as shown in Table 5.1. Each temperature setting was repeated 3 cycles and an averaged reading was obtained.

Table 5.1. IV profiles of solar array under temperature variation

Temperature	-75 Celsius		0 Celsius		+75 Celsius	
Cycle	V_{MP}	P_{MP}	V_{MP}	P_{MP}	V_{MP}	P_{MP}
1	13.23	25.45	10.64	21.97	8.09	17.81
2	13.23	25.48	10.60	21.97	8.09	17.81
3	13.23	25.45	10.62	22.01	8.09	17.81
Average	13.23	25.46	10.62	21.98	8.09	17.81

5.2.2 Insolation Variation

In order to simulate insolation variation in space, the HP 4350B is programmed according to the settings shown in Table 4.4. Figure 5.4, Figure 5.5 and Figure 5.6 show the solar power plotted against solar voltage (PV) when the solar array’s insolation angle is at 15°, 30° and 45° inclination, respectively.

Figure 5.4. PV plot at 15° inclination

Figure 5.5. PV plot at 30° inclination

Figure 5.6. PV plot at 45° inclination

The main parameters, V_{MP} and P_{MP} were recorded as shown in Table 5.2. Each temperature setting was repeated 3 cycles and an averaged reading is obtained.

Table 5.2. IV profiles of solar array under insolation variation

Insolation Angle	15 degree		30 degree		45 degree	
Cycle	V _{MP}	P _{MP}	V _{MP}	P _{MP}	V _{MP}	P _{MP}
1	8.07	17.24	8.05	15.62	8.00	12.60
2	8.07	17.24	8.05	15.62	8.00	12.60
3	8.07	17.24	8.05	15.62	8.00	12.58
Average	8.07	17.24	8.05	15.62	8.00	12.59

From Table 4.7 and Table 4.8, it is observed that the highest percentage error in power is 1.41% under both temperature and aspect angle variations. Since the measured error of 1.41% is below the maximum limit of 5%, it is concluded that the performance of the Solar Array Simulator is acceptable.

5.2.3 Performance Indicators

Tracking efficiency, n is used to gauge the effectiveness of the MPPT methods. It indicates the ratio of power that is extracted from the solar array to the maximum power available from the solar array, which is equivalent to solar power at peak power point. Equation 5.1 shows the calculation of the tracking efficiency, n .

$$\text{Tracking Efficiency, } n = \frac{\text{Extracted Solar Power}}{\text{Solar Power At Peak Power Point}} \% \qquad \text{Eq 5.1 [35]}$$

Beside factor n , the normalized voltage is also used to measure the tracking accuracy. The Normalized Solar Voltage is defined as below. Equation 5.2 shows the calculation of the Normalized Solar Voltage.

$$\text{Normalized Solar Voltage} = \frac{\text{Operating Solar Voltage}}{\text{Solar Voltage At Peak Power Point}} V/V \qquad \text{Eq 5.2 [21]}$$

Hence, the results in Table 5.1 and Table 5.2 (averaged V_{MP} and P_{MP}) are used as reference points for the subsequent calculations of tracking efficiency, n and Normalized

Solar Voltage in Section 5.4, Section 5.5 and Section 5.6. The Solar Power At Peak Power Point and Solar Voltage At Peak Power Point for each temperature and insolation levels are summarized in Table 5.3 below.

Table 5.3. Solar Power and Solar Voltage Levels (At Peak Power Point)

Insolation Angle (°)	Solar Voltage At Peak Power Point, V_{MP} (V)	Solar Power At Peak Power Point, P_{MP} (W)
15 degree	8.07	17.24
30 degree	8.05	15.62
45 degree	8.00	12.59
Temperature (°C)	Solar Voltage At Peak Power Point, V_{MP} (V)	Solar Power At Peak Power Point, P_{MP} (W)
-75	13.23	25.46
0	10.62	21.98
+75	8.09	17.81

5.3 Variables for MPPT Algorithm

A fast tracking MPPT system is preferred due to its ability to shift the solar voltage to the peak power point in short time. The tracking speed is determined by the unit change, known as Unit threshold voltage, V_T that is set in the MPPT algorithm. In the MPPT algorithms, the sampling size is another important parameter that affects the tracking efficiency. The unit change and sampling size are further elaborated below.

5.3.1 Unit threshold voltage, V_T

The tracking mechanism of the MPPT system is done by changing the duty cycle of the buck regulator, as described in Table 4.12. The unit change of duty cycle would determine the MPPT tracking speed. As the unit change of duty cycle increases, the MPPT system requires shorter duration in shifting the solar voltage to the peak power voltage point. Hence, a large unit change of duty cycle is favored. However, a large unit change of duty cycle may compromise the tracking efficiency. The duty cycle is directly controlled and proportional to the $V_{REF(DIGITAL)}$ described in Figure 4.1. The $V_{REF(DIGITAL)}$ is an 8-bit signal and its smallest unit change is 1-bit change in the Least Significant Bit. This 1-bit change is equivalent to a magnitude of $1/255$. Figure 5.7 compares 1-unit ($1/255$) and 3-unit ($3/255$) change in tracking the peak power. The 3-unit reached the peak power in 2 steps (~1.5 sec), while the 1-unit required 9 steps (~12 sec).

Figure 5.7. Impact of Unit Threshold Voltage V_T on MPPT tracking speed

As for tracking efficiency, the 1-unit and 3-unit's performances are 99.98% (measured to 2 decimal places). Hence, the 3-unit is more suitable to be used than the 1-unit because of shorter tracking time without compromising in tracking efficiency.

Since larger unit change means shorter tracking time, the author proceed to evaluate the tracking efficiency of the 5-unit (5/255) and 7-unit (7/255) change. During peak power output of 17.78W from the solar array, the tracking efficiencies are 99.29% (3-unit), 95.05% (5-unit) and 94.34% (7-unit). The author chose the 3-unit change to ensure the MPPT system to reach tracking efficiency above 99.0%. All subsequent tests would be based on the 3-unit change. This parameter is identified as V_T in all the MPPT algorithms.

This V_T (known as $V_{REF (ANALOG)}$) is then compared with a constant frequency ramp (100 kHz) to generate the gate drive signal.

5.3.2 Sampling size

It is favored to have large sample size because this translates to better tracking efficiency. However, a small sample size means shorter sampling time, hence shorter time to reach the solar peak power point. The system tracking efficiency would be compromised if they were under-sampled, whereas longer tracking time is needed in an over-sampled case. Here, different sample sizes are evaluated to find the optimum sample size. With reference to Figure 4.7, the Voltage & Current Sensors send both the solar voltage, V_S and solar current, I_S to be sampled by the micro-controller.

Figure 5.8. Impact of Sample Sizes on MPPT Tracking Efficiency

Table 5.4. Impact of Sample Sizes on MPPT Tracking Efficiency

Sample Size	Tracking Efficiency (%) at Steady State	Tracking time taken (sec)
500	68.16	Failed tracking
600	99.96	10.7
700	99.96	12.0
800	99.96	13.0

Figure 5.8 compares sample size of 500, 600, 700 and 800. In the 500 samples setting, the MPPT system did not reach the solar peak power of 25.44W. Under-sampling occurred and it only reached 17.34W (tracking efficiency 68.16%) at steady state. Based on Table 5.4, the sample sizes of 600, 700 and 800 have same tracking efficiency of 99.96%. Without compromising tracking efficiency, the optimum sample size is chosen to be 600 because its shortest tracking time compared to the 700 and 800 sample sizes. All subsequent tests would be based on the 3-unit change. This parameter is identified as ‘max_poll_cycle’ in all the MPPT algorithms.

Based on the 2 critical variables, V_T and Sampling size that have been determined, the next section would examine the operation of the 3 main MPPT methods, V_{OC} , Perturbation & Observation, Incremental Conductance and Global MPPT.

5.4 MPPT- V_{OC} Method

The V_{OC} method is tested under the varying conditions of both temperature and insolation level based on Table 4.2 and Table 4.4. For each setting of temperature and insolation level, the algorithm of V_{OC} is repeated 3 cycles to obtain accurate readings of the ‘Extracted Solar Power’ and ‘Operating Solar Voltage’. The complete program code of the V_{OC} method (at $-75\text{ }^{\circ}\text{C}$) is included in Appendix B and explained in Section 3.3.1.

5.4.1 Performance Indicators – Temperature Variation

Figure 5.9(a)-(c) show the Extracted Solar Power in terms of tracking efficiency (based on Equation 5.1) during steady state operation. Figure 5.10(a)-(c) show the Normalized Solar Voltage (based on Equation 5.2) during steady state operation. For clearer graph illustration, only 1 cycle out of 3 is shown in Figure 5.9(a)-(c) and Figure 5.10(a)-(c).

Figure 5.9(a) V_{OC} method-Tracking Efficiency at $-75\text{ }^{\circ}\text{C}$

Figure 5.9(b) V_{OC} method-Tracking Efficiency at $0\text{ }^{\circ}\text{C}$

Figure 5.9(c) V_{OC} method-Tracking Efficiency at $+75\text{ }^{\circ}\text{C}$

Figure 5.10(a) V_{OC} method- Normalized Solar Voltage at -75°C

Figure 5.10(b) V_{OC} method- Normalized Solar Voltage at 0°C

Figure 5.10(c) V_{OC} method- Normalized Solar Voltage at $+75^{\circ}\text{C}$

Figure 5.9(a)-(c) show that spikes reach about 115% for very short time. These spikes occur due to time lag between the solar voltage and solar current. It is observed that the tracking efficiency continues to fluctuate to 0%. This is an inherent characteristic of the V_{OC} method at steady state, as described in Section 3.3.1. In order to sample the open circuit voltage of the solar array, the solar array has to be disconnected from the load, which effectively prevent any solar power going into the load. Hence, the Extracted Solar Power is zero and its tracking efficiency is 0%. After the sampling, the solar array is connected back to the load hence it is observed that the tracking efficiency increases to above 80%. Even after it is being reconnected, this V_{OC} MPPT method still continues to fluctuate in small variation between 82% and 99%, as can be seen from the tracking efficiency in Figure 5.9(a)-(c). This toggling occurs around the point of the solar array that is perceived as the peak power point.

When the solar array is connected to the load, the normalized solar voltage is below unity, as seen in Figure 5.10(a)-(c). Upon the disconnection of the load and solar array, the

normalized solar voltage exceeds unity and varies in the range of 1.10-1.16. The solar array open circuit voltage, which is measured upon disconnection, is always larger than the solar voltage at peak power point. With reference to Equation 5.2, by dividing a larger number with a small number would surely results with a figure exceeding unity.

Table 5.5 and Table 5.6 summarize the measurements of the Tracking Efficiency and Normalized Solar Voltage for all the 3 cycles. Table 5.5 summarizes the tracking efficiency of the V_{OC} MPPT method. The tracking efficiency increases from 84.91% to 89.00% as the temperature rises from -75°C to $+75^{\circ}\text{C}$. Table 5.6 shows the Normalized Solar Voltage by using the V_{OC} MPPT method. The Normalized Solar Voltage measurements do not reach unity, hence it clearly shows that the peak power point of the solar array does not always equal to $0.78 \cdot V_{OC}$ as observed in Ref [35]. The true relationship between V_{MP} and V_{OC} is dependent on the type of solar cells used.

Table 5.5. Tracking Efficiency of V_{OC} MPPT method (Temperature Variation)

Temperature (degree Celsius)	Extracted Solar Power (W)			Average Extracted Solar Power (W)	Tracking Efficiency (%)
	Reading 1	Reading 2	Reading 3		
-75	21.72	21.63	21.52	21.62	84.92
0	18.63	19.02	18.96	18.87	85.84
+75	15.81	15.74	16.00	15.85	89.00

Table 5.6. Normalized Solar Voltage of V_{OC} MPPT method (Temperature Variation)

Temperature (degree Celsius)	Operating Solar Voltage (V)			Average Operating Solar Voltage (V)	Normalized Solar Voltage
	Reading 1	Reading 2	Reading 3		
-75	11.97	11.97	11.95	11.96	0.90
0	9.67	9.64	9.63	9.65	0.91
+75	7.79	7.81	7.79	7.80	0.96

5.4.2 Performance Indicators – Insolation Variation

Figure 5.11(a)-(c) show the Extracted Solar Power in terms of tracking efficiency (based on Equation 5.1) during steady state operation. Figure 5.12(a)-(c) show the Normalized Solar Voltage (based on Equation 5.2) during steady state operation. For clearer graph illustration, only 1 cycle out of 3 is shown in Figure 5.11(a)-(c) and Figure 5.12(a)-(c). Table 5.7 and Table 5.8 summarize the measurements of the Tracking Efficiency and Normalized Solar Voltage for all the 3 cycles.

Figure 5.11(a). V_{OC} method- Tracking Efficiency At 15° Inclination

Figure 5.11(b). V_{OC} method- Tracking Efficiency At 30° Inclination

Figure 5.11(c). V_{OC} method- Tracking Efficiency At 45° Inclination

The spikes seen in Figure 5.11(a)-(c) are caused by time lag between the solar voltage and solar current, which is similar in Figure 5.9(a)-(c). In the same way that the tracking efficiency reduces to 0% is due to the open circuit between the solar array and load. At any external conditions whether under temperature or insolation variation, the MPPT-

V_{OC} method requires to disconnect the solar array from the load during solar voltage sampling.

Figure 5.12(a). V_{OC} method- Normalized Solar Voltage At 15° Inclination

Figure 5.12(b). V_{OC} method- Normalized Solar Voltage At 30° Inclination

Figure 5.12(c). V_{OC} method- Normalized Solar Voltage At 45° Inclination

The normalized solar voltage reaches 1.16 when the sampling process of the solar open circuit voltage that results in the solar array being disconnected from the loads. This is consistent with the observation in Figure 5.10(a)-(c). When the load is reconnected to the solar array, Figure 5.12(a)-(c) show the normalized solar voltage fluctuate around 0.87-0.97 and not around unity.

Table 5.7 summarizes the average tracking efficiency of the V_{OC} MPPT method. The tracking efficiency ranges from 89.04% to 89.46% as the insolation angle varies from 15° to 45°. Table 5.8 shows the Normalized Solar Voltage by using the V_{OC} MPPT method. The normalized solar voltages of each insolation levels are very close in magnitude. This

is due to minimal change in V_{MP} during variation in insolation level. The open circuit solar voltage and solar voltage at peak power point are almost constant as seen in Figure 2(a).

Table 5.7. Tracking Efficiency of V_{OC} MPPT method (Insolation Variation)

Insolation (degree)	Angle	Extracted Solar Power (W)			Average Extracted Solar Power (W)	Tracking Efficiency (%)
		Reading 1	Reading 2	Reading 3		
15		15.26	15.25	14.77	15.09	87.55
30		13.88	13.81	14.23	13.97	89.46
45		11.23	11.22	11.18	11.21	89.04

Table 5.8. Normalized Solar Voltage of V_{OC} MPPT method (Insolation Variation)

Insolation (degree)	Angle	Operating Solar Voltage (V)			Average Operating Solar Voltage (V)	Normalized Solar Voltage
		Reading 1	Reading 2	Reading 3		
15		7.68	7.64	7.66	7.66	0.95
30		7.67	7.68	7.63	7.66	0.95
45		7.59	7.59	7.61	7.60	0.95

The V_{OC} method that has been implemented here is operating as expected based on the description outlined in Section 3.3.1, which has been established according to past literatures.

5.5 MPPT- Perturbation & Observation Method

The Perturbation & Observation (P&O) method is tested under the varying conditions of both temperature and insolation level based on Table 4.2 and Table 4.4. For each setting of temperature and insolation level, the P&O algorithm is repeated 3 cycles to obtain accurate readings of the ‘Extracted Solar Power’ and ‘Operating Solar Voltage’. The complete program code of the P&O method (at $-75\text{ }^{\circ}\text{C}$) is included in Appendix C and explained in Section 3.3.1.

5.5.1 Performance Indicators – Temperature Variation

Figure 5.13(a)-(c) show the Extracted Solar Power in terms of tracking efficiency (based on Equation 5.1) during steady state operation. Figure 5.14(a)-(c) show the Normalized Solar Voltage (based on Equation 5.2) during steady state operation. For clearer graph illustration, only 1 cycle out of 3 is shown in Figure 5.13(a)-(c) and Figure 5.14(a)-(c). Table 5.9 and Table 5.10 summarize the measurements of the Tracking Efficiency and Normalized Solar Voltage for all the 3 cycles.

Figure 5.13(a). P&O method- Tracking Efficiency At $-75\text{ }^{\circ}\text{C}$

Figure 5.13(b). P&O method- Tracking Efficiency At $0\text{ }^{\circ}\text{C}$

Figure 5.13(c). P&O method- Tracking Efficiency At +75 °C

It is observed that the tracking efficiency continues to fluctuate during steady state as seen in Figure 5.13(a)-(c). In P&O, the perturbation process is continuous even when V_{MP} is reached. This is an inherent characteristic of the P&O method at steady state, as described in Section 3.3.1. Minimal overshooting beyond 100% tracking efficiency occur in Figure 5.13(a)-(c), which is due to the time lag between solar voltage and solar current measurement. The tracking efficiency varies from 97.59% to 98.03%, based on Table 5.9.

In Figure 5.14(a)-(c), it is observed that the P&O MPPT method tracks the V_{MP} very closely by toggling around unity under all temperature conditions. Table 5.10 clearly indicates that it tracks the V_{MP} well since the normalized solar voltage varies from 0.99 to 1.00.

Figure 5.14(a). P&O method- Normalized Solar Voltage At –75 °C

Figure 5.14(b). P&O method- Normalized Solar Voltage At 0 °C

Figure 5.14(c). P&O method- Normalized Solar Voltage At +75 °C

Table 5.9. Tracking Efficiency of P&O MPPT method (Temperature Variation)

Temperature (degree Celsius)	Extracted Solar Power (W)			Average Extracted Solar Power (W)	Tracking Efficiency (%)
	Reading 1	Reading 2	Reading 3		
-75	24.85	24.84	24.84	24.85	97.59
0	21.53	21.51	21.51	21.52	97.89
+75	17.46	17.46	17.46	17.46	98.03

Table 5.10. Normalized Solar Voltage of P&O MPPT method (Temperature Variation)

Temperature (degree Celsius)	Operating Solar Voltage (V)			Average Operating Solar Voltage (V)	Normalized Solar Voltage
	Reading 1	Reading 2	Reading 3		
-75	13.11	13.11	13.12	13.11	0.99
0	10.57	10.58	10.59	10.58	1.00
+75	8.00	8.00	8.00	8.00	0.99

5.5.2 Performance Indicators – Insolation Variation

Figure 5.15(a)-(c) show the Extracted Solar Power in terms of tracking efficiency (based on Equation 5.1) during steady state operation. Figure 5.16(a)-(c) show the Normalized Solar Voltage (based on Equation 5.2) during steady state operation. For clearer graph illustration, only 1 cycle out of 3 is shown in Figure 5.15(a)-(c) and Figure 5.16(a)-(c). Table 5.11 and Table 5.12 summarize the measurements of the Tracking Efficiency and Normalized Solar Voltage for all the 3 cycles.

Figure 5.15(a) P&O- Tracking Efficiency At 15° Inclination Figure 5.15(b) P&O- Tracking Efficiency 30° Inclination

Figure 5.15(c) P&O- Tracking Efficiency At 45° Inclination

It is observed that the tracking efficiency continues to fluctuate between tracking efficiency of 91% to above 100% as seen in Figure 5.15(a)-(c). This is consistent with observation in Figure 5.13(a)-(c). Minimal overshooting beyond 100% tracking efficiency occur in Figure 5.13, which is due to the time lag between solar voltage and solar current measurement.

In Figure 5.16(a)-(c), it is observed that the P&O MPPT method tracks the V_{MP} very closely by toggling around unity under all insolation conditions. Table 5.10 clearly indicates that it tracks the V_{MP} well since the normalized solar voltage varies from 0.99 to 1.00.

Figure 5.16(a) P&O- Normalized Solar At 15 ° Inclination

Figure 5.16(b) P&O- Normalized Solar At 30 ° Inclination

Figure 5.16(c) P&O- Normalized Solar At 45° Inclination

Table 5.11. Tracking Efficiency of P&O MPPT method (Insolation Variation)

Insolation Angle (degree)	Extracted Solar Power (W)			Average Extracted Solar Power (W)	Tracking Efficiency (%)
	Reading 1	Reading 2	Reading 3		
15	16.98	16.99	16.98	16.98	98.51
30	15.41	15.41	15.41	15.41	98.66
45	12.25	12.25	12.25	12.25	97.30

Table 5.12. Normalized Solar Voltage of P&O MPPT method (Insolation Variation)

Insolation Angle (degree)	Operating Solar Voltage (V)			Average Operating Solar Voltage (V)	Normalized Solar Voltage
	Reading 1	Reading 2	Reading 3		
15	8.04	8.05	8.06	8.05	1.00
30	7.98	7.99	7.99	7.99	0.99
45	7.94	7.94	7.95	7.94	0.99

The P&O method that has been implemented here is operating as expected based on the description outlined in Section 3.3.1, which has been established according to past literatures.

5.6 MPPT- Incremental Conductance Method

The Incremental Conductance (IncCond) method is tested under the varying conditions of both temperature and insolation level based on Table 4.2 and Table 4.4. For each setting of temperature and insolation level, the IncCond algorithm is repeated 3 cycles to obtain accurate readings of the 'Extracted Solar Power' and 'Operating Solar Voltage'. The complete program code of IncCond MPPT Method (at -75°C) is included in Appendix D and explained in Section 3.3.1.

With reference to Figure 3.8, the point of equilibrium occurs where Equation 3.1 is satisfied. At this point, the parameter V_{REF} is kept constant in order to continue operating at the same solar voltage level. However, Equation 3.1 has to be modified to account for noise in the solar voltage and solar current. A margin has to be included into Equation 3.1 as shown below.

$$\frac{dI}{dV} + \frac{I}{V} = \alpha \quad \text{Eq5.1}$$

During this research, this margin α affects the Tracking Efficiency and Normalized Solar Voltage. In order to sustain the best level in these performance indicators, this margin α is varied according to the temperature and insolation level.

5.6.1 Performance Indicators – Temperature Variation

Figure 5.17(a)-(c) show the Extracted Solar Power in terms of tracking efficiency (based on Equation 5.1) during steady state operation. Figure 5.18(a)-(c) show the Normalized Solar Voltage (based on Equation 5.2) during steady state operation. For clearer graph illustration, only 1 cycle out of 3 is shown in Figure 5.17(a)-(c) and Figure 5.18(a)-(c). Table 5.13 and Table 5.14 summarize the measurements of the Tracking Efficiency and Normalized Solar Voltage for all the 3 cycles.

Figure 5.17(a) IncCond-Tracking Efficiency At -75°C

Figure 5.17(b) IncCond-Tracking Efficiency At 0°C

Figure 5.17(c) IncCond-Tracking Efficiency At $+75^{\circ}\text{C}$

Figure 5.18(a) IncCond-Normalized Solar Voltage At -75°C

Figure 5.18(b) IncCond-Normalized Solar Voltage At 0°C

Figure 5.18(c) IncCond-Normalized Solar Voltage At $+75^{\circ}\text{C}$

Based on temperature varying conditions, Figure 5.17(a)-(c) and Table 5.13 show that the IncCond MPPT method follows the solar peak power point very closely. The blue curve (-75°C) in Figure 5.17(a) tracks the P_{MP} constantly with an accuracy of 99.87%. This is only possible with IncCond MPPT method because it locks the solar operating voltage to the P_{MP} point until the IV profile of the solar array changes. Its tracking and locking mechanisms are explained in Section 3.3.1 in details, with examples of a few literature reviews. The red curve (0°C) in Figure 5.17(b) has a stabilized tracking efficiency of 99.97%, with 0.1% spike from 93.3th second onwards. The spike is measured across the peak-to-peak tracking efficiency. This spike is not caused by any changes in the solar array IV profile because the normalized solar voltage (red curve) recorded in Figure 5.18(b) shows a constant. The spike is due to changes in solar output current around the Maximum Solar Power Point of the solar current-voltage profile, as seen in Figure 1.1. When the normalized solar voltage exceeds unity, the solar array begins to operate in the Constant Voltage Source (Region B based on Figure 1.1). It is in this region that the solar

current changes easily. This spike is seen in the green curves (+75 °C) in Figure 5.17(c), has the same root cause like the situation in 0 °C.

Table 5.13. Tracking Efficiency of IncCond MPPT method (Temperature Variation)

Temperature (degree Celsius)	Extracted Solar Power (W)			Average Extracted Solar Power (W)	Tracking Efficiency (%)
	Reading 1	Reading 2	Reading 3		
-75	25.43	25.42	25.43	25.43	99.87
0	21.97	21.96	21.95	21.96	99.91
+75	17.68	17.70	17.69	17.69	99.33

Table 5.14. Normalized Solar Voltage of IncCond MPPT method(Temperature Variation)

Temperature (degree Celsius)	Operating Solar Voltage (V)			Average Operating Solar Voltage (V)	Normalized Solar Voltage
	Reading 1	Reading 2	Reading 3		
-75	13.17	13.17	13.17	13.17	1.00
0	10.64	10.64	10.64	10.64	1.00
+75	8.16	8.18	8.18	8.17	1.01

5.6.2 Performance Indicators – Insolation Variation

Figure 5.19(a)-(c) show the Extracted Solar Power in terms of tracking efficiency (based on Equation 5.1) during steady state operation. Figure 5.20(a)-(c) show the Normalized Solar Voltage (based on Equation 5.2) during steady state operation. For clearer graph illustration, only 1 cycle out of 3 is shown in Figure 5.19(a)-(c) and Figure 5.20(a)-(c). Table 5.15 and Table 5.16 summarize the measurements of the Tracking Efficiency and Normalized Solar Voltage for all the 3 cycles.

Figure 5.19(a) IncCond-Tracking Efficiency At 15° Inclination

Figure 5.19(b) IncCond-Tracking Efficiency At 30° Inclination

Figure 5.19(c) IncCond-Tracking Efficiency At 45° Inclination

Under insolation variation ambient, the IncCond technique proves to be very effective in following the P_{MP} with tracking efficiency ranging from 99.26% to 99.83%, based on Table 5.15.

When the inclination reaches 15°, the tracking efficiency reaches 99.83% as seen in Table 5.15. It is observed in Figure 5.19(a) that the blue curve is closest to the 100% mark

compared to the other insolation angles, however its spike increases to a magnitude of 0.3%. Figure 5.20(a) shows there are spikes in the normalized solar voltage under 15° inclination. The spikes in Figure 5.20(a) are measured across the peak-to-peak normalized solar voltage. When the solar array is operating directly on the Maximum Solar Power Point, it operates in the transitional state between a Constant Voltage Source and Constant Current Source. This is described in Figure 1.1. The spikes that are due to operating at the Maximum Power Point are dependent by the flatness of the solar current-voltage profile, which is the characteristic of the solar cell. The magnitude of this spike is small in a relatively flat solar current-voltage profile.

There is only 0.1% variation in the tracking efficiency during 30° inclination, as seen in Figure 5.19(b). This is due to the operation of the solar array in the Constant Voltage Source, as described in Section 5.6.1. There is no spike during 45° inclination, as can be seen in Figure 5.19(c) and Figure 5.20(c) (green curves).

Figure 5.20(a) IncCond-Normalized Solar Voltage at 15° Inclination

Figure 5.20(b) IncCond-Normalized Solar Voltage at 30° Inclination

Figure 5.20(c) IncCond-Normalized Solar Voltage at 45° Inclination

Table 5.15. Tracking Efficiency of IncCond MPPT method (Insolation Variation)

Insolation (degree)	Angle	Extracted Solar Power (W)			Average Extracted Solar Power (W)	Tracking Efficiency (%)
		Reading 1	Reading 2	Reading 3		
15		17.21	17.20	17.22	17.21	99.83
30		15.59	15.59	15.59	15.59	99.81
45		12.49	12.50	12.50	12.50	99.26

Table 5.16. Normalized Solar Voltage of IncCond MPPT method (Insolation Variation)

Insolation (degree)	Angle	Operating Solar Voltage (V)			Average Operating Solar Voltage (V)	Normalized Solar Voltage
		Reading 1	Reading 2	Reading 3		
15		8.06	8.07	8.09	8.07	1.00
30		8.03	8.03	8.03	8.03	1.00
45		7.81	7.83	7.83	7.82	0.98

The IncCond method that has been implemented here is operating as expected based on the description outlined in Section 3.3.1, which has been established according to past literatures.

5.7 Comparisons of different MPPT methods

Table 5.17 summarizes all the tracking efficiencies of each MPPT method. It clearly proves that the Incremental Conductance method is more effective in tracking the P_{MP} under all temperature and insolation settings. Due to its locking mechanism to the P_{MP} point, this method is achieving above 99% tracking efficiency under all ambient conditions that a micro-satellite could expect. With such high tracking efficiency, only less than 1% of solar array power would be dissipated as heat in the solar array. The micro-satellite with IncCond method requires smaller solar array area for the same load power requirements, compared to those employing other MPPT methods.

Table 5.17. Tracking Efficiencies (%) of different MPPT methods

	Voc	P&O	IncCond
Temperature (°C)			
-75	84.92	97.59	99.87
0	85.84	97.89	99.91
+75	89.00	98.03	99.33
Insolation Angles (°)			
15	87.55	98.51	99.83
30	89.46	98.66	99.81
45	89.04	97.30	99.26

Now, the foundational feature of maximum solar power point tracking has been developed and tested. The Hybrid MPPT algorithm that performs the GMT operation would be based on the Incremental Conductance MPPT method due to its superiority over other MPPT methods. The algorithm of the Hybrid MPPT is elaborated in the next section.

5.8 GMT- Hybrid MPPT Method

As described, the Hybrid MPPT enables the tracking of the global maxima point when portion of the solar array have unmatched electrical characteristic, which is due to factors stated in Section 3.2. This section presents the setup to simulate such solar arrays with unmatched characteristics. It shows the setup for conducting the Hybrid MPPT test that includes the integration of the Solar Array Simulators, SMPS (with Hybrid MPPT algorithm) and Passive Load. The Hybrid MPPT algorithm and process flow would be explained. This would be followed by the analysis of the Tracking Efficiency of the Hybrid MPPT.

5.8.1 Setup of Solar Array Simulators (E4350B) and DC Electronic Load (HP 6050)

In this research, it is assumed that the entire solar array can be grouped into two segments of different characteristics. A second unit of Solar Array Simulator (E4350B) is connected in series to the setup configuration in Figure 4.6. Each Solar Array Simulator would simulate one segment of the unmatched portions of the entire solar array. Figure 5.21 below describes the configuration used to obtain the new solar current-voltage profile.

Figure 5.21. Setup of Solar Array Simulators and DC Electronic Load for Hybrid MPPT

5.8.2 Solar IV Profile of Unmatched Characteristics

The 2 units of Solar Array Simulators (E4350B) are programmed with unmatched IV settings to simulate external conditions spelled out in Section 3.2. In general, there are 2 scenarios that the unmatched characteristics of the solar array can occur. In the first Scenario (1), the global power maximum point is at higher solar voltage than of the local power maximum as shown in Figure 5.22. The second Scenario (2) simulates the global power maximum point to be at lower solar voltage than of the local power maximum point as shown in Figure 5.23.

Figure 5.22. IV Curve Under Scenario (1) Figure 5.23. IV Curve Under Scenario (2)

Table 5.18 shows the 2 settings to program each of the simulators under both Scenario (1) and Scenario (2). The entire solar array is grouped into Segment A and Segment B, with different characteristics. The settings in bracket are used to simulate Segment A by using the Solar Array Simulator A. With the Solar Array Simulator B, the settings in non-bracket are used to simulate Segment B.

Table 5.18. Solar Array’s Parameters for Solar Array Simulators

Conditions	ISC (Amp)	IMP (Amp)	VOC (Volt)	VMP (Volt)
Scenario (1)	1.3 (0.9)	1.2 (0.8)	6.5 (6.5)	7.0 (7.0)
Scenario (2)	1.3 (0.5)	1.2 (0.4)	7.5 (7.5)	8.0 (8.0)

Based on setup in Figure 5.21 and Solar Array Simulators’ settings in Table 5.18, the solar IV profiles are plotted in Figure 5.2 and Figure 5.3 above. Table 5.19 summarizes the location of both the global and local maximum points for both scenarios. The global maxima solar power points that are established here would be used as the ‘Maximum

Available Solar Power’ to calculate the ‘Tracking Efficiency’ in subsequent section. The global maxima solar voltage points that are established here would be used as the V_{MP} to calculate the ‘Normalized Solar Voltage’ in subsequent section.

Table 5.19. Global & Local Maxima points under Scenario (1) and Scenario (2)

Conditions	Parameters	Global Maxima	Local Maxima
Scenario (1)	P_{MP} (W)	10.90	6.96
	V_{MP} (V)	12.97	5.70
Scenario (2)	P_{MP} (W)	8.21	6.61
	V_{MP} (V)	6.68	14.77

When the solar array is operating at the local maxima in Scenario (1) Table 5.19, the operating solar voltage is 5.70V and the output solar power is 6.96W. The tracking efficiency at this operating point is found by dividing the output solar power with the maximum solar power available from the solar array, which is the solar power at global maxima point. Hence, the tracking efficiency at this operating point is only $6.96W/10.90W*100\%=63.9\%$.

5.8.3 Setup of Hybrid MPPT Testing

A slight reconfiguration of the setup to test the MPPT is used here to test the Hybrid MPPT algorithm. A second unit of Solar Array Simulator (E4350B) is connected in series to the setup configuration in Figure 4.1. The configuration of other instruments and the SMPS remain unchanged from Figure 4.1. Figure 5.24 below describes the configuration used to the test the Hybrid MPPT algorithm.

Figure 5.24. Functional Diagram of SMPS with Hybrid MPPT

As seen in Figure 5.24, the micro-controller that is part of the SMPS (shaded box) is embedded with the Hybrid MPPT algorithm. The following Figure 5.25 shows the complete process flow of the Hybrid MPPT method. The concept of Hybrid MPPT is to firstly locate the estimated position of the true maximum solar power point (global maxima) within a short duration, which is then followed by operating the Incremental

Conductance MPPT algorithm around this estimated position to locate the exact global solar power maxima point.

Based on Section 3.5, the Hybrid MPPT consists of two algorithms; P&O and IncCond. In Figure 5.25, the term ‘Voltage Sampling’ is used instead of ‘P&O’. The Voltage Sampling’s core algorithm is still based on the P&O algorithm with minor modification. This modification is needed to ensure scanning of the entire spectrum of the solar voltage from 0V to V_{OC} , whereas the original P&O algorithm would just track around the V_{MP} point. Hence, the term ‘Voltage Sampling’ is more suitable than P&O in describing its actual operation.

The V_{REF} in Figure 5.25 refers to the same V_{REF} from the output of micro-controller in Figure 4.1. Here, this parameter is increased in steps during the Voltage Sampling process as the solar voltage (V_S) and solar current (I_S) are measured. At each level of V_{REF} , the multiplication of V_S and I_S would be compared to that of the previous cycle. The highest reading of $V_S \cdot I_S$ over the full spectrum of solar voltage is recorded at the end of the Voltage Sampling. The V_{REF} that corresponds to the highest reading of $V_S \cdot I_S$ is the estimated location of the global maxima point. Finally, the Incremental Conductance algorithm would use this V_{REF} to locate the exact global maxima point. The complete program code for the Hybrid MPPT (Scenario (A)) is included in Appendix E and explained in Section 3.5.

Figure 5.25. Process flow of Hybrid MPPT

The subsequent section presents the Tracking Efficiency and Normalized Solar Voltage of the GMT under both Scenario (1) and Scenario (2).

5.8.4 Performance Indicators

This section would present the results on the Voltage Sampling process and the power distribution among the solar arrays of unmatched characteristics. Finally the Tracking Efficiency and Normalized Solar Voltage of the Hybrid MPPT method would be presented and analyzed.

Figure 5.26 and Figure 5.27 show the dynamics of the solar array power during the Voltage Sampling process. At the 6th second, the micro-controller is reset to initiate the Voltage Sampling process, which can be seen from the slowly incrementing V_T (light blue curves in Figure 5.26 and Figure 5.27). Each increment in V_T increases the operating solar voltage (red curves in Figure 5.26 and Figure 5.27) and decreases the operating solar current (green curves in Figure 5.26 and Figure 5.27). At each change in V_T , the solar power (dark blue curves in Figure 5.26 and Figure 5.27) is measured to find the highest in the solar voltage spectrum. The 70th second in this test marks the end of the Voltage Sampling process, which initiates the MPPT process by IncCond method. Based on the observations in Figure 5.26 and Figure 5.27, the Voltage Sampling algorithm is operating as expected in the design. The next section will look into the tracking of the global maxima point using the IncCond MPPT method.

Figure 5.26 Voltage Sampling Process of Hybrid MPPT-Scenario (A)

Figure 5.27 Voltage Sampling Process of Hybrid MPPT-Scenario (B)

Figure 5.28 and Figure 5.29 shows the solar power distribution among Segment A and Segment B of the solar array, during steady state.

Figure 5.28 Solar Power Distribution among unmatched solar array (Scenario 1)

Figure 5.29 Solar Power Distribution among unmatched solar array (Scenario 2)

In Figure 5.28, Segment A of the solar array is producing 5.26W and Segment B of the solar array is producing 5.61W. The total solar power of 10.87W is equivalent to tracking efficiency of 99.72% under Scenario (1), as seen in Figure 5.30 below. The Hybrid MPPT algorithm proves to be able to differentiate the true global maxima point from the local maxima point at 5.70V (6.96W) in Scenario (1). Whereas for Scenario (2) in Figure 5.29, Segment A and Segment B are producing 8.98W and -0.85W, respectively. The total solar power of 8.13W is equivalent to tracking efficiency of 99.05%, as seen in Figure 5.31 below. The Hybrid MPPT algorithm proves to be able to differentiate the true global maxima point from the local maxima point at 14.77V (6.91W) in Scenario (2). The spikes observed in both Figure 5.30 and Figure 5.31 are due to similar aspect as in Section 5.6.1 and Section 5.6.2. The negative solar power from Segment B is actually power dissipated in the bypass diode that is connected to Segment B based on Figure 3.1. In fact, the solar array in Segment B is not producing any power.

Figure 5.30. Performance Indicators under Scenario (1)

Figure 5.31. Performance Indicators under Scenario (2)

5.9 Chapter Discussion

Ripples are observed in Figure 5.9 to Figure 5.20 when using various MPPT methods. These ripples are normal observation and results of operating the solar array at a voltage that is above or below V_{MP} . In this operating condition, the solar array is supplying an output power (known as the ‘Extracted Power’) lower than the total available power (known as the ‘Solar Power At Peak Power Point’), based on Equation 5.1. The remaining power that is not extracted out from the solar array is dissipated as heat within the solar array. With IncCond MPPT, the dissipated heat in the solar array under all orbital conditions, is less than 0.74% (based on 99.26% tracking efficiency at insolation angle of 45^0 in Table 5.17), which is equivalent to 0.09W. This amount of heat dissipated is the least among all the MPPT methods. The TsingHua-1 satellite [29] that employs the V_{OC} MPPT system dissipates more heat than IncCond method and it is still functioning without any damage to the solar array at the point of this research. In V_{OC} method, the dissipated heat under all orbital conditions is 15.08% (based on 84.92% tracking efficiency at temperature of -75^0C in Table 5.17). Many other satellites than use the P&O method that dissipates more heat than IncCond, are still operational. Hence, the ripples in Figure 5.9 to Figure 5.20 are normal and would not cause critical damage to the solar array.

5.10 Chapter Summary

A fully functional SMPS with Incremental Conductance algorithm has been successfully developed and tested. This has tracking efficiency of above 99.33% under all temperature and insolation changes of a micro-satellite.

For a micro-satellite that has many physical parts assembled on its body and requires extended design lifetime, the Hybrid MPPT would be a more suitable choice because of its ability to track the true global maxima point in the presence of multiple local maxima points.

CHAPTER SIX

CONCLUSIONS & RECOMMENDATIONS

6.1 Conclusions

The basic principles of the design aspects and analysis of the Maximum Power Point Tracking of small satellite solar power are reviewed. The emphasis of this research work has been the control of the dynamic operating solar voltage point which is primarily dependent on the external ambient temperature and sun insolation level. When the operating solar voltage point is controlled to be at V_{MP} , maximum solar power that is available from the solar array is channeled to the loads.

The MPPT techniques that are analyzed in this research are the Open Circuit Solar Voltage, Perturbation & Observation, Incremental Conductance and Hybrid. The algorithms of these techniques are analyzed and being coded into a microcontroller. A Buck Type Switch Mode Power Supply with variable duty cycle is built and integrated to the microcontroller for the testing of each MPPT techniques.

The simplest technique is the Open Circuit Solar Voltage method, which requires only a single input data (solar voltage) to track the maximum solar power point. It can be developed using the least number of components. This makes it very suitable for nano-satellite that has space and weight constraints. However, it has the lowest tracking efficiency compared to its rivals.

The Perturbation & Observation MPPT technique tracks very closely to the P_{MP} under all variations of external ambient temperature and sun insolation level. By continuously measuring the input solar power and perturbing the system to operate around the P_{MP} , this technique achieves tracking efficiency of above 97.30%.

The Incremental Conductance technique outperforms the other MPPT techniques with its tracking efficiency of above 99.26%. It is more intelligent than the Perturbation & Observation technique due to its ability to identify and track the Maximum Solar Power

Point under fast varying external conditions. Both the Perturbation & Observation and Incremental Conductance technique employ more complicated circuitry, which is designed to measure two inputs, solar voltage and solar current. Therefore these two techniques track the Maximum Solar Power Point very accurately under a typical orbit of a micro-satellite. The Incremental Conductance technique has great potential especially in imaging micro-satellites with wide and fast changing angle of maneuver.

An improved version of MPPT technique is developed in this research to overcome the problem of unmatched solar cells within the array that results in multiple peak solar power. This improved MPPT called the Hybrid MPPT is verified to extract up to 99.05-99.72% of the maximum solar power available from the solar array. This Hybrid MPPT technique is promising for satellites with long designed life whereby the degradation of solar cells is inevitable.

6.2 Recommendations for future works

Future research and development could be extended to implementing redundancy scheme in the satellite power supply system [63] to prevent critical failure of the satellite power supply system. The entire satellite mission would be brought to a halt by a single component failure, also known as the single point failure. This requires extensive understanding of the different failure modes of components/ sub-systems of the entire satellite power system. In order not to over-design the redundancy system that results in higher failure risk due to higher component count, one should implement redundancy scheme on critical components/ sub-systems. This extended research would involve deeper study and analysis of the space environment especially the impact of Single Event Upset and Total Irradiation Dosage on components-off-the-shelves. It would involve identifying critical components/ sub-systems by using statistical tools to derive reliability data.

The Open Circuit Voltage technique could be further studied and developed for higher tracking efficiency. This technique with the lowest component count and simplest design of all other MPPT techniques has great potential in offering the most reliable power control system. The tracking efficiency of this technique is directly dependent on its constant used to estimate the V_{MP} , which is a factor of external ambient temperature, sun insolation and solar cells ageing. Extensive study and analysis are needed to understand the impact of each of these factors on the solar open circuit voltage constant. Statistical tools would be required to draw correlation between these cumulative factors and the solar open circuit voltage constant.

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Appendix A

IV Curve Test

Source file: "C:\\My Documents\\Thesis\\MPT (with uC)\\IV CURVE TEST 9.vee"

File last revised: Fri Apr 16 14:46:50 2004

Date documented: Sat May 08 11:27:27 2004

VEE revision: 4.01

Execution mode: VEE 3 Compatibility

Convert Infinity on Binary Read: no

I/O Configuration

My configuration

HP-IB0

fgen(@ (NOT LIVE))

Panel Driver: hp3325b.cid

Timeout (sec): 5.000000

Byte ordering: MSB

GPIO_Transfer(@ (NOT LIVE))

Timeout (sec): 5.000000

Byte ordering: MSB

hp34510a(@ (NOT LIVE))

Panel Driver: hp34510.cid

Timeout (sec): 5.000000

Byte ordering: MSB

HP_3852A(@ (NOT LIVE))

Timeout (sec): 5.000000

Byte ordering: MSB

SAS(@ (NOT LIVE))

Timeout (sec): 5.000000

Byte ordering: MSB

HP-IB14

ElecLoad(hp6050a@1401)

Plug&play Driver: HP605X

VISA address: GPIB0::1::INSTR

Panel Driver: hp605x.cid

Timeout (sec): 5.000000

Byte ordering: MSB

hp6050(hp6050a@1401)

Panel Driver: hp605x.cid

Timeout (sec): 5.000000

Byte ordering: MSB

SAS-M(hpe4350b@1415)

Plug&play Driver: HPE435XB

VISA address: GPIB0::15::INSTR

Timeout (sec): 5.000000

Byte ordering: MSB

SAS-S(@1405)

Timeout (sec): 5.000000

Byte ordering: MSB

SigGen(hp33120a@1410)

Panel Driver: hp33120a.cid

Timeout (sec): 5.000000

Byte ordering: MSB

M: Main

Device Type : Main
Context is secured : off
Trig mode : Degrees
Popup Panel Title Text : Untitled
Show Popup Panel Title : on
Show Popup Panel Border : on
Popup Moveable : on
Popup Panel Title Text Color : Black
Popup Panel Title Background Color : Gray
Popup Panel Title Text Font : Object Title Text
Delete Globals at Prerun : off

M.33: Main/Start

Device Type : Start

M.40: Main/Stop

Device Type : OK
Input pin 1 : XEQ (Any, Any)
Output pin 1 : Go
Output pin 2 : Error
Assign to Enter Button : on
Assign to Escape Button : on

M.42: Main/Until Break

Device Type : Until Break
Output pin 1 : Continuous

M.51: Main/Break

Device Type : Break

M.67: Main/Card_1

Device Type : Constant
Output pin 1 : Int32
Wait For Event : off
Auto execute : off
Initialize At Prerun : off
Initialize at Activate : off
Constant size fixed : off
Password masking : off
Int32 Value : 0

M.71: 9112 Initial

Device Type : UserObject
Input pin 1 : Card_ID (Any, Any)
Context is secured : off
Trig mode : Degrees
Popup Panel Title Text : 9112 Initial
Show Popup Panel Title : on
Show Popup Panel Border : on
Popup Moveable : on
Popup Panel Title Text Color : Object Title Text
Popup Panel Title Background Color : Object Title
Popup Panel Title Text Font : Object Title Text

M.71.0: 9112 Initial/Import Library

Device Type : Import
Library Type : Compiled Function
Library Name : P9112
File Name : ..\\..\\Thesis\\MPT (with uC)\\\\vee9112.dll
Definition File : ..\\MPT (with uC)\\9112VEE.H

```

Remote Host Name      : localhost
Remote File Name      : /users/myDir/myFile.vee
Remote Timeout        : 60
Display Server        : sec-pc4
Geometry (800x500+0-0) :
Remote Debug          : off

M.71.1: 9112 Initial/Call P9112.W_9112_Initial
Device Type           : Call
Input pin 1           : Card_ID (Int32, Any)
Input pin 2           : Base_Address (Int32, Any)
Input pin 3           : IRQ_NO (Int32, Any)
Output pin 1          : Y
Output pin 2          : Z
Output pin 3          : X
Function name         : P9112.W_9112_Initial

M.71.5: 9112 Initial/Integer
Device Type           : Constant
Output pin 1          : Int32
Wait For Event        : off
Auto execute          : off
Initialize At Prerun  : off
Initialize at Activate : off
Constant size fixed   : off
Password masking      : off
Int32 Value           : 0

M.71.6: 9112 Initial/Integer
Device Type           : Constant
Output pin 1          : Int32
Wait For Event        : off
Auto execute          : off
Initialize At Prerun  : off
Initialize at Activate : off
Constant size fixed   : off
Password masking      : off
Int32 Value           : 0

M.101: Main/Note Pad
Device Type           : Note Pad
Note Contents         :
1. Analog Inputs
2. Ch0 -> I solar panel
3. Ch1 -> V solar panel
4. Ch2 -> I load
5. Ch3 -> V load
6.
7. Analog output
8. Ch1 -> Vref

M.104: Main/I load
Device Type           : AlphaNumeric
Input pin 1           : Data (Any, Any)
Clear At Prerun       : on
Clear at Activate     : on

M.105: Main/V load (actual)
Device Type           : AlphaNumeric
Input pin 1           : Data (Any, Any)
Clear At Prerun       : on

```

```

Clear at Activate      : on

M.107: Main/V solar
Device Type           : AlphaNumeric
Input pin 1           : Data (Any, Any)
Clear At Prerun       : on
Clear at Activate     : on

M.108: Main/I solar
Device Type           : AlphaNumeric
Input pin 1           : Data (Any, Any)
Clear At Prerun       : on
Clear at Activate     : on

M.109: Main/To File
Device Type           : To File
Input pin 1           : A (Any, Any)
Transactions          : WRITE TEXT a.Vsolar, " ", a.Isolar, " ",
a.Psolar, " ", a.Iload, " ", a.Vload EOL
From                  : ..\..\Thesis\Isro\MaxIns3.xls
Clear at PreRun & Open : yes

M.110: Main/Build Record
Device Type           : Build Record
Input pin 1           : Isolar (Any, Any)
Input pin 2           : Vsolar (Any, Any)
Input pin 3           : Iload (Any, Any)
Input pin 4           : Vload (Any, Any)
Input pin 5           : Psolar (Any, Any)
Output pin 1          : Record
Record output shape   : Scalar

M.123: Main/9112 Set Mode
Device Type           : Call
Input pin 1           : card_number (Int32, Any)
Input pin 2           : ad_mode (Int32, Any)
Output pin 1          : Ret Value
Function name         : P9112.W_9112_AD_Set_Mode

M.124: Main/0
Device Type           : Constant
Output pin 1          : Int32
Wait For Event        : off
Auto execute          : off
Initialize At Prerun  : off
Initialize at Activate : off
Constant size fixed   : off
Password masking      : off
Int32 Value           : 0

M.125: Main/9112 Set range
Device Type           : Call
Input pin 1           : card_number (Int32, Any)
Input pin 2           : range (Int32, Any)
Output pin 1          : Ret Value
Function name         : P9112.W_9112_AD_Set_Range

M.126: Main/5
Device Type           : Constant
Output pin 1          : Int32
Wait For Event        : off

```

```

Auto execute           : off
Initialize At Prerun   : off
Initialize at Activate : off
Constant size fixed    : off
Password masking       : off
Int32 Value            : 5

M.142: Main/Delay
Device Type            : Delay
Output pin 1           : Done
Delay                  : 0.001

M.149: Main/Formula
Device Type            : Formula
Input pin 1            : A (Any, Any)
Input pin 2            : B (Any, Any)
Output pin 1           : Result
Formula                : A*B

M.150: Main/Solar Power
Device Type            : AlphaNumeric
Input pin 1            : Data (Any, Any)
Clear At Prerun        : on
Clear at Activate      : on

M.151: Main/ElecLoad (hp6050a @ 1401)
Device Type            : Direct I/O
Output pin 1           : X
Output pin 2           : Y
Transactions           :
1. WRITE TEXT "MEAS:VOLT?" EOL
2. READ TEXT x REAL
3. WRITE TEXT "MEAS:CURREN?" EOL
4. READ TEXT y REAL

M.185: Main/Load
Device Type            : AlphaNumeric
Input pin 1            : Data (Any, Any)
Clear At Prerun        : on
Clear at Activate      : on

M.186: Main/Formula
Device Type            : Formula
Input pin 1            : A (Any, Any)
Input pin 2            : B (Any, Any)
Output pin 1           : Result
Formula                : A*B

M.252: Main/ElecLoad (hp6050a @ 1401)
Device Type            : Direct I/O
Input pin 1            : A (Real, Any)
Transactions           :
1. WRITE TEXT "CURREN", A REAL STD FW:20 RJ EOL
2. WRITE TEXT "OUTP 1" EOL

M.290: Main/OFF
Device Type            : Start

M.291: Main/ElecLoad (hp6050a @ 1401)
Device Type            : Direct I/O
Transactions           : WRITE TEXT "INPUT OFF" EOL

```


M.293: Main/Counter
 Device Type : Counter
 Input pin 1 : Data (Any, Any)
 Output pin 1 : Count
 Clear At Prerun : on
 Clear at Activate : on

M.294: Main/Formula
 Device Type : Formula
 Input pin 1 : A (Real, Any)
 Input pin 2 : B (Any, Any)
 Output pin 1 : Result
 Formula : (A/100)+B

M.296: Main/Real
 Device Type : Constant
 Output pin 1 : Real
 Wait For Event : off
 Auto execute : off
 Initialize At Prerun : off
 Initialize at Activate : off
 Constant size fixed : off
 Password masking : off
 Real Value : 1.9

M.297: Main/Until Break
 Device Type : Until Break
 Output pin 1 : Continuous

M.300: Main/Delay
 Device Type : Delay
 Output pin 1 : Done
 Delay : 10

M.303: Main/SAS-M (hpe4350b @ 1415)
 Device Type : Direct I/O
 Transactions : WRITE TEXT "OUTPUT OFF" EOL

M.304: Main/SAS-M (hpe4350b @ 1415)
 Device Type : Direct I/O
 Output pin 1 : X
 Output pin 2 : Y
 Transactions :
 1. WRITE TEXT "MEAS:VOLT?" EOL
 2. READ TEXT x REAL
 3. WRITE TEXT "MEAS:CURREN?" EOL
 4. READ TEXT y REAL

M.305: Main/ElecLoad (hp6050a @ 1401)
 Device Type : State Driver
 Input pin 1 : CURREN (Real, Scalar)

M.306: Main/ISRO
 Device Type : Direct I/O
 Transactions :
 1. WRITE TEXT "CURREN:SAS:ISC 2.29 ;IMP 2.15; :VOLT:SAS:VMP 8.0; VOC
 9.4" EOL
 2. WRITE TEXT "CURREN:MODE SAS" EOL
 3. WRITE TEXT "OUTP ON" EOL

Appendix B

Program Codes Of V_{oc} MPPT Method

```
#include "Regc515c.h"
#include <float.h>
#include <stdlib.h>
#include <stdio.h>
#define max_channel 3      //Solar Voltage and Solar Current each
#define max_poll_cycle 600 //number of pooling cycles of each Vs and Is
#define poll_period 0//duration between two consecutive readings
#define sampl_count 18      //sampl_count is interval for Voc sampling. 18 is
estimated to be 1min (18 x 3.5sec=63sec)

int main()
{

float Vs, Is, Va, Ia, analog[max_channel];
int flag=0, i, n;
unsigned char j=0x08;
int Vt=0, Vtemp=0;
long k, h;
int Vref=60; //Vref=Vdc/5*255=107(Vdc:2V)-> 8 bits Resolution
float Vmp=0;

// Voc: 15V, Vmp=3.50V=(15*0.7)/3      division by 3 corresponds to voltage divider
at Solar Voltage sensor
// Voc: 13V, Vmp=3.03V=(13*0.7)/3
// Voc: 11V, Vmp=2.57V=(11*0.7)/3

void init(void);

#ifndef MONITORS51
    SCON = 0X50;
    TMOD |= 0X20;
    TH1 = 221;
    TR1 = 1;
    TI = 1;
#endif

init() ;

h=18; //First sampling and setting of Voc

while(1)
{
```

```

/////////////////////////////////////////////////////////////////
// Sampling of Voc//

    if (h==sampl_count) {

        P5=0xFF;    //Set Vt to highest to switch power MOSFET OFF

        for(k=0; k<30000;) //delay for Result of Vt
            k++;

        //reading of Vs and Is are averaged
        Is=0.0;
        Vs=0.0;
        Va=0.0;
        Ia=0.0;

        for (n=0; n<max_poll_cycle; n++) {

            for (i=2; i<max_channel; i++) {

                ADCON0 &= 0xF8; //choose P6.0
                ADCON0 |= 0x40; //set CLK pin active
                ADCON1 |= i;
                ADDATL = 1;
                while (BSY);

                //10 bits resolution
                analog[i]=ADDATH<<2 | ADDATL>>6;

            }

            for(k=0; k<poll_period; ) {k++;} //delay between each pooling

            Vs= Va + analog[2]*5/1023; //Channel 2 is Solar Voltage
            Is= Ia + analog[1]*5/1023; //Channel 1 is Solar Current
            Va= Vs;
            Ia= Is;

        } //end of Solar Current and Voltage pooling

        Vs= Va/max_poll_cycle;
        Is= Ia/max_poll_cycle;
    
```

```

Vmp=Vs*0.78;      //setting of Vmp

h=0;  //reset sampl_count

}      //end of Voc Sampling

```

```

/////////////////////////////////////////////////////////////////
//Reading of Vs and Is//

```

```

//printf("Initialise\n");
Is=0.0;
Vs=0.0;
Va=0.0;
Ia=0.0;

//reading of Vs and Is are averaged
for (n=0; n<max_poll_cycle; n++)  {

    for (i=1; i<max_channel; i++)      {

        ADCON0 &= 0xF8; //choose P6.0
        ADCON0 |= 0x40; //set CLK pin active
        ADCON1 |= i;
        ADDATL = 1;
        while (BSY);

        //10 bits resolution
        analog[i]=ADDATH<<2 | ADDATL>>6;

    }

    for(k=0; k<poll_period; ) {k++;}    //delay between each pooling

    Vs= Va + analog[2]*5/1023; //Channel 2 is Solar Voltage
    Is= Ia + analog[1]*5/1023;  //Channel 1 is Solar Current
    Va= Vs;
    Ia= Is;

}      //end of Solar Current and Voltage pooling

```



```

Vs= Va/max_poll_cycle;
Is= Ia/max_poll_cycle;

/////////////////////////////////////////////////////////////////
//MPT Algorithm starts tracking//

    if (flag==1)  {

        if (Vs>=Vmp)      Vt=Vt-5;
        else if (Vs<Vmp)  Vt=Vt+5;

        //Add DC shift to Vref
        j=Vref+Vt;    //Each addition/reduction of Vt corresponds to 5*5V/255

        //port test to P4
        P5=j;

        //printf("Vref=0x%X\n", j);
        for(k=0; k<30000;) //delay for Result of Vt
            k++;
        }

        //update sampl_count
        h++;

        if (flag ==0)  {
            flag=flag+1;
            Vt=Vt-1;
        }

    } //end of while(1) loop
}
/////////////////////////////////////////////////////////////////
//Initialising Ports//

void init ()
{

    P2 |= 0X05;

    T2CON = 0x11;
    CCEN = 0X08;
    CRCH = 0XFF;
    CRCL = 0XF3;
    CCH1 = 0XFF;
    CCH1 = 0XF3;
}

```

Appendix C

Program Codes Of P&O MPPT Method

```

#include "Regc515c.h"
#include <float.h>
#include <stdlib.h>
#include <stdio.h>
#define max_channel 3 //Solar Voltage and Solar Current each
#define max_poll_cycle 600 //number of pooling cycles of each Vs and Is
#define poll_period 0 //duration between two consecutive readings
#define eps 80*(5/256)
#define margin1 23

int main()
{

float Vs, Is, Va, Ia, analog[max_channel], Pt, Ptemp;//, tmp1, tmp2;
int flag=0, i, n, delta=5;
unsigned char j=0x008;
int Vt=0, Vtemp=0, direc;
long k;
int Vref=60; //Vref=1.5/5*255= 76.5=+1.5V=> 8 bits Resolution

void init(void);

#ifdef MONITORS51
    SCON = 0X50;
    TMOD |= 0X20;
    TH1 = 221;
    TR1 = 1;
    TI = 1;
#endif

init();

while(1)
{

////////////////////////////////////
//Ouput to Analog Port

j=Vref+Vt;
P5=j;

for(k=0;k<30000;)
    k++; //count of 10 is equivalent to about 6us

```

```
////////////////////////////////////////////////////////////////
```

```
//Measuring of Vs and Is//
```

```
Is=0.0;
Vs=0.0;
Va=0.0;
Ia=0.0;
```

```
for (n=0; n<max_poll_cycle; n++) {
```

```
    for (i=1; i<max_channel; i++) {
```

```
        ADCON0 &= 0xF8; //choose P6.0
        ADCON0 |= 0x40; //set CLK pin active
        ADCON1 |= i;
        ADDATL = 1;
        while (BSY);
```

```
        analog[i]=ADDATH<<2 | ADDATL>>6;
```

```
    }
```

```
    for(k=0; k<poll_period; ) {k++;} //delay between each pooling
```

```
    Vs= Va + analog[2]*5/1023; //Channel 0 is Solar Voltage
    Is= Ia + analog[1]*5/1023; //Channel 1 is Solar Current
    Va= Vs;
    Ia= Is;
```

```
    } //end of Solar Current and Voltage pooling
```

```
Vs= Va/max_poll_cycle;
Is= Ia/max_poll_cycle;
```

```
////////////////////////////////////////////////////////////////
```

```
//MPT Algorithm starts tracking//
```

```
Pt=Vs*Is;
```

```
if (flag==1) {
```

```

if (Pt>Ptemp) {
    if (direc== -1)      {Vt=Vt-delta;  direc=-1;}
    else if (direc==+1) {Vt=Vt+delta;   direc=+1;}
}

else if (Pt<Ptemp) {
    if (direc== -1)      {Vt=Vt+delta;  direc=+1;}
    else if (direc==+1) {Vt=Vt-delta;   direc=-1;}
}
Ptemp=Pt;

}          //end of IF statement


if (flag ==0) {
    flag=1;
    Vt=Vt+delta;
    direc=-1;
    Ptemp=Pt;
}


} //end of while(1) loop
}
////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
//Initialising Ports//

void init ()
{

P2 |= 0X05;

T2CON = 0x11;
CCEN = 0X08;
CRCH = 0XFF;
CRCL = 0XF3;
CCH1 = 0XFF;
CCH1 = 0XF3;
}

```


Appendix D

Program Codes Of IncCond MPPT Method

```
//Code with optimised max_poll_cycle(400), pool_period(0) and zero delay for solar
//voltage and current to settle
```

```
#include "Regc515c.h"
#include <float.h>
#include <stdlib.h>
#include <stdio.h>
#define max_channel 3 //Solar Voltage and Solar Current each
#define max_poll_cycle 600 //number of pooling cycles of each Vs and Is
#define poll_period 0 //duration between two consecutive readings
#define eps 5/256

int main()
{

float Vu, Iu, Vs, Is, Va, Ia, analog[max_channel], Pt, Ptemp, dV, dI;//, tmp1, tmp2;
int flag=0, i, n, delta=1, flag1=0;
unsigned char j=0x008;
int Vt=0, Vtemp=0;
long k;
int Vref=60; //Vref=1.5/5*255= 76.5=+1.5V=> 8 bits Resolution

void init(void);

#ifdef MONITORS51
    SCON = 0X50;
    TMOD |= 0X20;
    TH1 = 221;
    TR1 = 1;
    TI = 1;
#endif

init();

while(1)
{

////////////////////////////////////
//Ouput to Analog Port

j=Vref+Vt;
P5=j;
```

```

for(k=0;k<30000;)
    k++; //count of 10 is equivalent to about 6us

```

```

/////////////////////////////////////////////////////////////////
//Measuring of Vs and Is//

```

```

Is=0.0;
Vs=0.0;
Va=0.0;
Ia=0.0;

```

```

for (n=0; n<max_poll_cycle; n++)  {

    for (i=1; i<max_channel; i++)    {

        ADCON0 &= 0xF8; //choose P6.0
        ADCON0 |= 0x40; //set CLK pin active
        ADCON1 |= i;
        ADDATL = 1;
        while (BSY);

        analog[i]=ADDATH<<2 | ADDATL>>6;

    }

    for(k=0; k<poll_period; ) {k++;}    //delay between each pooling

    Vs= Va + analog[2]*5/1023; //Channel 0 is Solar Voltage
    Is= Ia + analog[1]*5/1023;    //Channel 1 is Solar Current
    Va= Vs;
    Ia= Is;

    }    //end of Solar Current and Voltage pooling

```

```

Vs= Va/max_poll_cycle;
Is= Ia/max_poll_cycle;

```

```

/////////////////////////////////////////////////////////////////
//MPT Algorithm starts tracking//

```

```

if (flag==1) {

dI=Is-Iu; dV=Vs-Vu;

if (abs(100*dV)<25 && flag1==1) {
    if (abs(100*dI)<30) goto update;
    else {
        if (dI> 0.0) Vt=Vt+5;
        else Vt=Vt-5; }
    }

else {

    if (dI/dV+Is/Vu<0.9) {
        if (dI/dV+Is/Vu>-2.5) {flag1=1; goto update;}
        else Vt=Vt-5;
    }

//      else if (dI/dV+Is/Vu<1.2) goto update;

    else Vt=Vt+5;

}

update:
    Vu=Vs; Iu=Is;

}      //end of IF statement


if (flag ==0) {
    flag=flag+1;
    Vt=Vt+5;
    Ptemp=Pt;
}

} //end of while(1) loop
}
////////////////////////////////////
//Initialising Ports//

void init ()
{

```

```
P2 |= 0X05;
```

```
T2CON = 0x11;
```

```
CCEN = 0X08;
```

```
CRCH = 0XFF;
```

```
CRCL = 0XF3;
```

```
CCH1 = 0XFF;
```

```
CCH1 = 0XF3;
```

```
}
```


Appendix E

Program Codes Of Hybrid MPPT Method

```
#include "Regc515c.h"
#include <float.h>
#include <stdlib.h>
#include <stdio.h>
#define max_channel 3      //Solar Voltage and Solar Current each
#define max_poll_cycle 600 //number of pooling cycles of each Vs and Is
#define poll_period 0 //duration between two consecutive readings

#define e1 1.95 //1*eps
#define e2 3.91 //2*eps
#define e3 58.5 //30*eps

int main()
{

float Vs, Is, Va, Ia, analog[max_channel], Pt, Ptemp=0, Vu, Iu, dV, dI;
int flag=0, i, n, flag1=0;
unsigned char j=0x08;
int Vt=0, Vtemp=0;
long k;
int Vref=0; //Method 1: Count up, Method2: Counting down (Vref=128 is equivalent
to max output voltage (+2.5V) from DAC chip to PWM chip)

void init(void);

#ifndef MONITORS51
    SCON = 0X50;
    TMOD |= 0X20;
    TH1 = 221;
    TR1 = 1;
    TI = 1;
#endif

init();

while(1) //Sweeping Vsolar
{

    j=Vref; P5=j;//Set Vt to start tracking from Voc
    for(k=0; k<30000;) //delay for Result of Vt
        k++;

    //Reading of Vs and Is//
```

```

//printf("Initialise\n");
Is=0.0;
Vs=0.0;
Va=0.0;
Ia=0.0;

//reading of Vs and Is are averaged
for (n=0; n<max_poll_cycle; n++) {

    for (i=1; i<max_channel; i++) {

        ADCON0 &= 0xF8; //choose P6.0
        ADCON0 |= 0x40; //set CLK pin active
        ADCON1 |= i;
        ADDATL = 1;
        while (BSY);

        //10 bits resolution
        analog[i]=ADDATEH<<2 | ADDATL>>6;

    }

    for(k=0; k<poll_period; ) {k++;} //delay between each pooling

    Vs= Va + analog[2]*5/1023; //Channel 0 is Solar Voltage
    Is= Ia + analog[1]*5/1023; //Channel 1 is Solar Current
    Va= Vs;
    Ia= Is;

    } //end of Solar Current and Voltage pooling

Vs= Va/max_poll_cycle;
Is= Ia/max_poll_cycle;

Pt=Is*Vs;
if (Pt>Ptemp)
{
    Ptemp=Pt; //store Ps for comparison
    Vtemp=Vref; //store Vt as ref
}

Vref=Vref+5; //5 is step size of change

if (Vref>=170)goto startMPPT; //The equivalent of 170 is +3.3V, which is
max voltage to adjust duty cycle of PWM

} //end of while loop to sweep Vsolar

```

```

startMPPT:

Vref=Vtemp+10; //start MPPT at point higher than Vmp
j=Vref;
P5=j;

for(k=0;k<100000;) //extra delay for solar current to build up from near zero
    k++; //count of 10 is equivalent to about 6us

while(1)
{
    //////////////////////////////////////
    //Output to Analog Port

    j=Vref+Vt;
    P5=j;

    for(k=0;k<30000;)
        k++; //count of 10 is equivalent to about 6us

    //////////////////////////////////////
    //Reading of Vs and Is//

    //printf("Initialise\n");
    Is=0.0;
    Vs=0.0;
    Va=0.0;
    Ia=0.0;

    //reading of Vs and Is are averaged
    for (n=0; n<max_poll_cycle; n++)    {

        for (i=1; i<max_channel; i++)    {

            ADCON0 &= 0xF8; //choose P6.0
            ADCON0 |= 0x40; //set CLK pin active
            ADCON1 |= i;
            ADDATL = 1;
            while (BSY);

            //10 bits resolution
            analog[i]=ADDATH<<2 | ADDATL>>6;

```

```

    }

    for(k=0; k<poll_period; ) {k++;}    //delay between each pooling

    Vs= Va + analog[2]*5/1023; //Channel 0 is Solar Voltage
    Is= Ia + analog[1]*5/1023;    //Channel 1 is Solar Current
    Va= Vs;
    Ia= Is;

    }    //end of Solar Current and Voltage pooling

Vs= Va/max_poll_cycle;
Is= Ia/max_poll_cycle;

////////////////////////////////////
//MPT Algorithm starts tracking//
    if (flag==1)    {

        dI=Is-Iu; dV=Vs-Vu;

        if (abs(100*dV)<2 && flag1==1) {
            if (abs(100*dI)<5) goto update;
            else {
                if (dI> 0.0) Vt=Vt+5;
                else Vt=Vt-5; }
            }

        else {

            if (dI/dV+Is/Vu<0.0) {
                if (dI/dV+Is/Vu>-2.0)    {flag1=1; goto update;}
                else Vt=Vt-5;
            }

            else    Vt=Vt+5;

        }

    update:
        Vu=Vs; Iu=Is;

    }    //end of IF(Flag==1) statement

```



```
        if (flag ==0)  {
            flag=flag+1;
            Vt=Vt+5;
            Ptemp=Pt;
        }

    }//end of while loop for MPPT tracking

}

////////////////////////////////////
//Initialising Ports//

void init ()
{
    P2 |= 0X05;

    T2CON = 0x11;
    CCEN = 0X08;
    CRCH = 0XFF;
    CRCL = 0XF3;
    CCH1 = 0XFF;
    CCH1 = 0XF3;
}
```