Thesis for the Degree of Master of Engineering

Design of Hybrid Energy Storage System for Dynamic Renewable Energy

by

Maru Mihret Gebreslassie
In the Department of Control and Instrumentation Engineering,

Graduate School,

Pukyong National University

August 24, 2018

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동적 신재생 에너지저장을 위한 하이브리드충전 시스템 설계

Advisor: Prof. Gi Sig Byun

by

Maru Mihret Gebreslassie

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Approved by:

(Chairman) Professor Yeon Wook Choe

(Member) Professor Nam Ho Kim

(Member) Professor Gi-Sig Byun

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Maru Mihret Gebreslassie

부겨대학교 대학원 제어계측 공학과

요약

본 논문에서는 신재생에너지 하이브리드 에너지 저장 시스템에 대한 에너지 수확, 슈퍼 커패시터의 충전, 배터리 충전이라는 세 가지를 연구하였다.

하이브리드 DC-DC 컨버터를 갖춘 하이브리드 에너지 저장 시스템은 동적 재생 에너지 시스템용으로 개발되었다. 이 논문에서는 모델의 설계 및 시뮬레이션의 구현을 진행하였다. 하이브리드 에너지 저장 시스템은 필요한 재생 에너지를 수확하는 2 개 이상의 에너지 저장 장치를 갖는 시스템이며, 재생 가능 에너지원의 불규칙성을 대비하여 하이브리드 에너지 저장은 공급원의 예측 불가능한 특성을 줄일 수 있다. 독립형 시스템에서 지속적인 전력 공급을 위해서는 매우 중요한 부분이다.

본 연구는 충전식 영구 기억 장치 (배터리) 고성능 저장 장치 (수퍼 커패시터), SEPIC (Single-ended primary-inductor converter) DC_DC 컨버터, 부스트 DC_DC 컨버터 및 솔라패널을 사용했다.

모든 모델링 설계 및 시뮬레이션의 구현은 MATLAB Simulink 와 PSIM 소프트웨어를 사용하여 실시했다. 이 소프트웨어 플랫폼은 전력 전자 연구의 연구 및 주요 과제를 수행하는데 사용되고 있다. 충방전시의 하이브리드 에너지 저장을 위한 제어 알고리즘을 개발하기 위해 MPPT (Maximum Power Point Tracking) 전압 및 전류 모드 컨트롤러를 갖춘 전압 모드 PI(proportional and integral) 컨트롤러를 사용했다. 이 시스템은 재생 가능한 전기 에너지를 수집 할 때 하이브리드 에너지 저장 (충전 용 배터리 및 슈퍼 커패시터)을 제어하는 데 사용된다.

현재 MPPT 배터리 충전이 일반적이지만, 본 연구에서는 내장 SEPIC(Single-ended primary-inductor converter) MPPT 및 전압 모드 PI 컨트롤러를 사용하여 슈퍼 커패시터를 충전했다. 그리고 이중 루프 배터리 관리 시스템을 갖춘 부스트 컨버터를 배터리 전압 컨트롤러와 배터리 전류 컨트롤러에 사용했다.

Design of Hybrid Energy Storage System for Dynamic Renewable Energy

Maru Mihret Gebreslassie

Department of Control & Instrumentation Engineering
Graduate School of
Pukyong National University

Abstract

Hybrid energy storage system for renewable energy performs three main tasks- harvesting energy, charging super capacitor and then battery. Hence, this hybrid energy storage systems with hybrid DC-DC converters are developed for dynamic renewable energy system. The Model design and simulation implementations are presented on this thesis. Hybrid energy storage system is a system with more than one energy storages to harvest the required renewable energy. Due to irregularity of renewable energy sources, hybrid energy storages are very important to reduce the unpredictable properties of the sources and to have continuous power supply in standalone systems.

Rechargeable permanent storage (battery), high powerful storage (super capacitor), SEPIC (Single-ended primary-inductor converter) DC_DC convertor, boost DC_DC converter and photo voltaic module are used on this research.

All modeling design and simulation implementations are done by using MATLAB Simulink and PSIM software for power electronics simulation. Those software plat forms are used to conduct researches and major educational materials in studying of power electronics. To develop the control algorithms for hybrid energy storage during charging and discharging, voltage mode PI controller with MPPT (Maximum Power Point Tracking), Voltage and current mode (Parallel) controllers was used. This system is used to control hybrid energy storage (rechargeable battery and super capacitor) when we harvest renewable electric energy (in our case photo voltaic energy).

Currently, MPPT battery charging is popular, but in this research the integrated SEPIC MPPT and voltage mode PI controllers are used to charge the super capacitor. And then Boost converter with Parallel battery management system was used for battery voltage controller and battery current controller.

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Chapter 1: Introduction

1.1 Basic background of the study

In a hybrid storage control system controls a super capacitor using MPPT and voltage mode PI controller with SEPIC DC_DC convertor and controlling battery permanent storage system using parallel PI controllers with boost DC_DC convertor are the most important things.

For the unpredictable renewable energy source that consists of good and bad weather conditions we need strong energy storage and strong control systems of energy storages.

On this study each of storage systems need to be control to have continuous and constant charging system conditions. For this case having only MPPT Battery charging directly from the renewable energy source has many problems such as degradation of the battery life cycle and discontinuity of the power supply due to irregularity of renewable source energy, the same is true being having only MPPT Super capacity charging has the problem of having self-discharging and low energy storage capability[1]. Hence, to overcome those problems having hybrid energy storage is the important solution especially for the remote areas like our country (Ethiopia). Therefore, the drawback of battery and super capacitor will be compensated on this system design.

1.2 Main Objective of this Study

So far, oil, fossil fuels, coal and natural gas are the essential conventional power sources in our world. However, those conventional energy sources have negative impact in environment such as greenhouse effect, high cost and having properties that are not eco-friendly[2]. Hence, with these issues of our environment and the diminution of conventional power sources, the increasing of electric vehicles, renewable power source are indispensable to the maintainable development of human life style[3].

Currently, renewable energies such as solar energy and wind energies are the main available electrical energy sources, environment friendly and clean energies that we can find everywhere and has been drawing boundless consideration in our world especially in developing countries. However, to have good standalone energy harvesting in our environment without grid connectivity, we need to have huge and rechargeable energy storages. Moreover, batteries and super capacitors (SC) are trustworthy energy storages systems that are main elements to allow these energy construction growths.

Hence, on this study unlike other previous studies, the hybrid storage energies are not connected separately to the renewable energy sources. That means all the converters and the storage systems are connected in series with each other in order to prevent the losses of energy that generates from the source energy and super capacitor storage system and then to have continuous battery charging without intervention of the unpredictable source of energy.

In general, the main objective of this research is to have full harvesting and smooth charging system such as constant current and constant voltage charging system of our battery. In addition, the instantaneous and variable electric power generated by solar module has excellent characteristics in time response and harvest into a large capacity super capacitor. And then, the harvested power in the super capacitor charges the battery by regulating the voltage and current while compensating the delay time and increase the charging efficiency of the battery.

Chapter 2: Renewable Energy and Storage System

2.1 Renewable Energy Review

Energies that are harvested from renewable sources are called renewable energies, which are tremendous and have long term accessibility throughout human life. Energies such as geothermal sources, waves, wind, hydro energies, biofuels and solar energies are very essential renewable energies for every nations[2] [5][4] . Most of the time, renewable energy affords energy in four main areas such as electricity, in heating/cooling system, transportation and in rural area (off-grid) energy services. Based on renewables 2010 global status report [6], the capacity of global renewable sources are raised in the rate of 10-60% every year.

In developing countries such as Ethiopia, grid off (standalone) renewable energy is the only alternative source of energy. Because in those remote and rural areas transmission and sharing conventional energy sources is very impossible and the most expensive one.

Nowadays, resources of renewable energies are gradually increasing connected in distribution systems utilizing power electronic converters.

Electric public utilities and electric power product end users are becoming more and more concerned about achieving the developing energy demand. But, currently most of total global energy demand is provided by the burning of fossil fuels. Due to increasing air pollution, global warming concerns, lessening conventional energies and their high cost have made it obligatory to look toward renewable sources as a future energy solution. Since the previous decade, there has been huge attention in many nations on renewable sources for power generation. Economic liberalization and every nation’s government motivation have further augmented the renewable energy area growth[7][6], [8]–[10].

Renewable source of energies are the main issues of sustainable development of every nation and key guiding principle of social and economic growth of one’s country in 21st century.

Generally speaking, renewable energy sources are very important and compatible with sustainable development than other conventional energies in respect to both resource boundaries and environmental influences. Accordingly, more or less all nationwide energy strategies contain four vital features for improving or upholding social advantages from energy: Improving renewable energy harvesting methods, enhancing the efficiency of supply and end-use, mitigation of environmental pollution, consideration life standard. The comparison of conventional and renewable energies are shown at the Figure1.

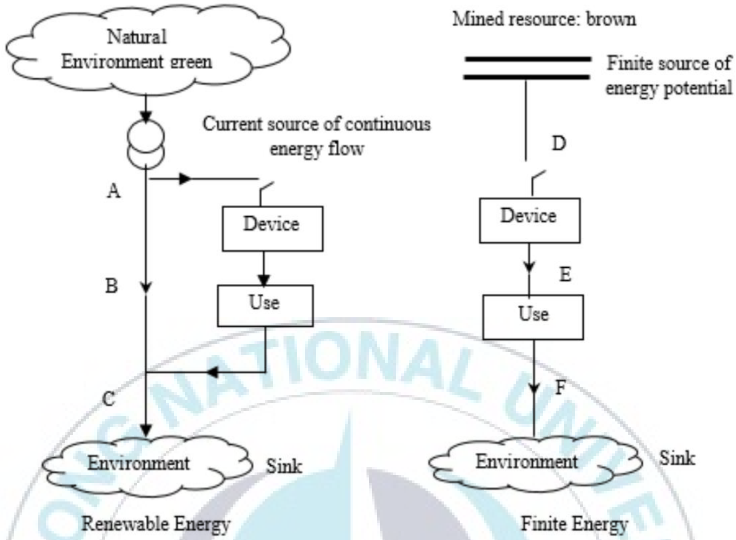

Figure 1 Comparison of renewable and finite energy sources [4].

The environmental energy flow ABC must be evaluated before established the direction flow through DEF.

2.2 Basic Theory of Solar System

Among the above renewable energies that pass through the earth, solar energy is the most dominant in the world. For example, total solar irradiation absorbed at sea level is approximately $1.2x10^{17}$W. And the solar irradiance reaching at the surface of earth is $\sim 20MW$ per person. This amount of energy is very large, which is quite enough to supply to around 50,000 people in one city. In Figure 2 shown below is indicating the dominancy of solar energy in the earth[11] [4].

Note the great range of energy flux (1: 10^5) and the dominance of solar radiation and heat is in terawatts (10^{12} W).

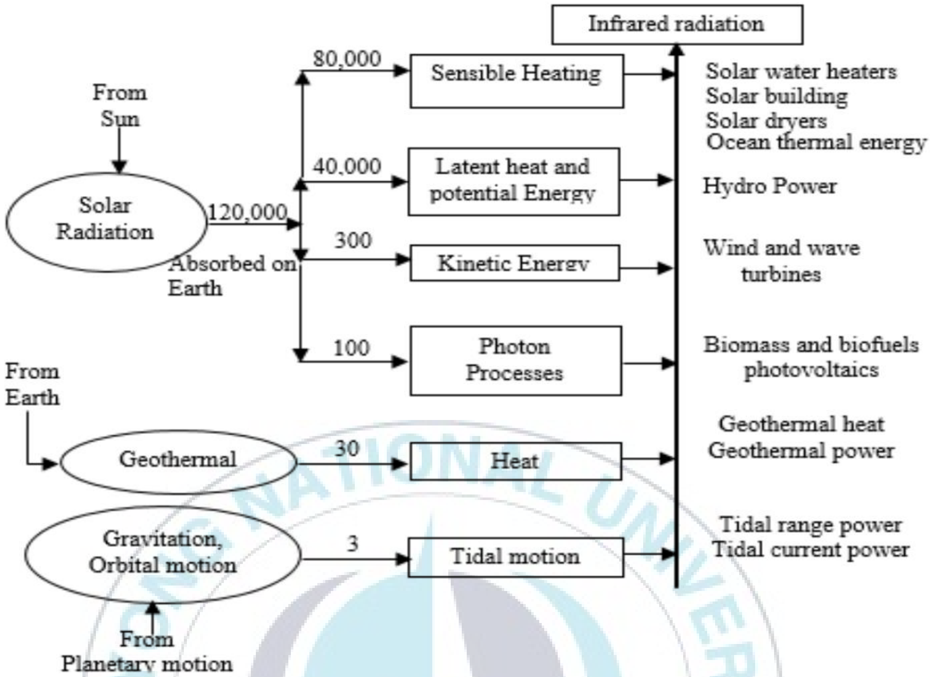

Figure 2 Natural renewable energy system on the earth[4].

Due to their eco-friendly nature and large reserves, photovoltaic (PV) energy has become an important solution for society. It is the future energy development trend, which uses to solve the energy and environment crisis. In addition, the reason why PV Panels are gaining attractiveness in the field of electric power generation is due to having very long life time and they require less maintenance during usage[12].

Based on the previous studies of the world energy consumption released by Agency of International Energy shows that in 2050, more than 45% of essential energy in the world will be only produced by solar arrays [13][14].

So our target is to investigate how to reduce the overall price and how to increase power conversion efficiency of solar panel. To store solar energy in a storage device, enhancement of battery charging efficiency with lesser charging time is required. To this end, Maximum Power Point Tracking algorithm is essential to upsurge the efficiency of the solar panel.

Photovoltaic (PV) system is composed of several photo voltaic solar cells. An individual small PV cell is capable of generating approximately 1~2 W of power, which depends on the type of material used[15]. The PV array has nonlinear physical characteristics and it is quite expensive and takes much time to get the operating curves of PV array under varying operating conditions. In order to overcome these obstacles, common and simple models of solar panel has been developed. Though these models are not sufficient for application concerning hybrid energy system, meanwhile they must have flexible regulation of some considerations in the system and not simply understandable for readers to use by themselves. Therefore, PV module mathematical modeling is the best and common understanding of researchers to have uniform and standard physical system. Hence, PV module mathematical modeling is being continuously updated from time to time in order to have a best understanding of its working principle. The models of PV module are different depending on their types of software used by researchers but the basic components of solar system is the same in all types of the software. In the Figure 3 below shows the solar module physical model design in PSIM and Matlab/Simulink, and the solar cell in Matlab/Simulink.

a b c

Figure 3 Solar module in PSIM (a) and Matlab (b) Solar cell in Matlab (c)

As shown in the Figure 3, the fundamental terminals of solar modules in PSIM power electronics tool and Matlab software tools are very similar which have irradiance terminals (S and Ir), temperature terminal(T in both), positive and negative output terminals and the maximum power outputs of both modules (m and M).

2.2.1 Basic parameters of solar module

The basic parameters of solar module are current source (I_s), diodes (I_0 andn_l), parallel resistance (R_p) to represent irradiance and temperature dependence I-V characteristics of the module as shown in Figure 4 below.

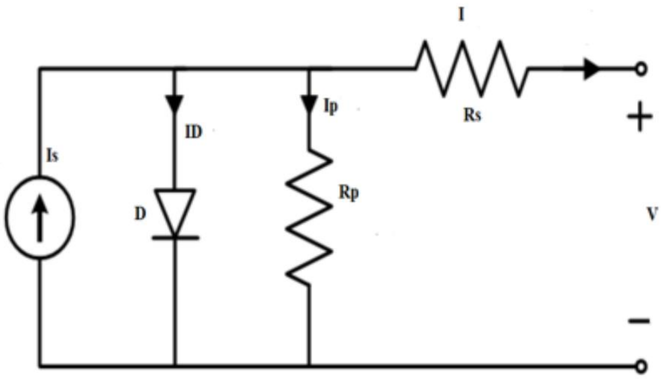

Figure 4 The PV cell equivalent circuit

Based on the equivalent circuit above the V-I characteristic equation of PV solar cell is provided in [15]–[17] as shown in equations(1~7)

The equivalent equations of the circuit using Kirchhoff's law

$$I = I_S - I_D - I_P \tag{1}$$

$$I_S = [I_{SC} + K_i(T - 298)] \times {}^{Ir}/_{I_{r0}} \tag{2}$$

Ideal Diode current using Shockley equation

$$I_D = I_0 \left[e^{\left(\frac{V+IR_S}{nV_T}\right)} - 1 \right] \tag{3}$$

$$V_T = \frac{KT_c}{q} \tag{4}$$

$$I_P = \left(\frac{V + IR_S}{R_P}\right) \tag{5}$$

By combining equations from (1∼5) gives us the output current of the single diode solar cell (I)

$$I = [I_{SC} + K_i(T - 298)] \times {}^{Ir}/_{1000} - I_0 \left[e^{\left(\frac{V+IR_S}{nV_T}\right)} - 1 \right] - \left(\frac{V + IR_S}{R_P}\right) \tag{6}$$

Where, I_S $is\ photo\ current\ in\ (A)$

I_D is the loss of voltage dependent current to recombination(I).

I_P is the loss of current due to parallel resistance(A).

n is the ideality factor of diode(values between 1 and 2, unit less)

I_0 is the saturation current(A) and V_T is thermal voltage (V)
$K = (1.381 \times 10^{-23} J/K)$ is Boltzmann's constant
$q = 1.602 \times 10^{-19} C$ is the electron charge
R_s is Series resistance (Ω)
R_P is shunt resistance (Ω)
I_{SC} *is short circuit current in* (A)
K_i *is constant current propertionality* (2.2×10^{-3})
and I_r *is solar irradiance of the celll*$\left({W}/{m^2}\right)$

To achieve the desired output energy from the module, the fundamental equations of the PV cell is multiplied by the number of cell in the module, which is assuming the module is combination of multiple cells in series.

$$I_M = I_S - I_0 \left[e^{\left(\frac{V_M + I_M N_S R_S}{n N_S V_T}\right)} - 1 \right] - \left(\frac{V_M + I_M N_S R_S}{N_S R_P} \right) \quad (7)$$

Where I_M PV module current, V_M is PV module Voltage and N_S is PV module cells in series. Note that this Module is only series connections of PV cells.

2.2.2 Number of PV modules in series

Regularly a number of identical solar modules block are coupled in series connection methods to form a solar array.

Figure 5 below shows two physical models of solar modules joined in series, and a connected block that models two modules. The model parameters of the joined block are identical with a single solar module, apart from that the amount of cells Ns is two times of the single PV solar module value. Note that when various PV modules are combined in series, bypass diode is necessary across each module if the ambient temperature and light intensity inputs are different. The bypass diodes are used to protect a modules of photovoltaic (PV) system from the hot spot consequence that can lead towards permanent destruction. Furthermore, a very small capacitor is needed through each module for mathematical convergence[18].

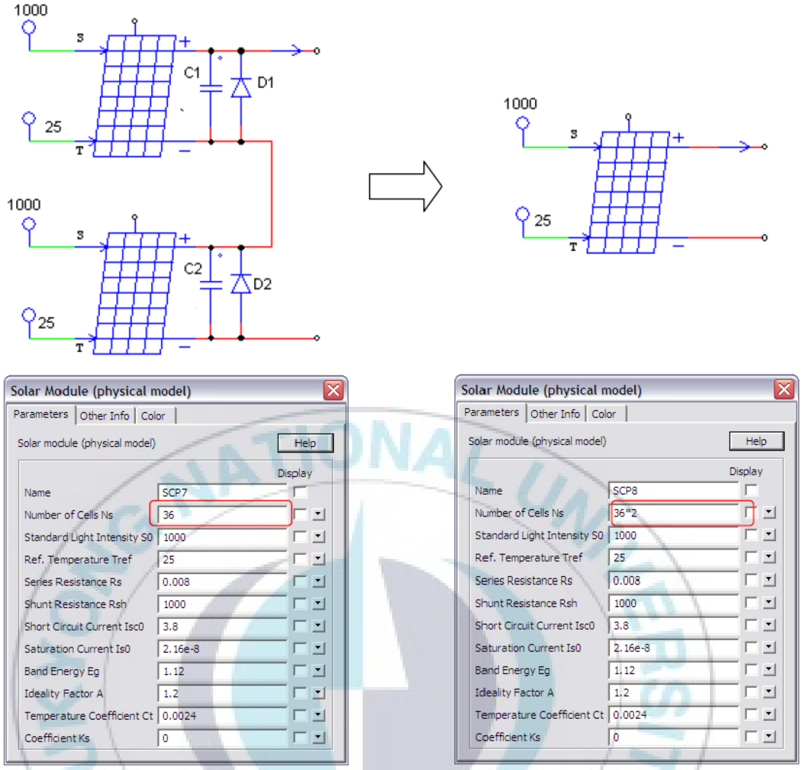

Figure 5 Configuration of PV modules in series

To plot the combined PV module blocks I-V curve, we have to change the quantities of number of cells (N_s), maximum power P_{max}, voltage at P_{max} and open-circuit voltage (V_{oc}) from the single module which is multiplication of the number of modules[19].

2.2.3 Number of PV modules in parallel

Several identical solar modules can also be connected in parallel connection to form a solar array[20].

Figure 6 shown below presents a solar modules connected in parallel, and a combined block that models two modules.

Some of the elements of the joined blocks are dissimilar as compared with the elements of single solar module, as emphasized in the red boxes in Figure 6.

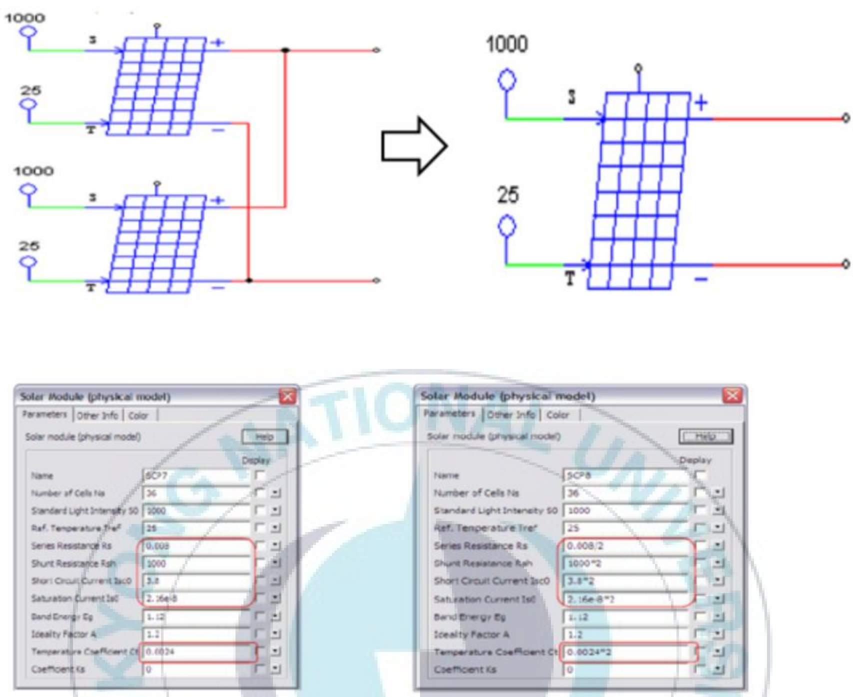

Figure 6 Parallel configuration of PV module

2.3 The Storage System

Storage systems are devices that capture an electrical energy produced from the energy source at specific time in order to use next time. Magnetic systems, electrochemical systems, hydro Systems, Pneumatic systems, mechanical systems and thermal systems are storage of energy technologies[21], [22]. Among the electrochemical systems super-capacitors and batteries have great role to mitigate the dynamic renewable energy harvesting impacts[23]. The comparison of electrochemical Energy storage systems and the BSH (battery-super capacitor hybrid) storage has been proposed as shown in Figure 7.

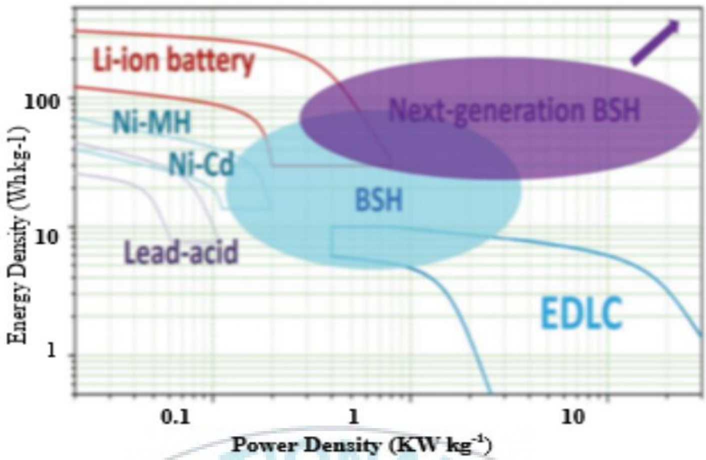

Figure 7 Comparison of electrochemical storage systems and BSH[3]

Battery storage systems are devices that produce an electrical energy through electrical reactions by involving cathode, anode and electrolyte. We have two types of batteries based on their chemical reactions, which are rechargeable and regular (none rechargeable) batteries. A battery which be able to charge for hundreds and thousands time called rechargeable battery[24].

The development of innovative rechargeable battery has been broadly used in countless energy applications, from private microelectronics to grid storage electronic devices, such as notebook computers, cellular phones, and camcorders[25].

According to their chemical composition, specific energy density and specific power density, batteries can be classified into different categories. Lithium ion, lead Acid and Nickel based are the most common batteries[26].

2.3.1 Lead acid battery

Lead-acid type battery is the oldest and supreme developed technology and has many power system applications. Having the low cost compared to other types of batteries is, the main advantage of lead-acid battery[27]. Lead acid batteries are up righting its round as being a strong and commercial power source for bulk use. Even though Lithium ion is making inroads in to the lead acid market the demand for lead acid batteries is still growing. The dynamic characteristics of Lithium ion and lied acid batteries has almost the same operating modes which are constant current, constant voltage mode[28].

2.3.2 Lithium ion battery

Li-Ion battery is one of the famous device that with low weight, high energy dense and high power dense. The production cost of this battery is very high and lifespan of the batteries reduce with deep discharges[27], [29].

2.3.3 Ultra Battery

Ultra-battery is a new energy storage developed by CSIRO technology which is a hybrid of lead acid battery and super capacitor in single unit cell. Ultra-battery is a combination of the energy storage potential of lead-acid battery technology in a hybrid device with a single common electrolyte and fast charging rates and longevity of super-capacitor technology[30], [31].

Ultra-Battery is highly efficient in continuous partial-state-of-charge (PSoC) operation which is neither totally full nor totally empty.

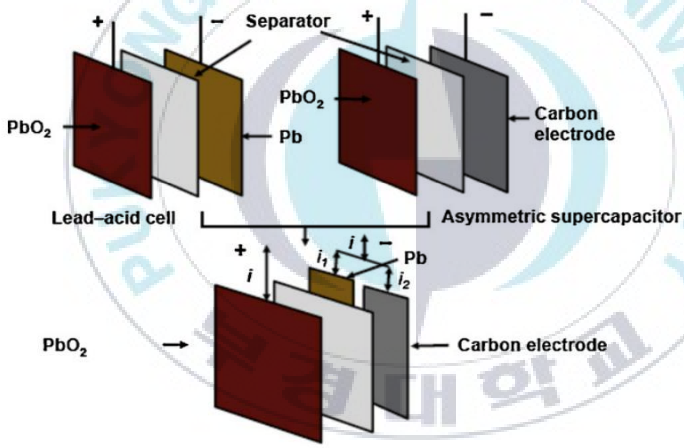

Figure 8 Ultra-Battery [35], [36]

2.3.4 Battery Model

In order to have simulation studies, the basic and simplified dynamic model of batteries are very necessary. The equivalent circuit mode in Matlab/Simulink is shown below. The battery block implements a basic dynamic prototypical parameterized to represent most common types of rechargeable batteries.

For lead acid battery

Discharge model (i*>0)

$$f1(it, i*, i, Exp) = E_0 - K\frac{Q}{Q-it}.i* - K.\frac{Q}{Q-it}.it + Laplace^{-1}\left(\frac{Exp(s)}{Sel(s)}\right).0 \tag{8}$$

Charging model (i*<0)

$$f2(it, i*, i, Exp) = E_0 - K.\frac{Q}{Q.0.1+it}.i* - K.\frac{Q}{Q-it}.it + Laplace^{-1}\left(\frac{Exp(s)}{Sel(s)}\right).\frac{1}{s} \tag{9}$$

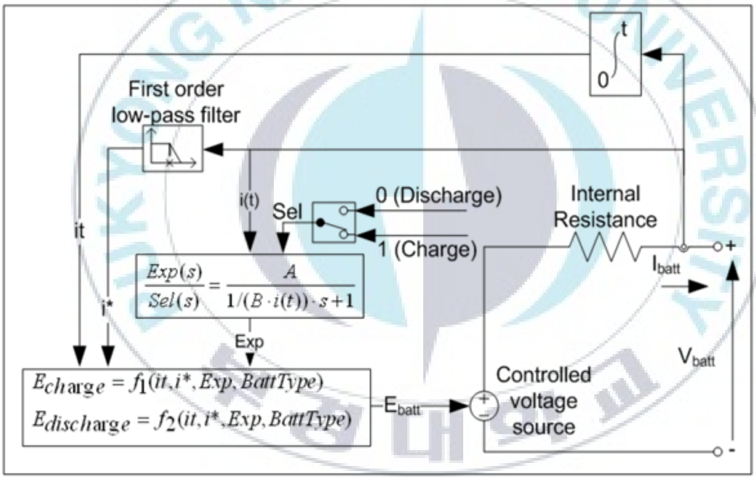

Figure 9 Equivalent circuit of battery with in Matlab Simulink[32], [33]

For lithium ion battery

Discharge model (i*>0)

$$f1(it, i*, i, Exp) = E_0 - K.\frac{Q}{Q-it}.i* - K.\frac{Q}{Q-it}.it + A.exp(-B.it) \tag{10}$$

Charging model (i*<0)

$$f2(it, i*, i, Exp) = E_0 - K.\frac{Q}{Q.0.1+it}.i* - K.\frac{Q}{Q-it}.it + A.exp(-B.it) \tag{11}$$

For the nickel metal hydride and nickel cadmium battery type

Discharge model (i*>0)

$$f1(it, i*, i, Exp) = E_0 - K\frac{Q}{Q - it}.i* - K.\frac{Q}{Q - it}.it + Laplace^{-1}\left(\frac{Exp(s)}{Sel(s)}\right).0 \tag{12}$$

Charge model (i*<0)

$$f2(it, i*, i, Exp) = E_0 - K.\frac{Q}{Q.0.1 + |it|}.i* - K.\frac{Q}{Q - it}.it + Laplace^{-1}\left(\frac{Exp(s)}{Sel(s)}\right).\frac{1}{s} \tag{13}$$

Where

E_{Batt} is nonlinear voltage (V), *E0* is constant voltage (V) and *Exp(s)* is exponential zone dynamics (V). The battery mode represents by *Sel(s).* During battery discharge *Sel(s)* = 0 and during battery charging *Sel(s)* = 1. *K* is polarization constant, in Ah^{-1}, *i** is low frequency current dynamics, in A and *i* is battery current, in A. ***it*** is extracted capacity, in Ah, *Q* is maximum battery capacity, in Ah, ***A*** is exponential voltage, in V and *B* is exponential capacity, in Ah^{-1}.

2.3.5 Super capacitor

Supercapacitor storage systems (SCSSs) are electrical double layer storages, which are gaining more consideration in the existing electric grid and grid off rapid growth of renewable source[34]. For short-term power exchange, the greatest commonly fulfilled technology was presented as supercapacitor storage energy that has characteristics of high energy density and good efficiency in wind energy applications[35], [36]. Due to good electrical behaviors, its long life-time and its relatively low initial cost, ultra-capacitor was preferred in short-distance city electric bus transportation[37], [38].

Ultra-capacitors, double-layer capacitors or supercapacitor they are also known as electrochemical capacitor. The energy stored among a pair of charged plates is significantly larger than conventional capacitor. In addition to that, super capacitor also provides a great advantage over batteries and conventional capacitor such as the capability to be charged and discharged continuously without degrading. Applications, such as starting actuators, engines and in electric vehicles for transient load razing and regenerating the energy of braking are common to supercapacitor[39].

2.3.6 Supercapacitor Model

To represent the most popular types of supercapacitor, the generic model of super capacitor block has been parameterize implemented as shown in Figure 10 bellow[40].

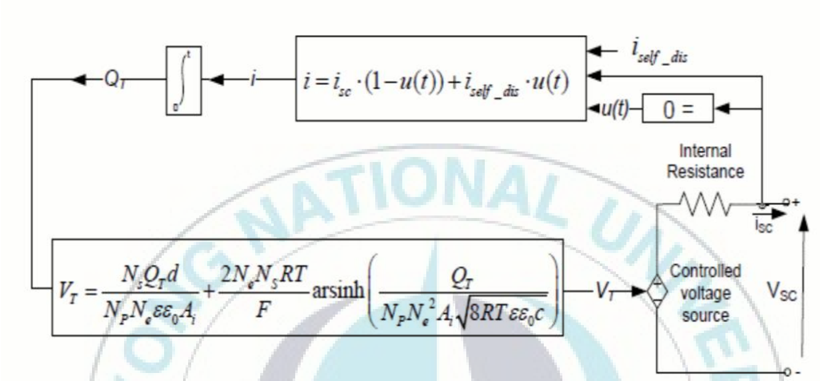

Figure 10 Equivalent circuit of super capacitor[40]

$$V_{SC} = \frac{N_s Q_T^d}{N_p N_e \varepsilon \varepsilon_0 A_i} + \frac{2N_e N_s RT}{F} \sinh^{-1}\left(\frac{QT}{N_P N_e^2 A_i \sqrt{8RT\varepsilon\varepsilon_0 c}}\right) - R_{SC} \cdot i_{SC} \qquad (14)$$

$$QT = \int i_{SC} dt \qquad (15)$$

When i_{SC} is zero the self-discharging phenomenon of super capacitor (SC) is modified as:

$$QT = \int i_{self\_dis} dt \qquad (16)$$

Where A_i is the area between electrolyte and electrodes (m^2),

c is the molar concentration ,c= $1/(8N_A r^3)$, F is faraday constant, i_{sc} is current of super capacitor (A), V_{sc} super capacitor voltage, R_{sc} total resistance of super capacitor, N_e is electrodes number of layer, N_p is number of parallel capacitors, N_s is number of series capacitors, Q_T is Electric charge (C),R is Ideal gas constant, d is molecular radius , T is operating temperature in (k), ε is material permittivity and ε_0 is free space permittivity.

Chapter 3: DC-DC Converters and MPPT Charging Technique

3.1 Types of Converters and MPPT

Usually, renewable energy power electronic converters with energy storage systems are employed to convert the output power of renewable sources to meet the load requirement. In addition, to increase the exciting and steady-state features of the green generation systems, to afford MPPT control, and to assimilate the energy storage system to deal with the challenge of the irregular nature of the renewable energy and the irregularity of the load demand[41].In general, energy convertors and MPPTs are non-separable power electronics devices of renewable energy harvesting systems. In renewable energy harvesting applications, DC-DC converters are as significant as the MPP tracking algorithm. DC-DC Boost, Buck, Buck-Boost and SEPIC has been considered in order to decide which one is more appropriate to be functional as Maximum Power Point Tracker (MPPT). The consideration among the related converters have been proposed based on simulation and analytical results.

There are also many energy generation algorithms that applied to extract available maximum power from renewable source of energy called maximum power point tracking (MPPT) algorism. For example, power generation from photovoltaic (PV) module has a nonlinear characteristics due to having dynamic solar irradiance, temperature levels as well as on load condition. Hence, by implementing MPPT algorisms we can harvest and increase the efficiency of energy harvesting in general[42]–[44].

3.2 SEPIC (Single Ended Primary Inductor Convertor)

Single-ended primary-inductor converter (SEPIC) is a comprehensive buck-boost type of DC-DC converter that allows the voltage output to be lower than, higher than or equal to the input voltage based on the converter topology. The output of the Single-ended primary-inductor converter (SEPIC) is controlled by the switch duty cycle[45]. In addition, the SEPIC converter was selected due to its high efficiency, possibility of measuring the open circuit without additional switches[43].

Most of the old-fashioned maximum power point tracking are dependent on boost or buck converters. However, boost converts are used when PV voltage is less than the load (battery) voltage, whereas buck converter are used when PV input voltage is greater than the battery load (voltage). In order to have flexible process Buck–Boost converters are preferred because if the load requires lesser voltage from the input Buck converter diminishes the voltage whereas Boost converter upsurges the voltage if the load needs more voltage from the input. However, the problem with buck-boost converter is having high input current ripple which needs additional filter for decrease of harmonic section in the current. Therefore SEPIC converter is good alternative than buck boost converter[46].

3.3 SEPIC Mode of Operation

The schematic diagram for SEPIC convertor as shown in Figure 11, in order to convert energy from one voltage level to another level exchanges energy between inductors and capacitors. The output of the single-ended primary-inductor converter (SEPIC) is controlled by the switch **Q** duty cycle[47].

3.3.1 SEPIC Continuous Mode of Operation

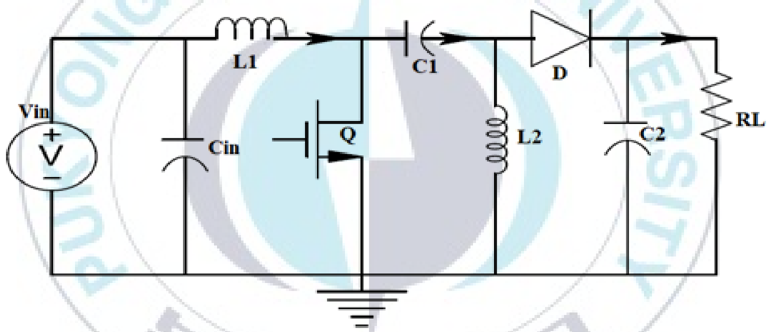

Figure 11 SEPIC Converter topology

This converter consists of an input capacitor C_{in}, coupling capacitor C_1 which is used for protection against short circuit load form input to output side, output capacitor C_2; coupled inductors L_1 and L_2; a power electronics switch MOSFET Q and a diode D. capacitor C_{in} and C_2 are used to protect DC biasing current from preceding stage.

When the current in the inductor L1 (I_{L1}) never falls to zero it is called SEPIC continuous conduction mode. During steady state operation of SEPIC the average voltage through capacitor C1 (V_{C1}) is the same with the input voltage V_{in}. Since C1 blocks direct current (DC), the average current across C1 (I_{C1}) is zero which means only inductor L2 is source of DC load current. Therefore, the average load current across the load is the same as the average current through inductor L2 (I_{L2}).

When the MOSFET switch Q is **ON** as shown in Figure12 the current in inductor L1 is increasing and the current across inductor L2 goes more negative.

To increase the current in the inductor L1, the energy is applied from the input source. The voltage at the inductor L1 is approximately V_{in} and the voltage across the inductor L2 is approximately negative voltage of C1 (V_{C1}).

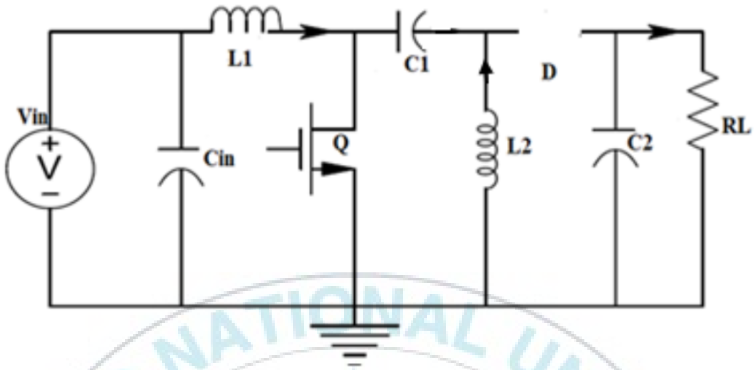

Figure 12 Closed mode of SEPIC converter

Hence, the capacitor C1 provides energy to increase the current through L2 and then the energy that stores in inductor L2 is increase.

When the MOSFET switch Q is **OFF** as shown Figure 13 the current in inductor L1 becomes the same as the current across C1 because inductors doesn't allow instantaneous change of current. As shown in Figure 13 the negative inductor L2 will added to the inductor current L1 in order to increase the current across the load (in our case battery or super-capacitor current), the energy is applied from the input source. The voltage at the inductor L1 is approximately V_{in} and the voltage across the inductor L2 is approximately negative voltage of C1 (V_{C1}). Therefore, we can conclude that during switch OFF the power delivered to the load is the summation of both inductors L1 and L2.

The input capacitor C_{in} is essential to reduce the special effects of the internal resistance and parasitic inductance of the power supply.

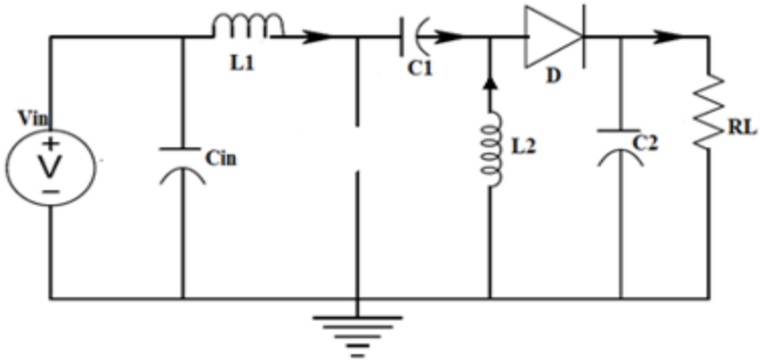

Figure 13 Open mode of SEPIC convertor.

The back boost abilities of the SEPIC are promising because of capacitor C1 and inductor L2. Switch Q and Inductor L1 produce a typical boost converter, which generates a voltage (V_Q) that is greater than V_{in} and the magnitude of V_Q is determined by the duty cycle of the switch Q. Since the average voltage through C1 is V_{in}, the output voltage (V_L) is $V_Q – V_{in}$. If V_Q is less than twice of V_{in}, at that point the output voltage will be a lesser amount of input voltage. If V_Q is larger than twice of V_{in}, then the voltage at the output terminal will be larger than the voltage at the input terminal.

3.4 DC-DC Boost Battery Charging System

Boost converts are very important when the source of energy is less than the load (battery) voltage. Because of its reliability, having less components, simple and easy structure to implement with less cost DC-DC boost choppers are most popular[48].

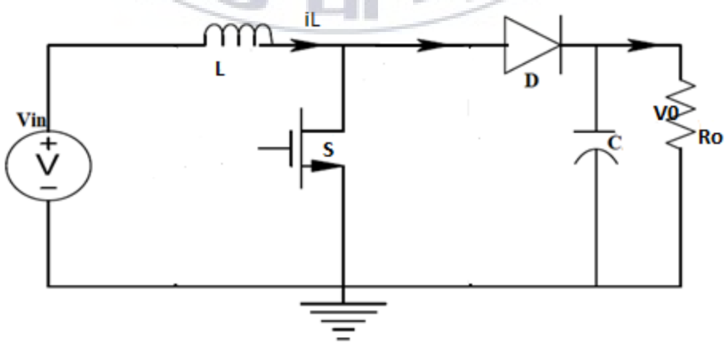

Figure 14 DC-DC Boost Convertor Topology

Boost converters in continuous mode of operation have two operational switching modes namely switch on (closed mode) and switch off (open mode) operations.

For the duration of closed mode, the converter dynamics can be stated in the following equations.

When switch S is ON state, the input voltage V_{in} appears through the inductor, which leads to change in current at the inductor;

$$\frac{dI_L}{dt} = \frac{V_{in}}{L} \tag{17}$$

Where dI_L is change in current at the inductor during the time period t

At the end of S switch ON state the inductor current is increase therefore,

$$dI_{Lon} = \frac{1}{L}\int_0^{DT} V_{in}dt = \frac{DT}{L}V_{in} \tag{18}$$

Where D is the duty cycle of the system and T is period during switch ON.

When the switch S is in open state (switch off) the inductor current flows across the diode and the load.

Hence;

$$V_{in} - V_0 = L\frac{dI_L}{dt} \tag{19}$$

$$dI_{Loff} = \int_{TD}^{T} \frac{(V_{in} - V_0)dt}{L} = \frac{(V_{in} - V_0)(1-D)T}{L} \tag{20}$$

dI_{Loff} is change of the inductor current during off state.

At the steady-state condition of the converter;

$dI_{Lon} + dI_{Loff} = 0 \ , which\ is\ the\ same\ as$

$$\frac{V_0}{V_{in}} = \frac{1}{1-D}, \qquad that\ is\ equal\ to\ D = 1 - \frac{V_{in}}{V_o}$$

Where V_0 is the output voltage of the converter.

3.5 Types of MPPT Techniques

Maximum power point tracking (MPPT) is an algorithm that incorporated in charge controllers and applied for extracting available maximum power from PV module under certain conditions. The voltage and current at which PV module can harvest maximum power is called 'maximum power points'. The extracting maximum power varies based on solar radiation, solar cell temperature and ambient temperature[47].

There are various types of maximum power point tracking algorithms for renewable energy generation applications. Constant voltage method, short current pulse method, open voltage method, perturb and observe methods, incremental conductance methods and temperature methods are the various types of MPPT[49].

By owing its simplicity to code using cheap digital devices, easy implementation and good performance of steady state operation, perturbation and observation (P&O) algorithms have been popular methods in solar energy harvesting application[14], [50].

The flowchart of P&O is shown below.

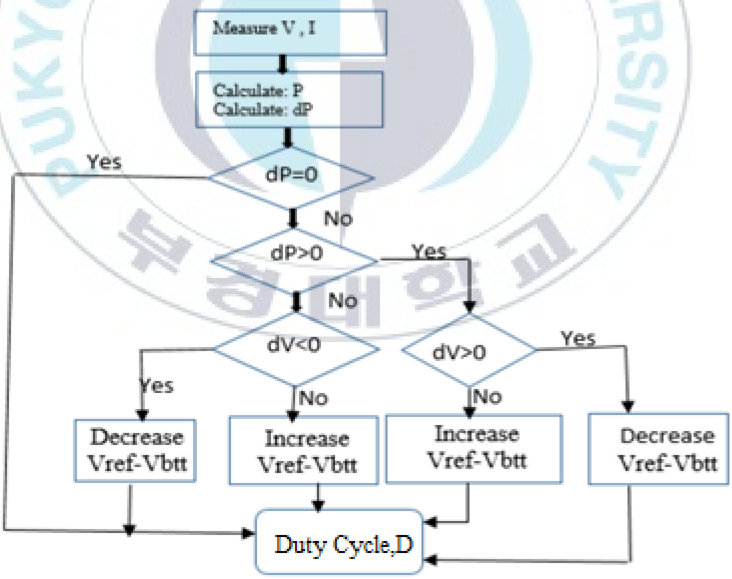

Figure 15 P&O MPPT Algorithm

Where Vbtt is battery voltage and Vref is reference voltage.

3.6 MPPT Battery Charging System

On this chapter presents the model and design of the PV charging control system with the SEPIC (single-ended primary inductance converter). The designed SEPIC provided PV module MPPT (maximum power point tracking) charge controller and the battery charging voltage controller. The control objective is to find the maximum power point and balance the power flow from the PV module to the battery. This chapter explains the full modeling of the SEPIC with input PV module and maximum power point tracking algorithm connecting with the storage system battery from previous researches[50]. Therefore, the battery voltage controller, in addition to the adaptive maximum power point tracking (MPPT) controller is designed.

Optimum charging configuration is require to upgrade lifecycle of battery with a smaller amount of charging time. For most of lead-acid batteries and Lithium ion batteries manufacture mentioned a charging must have constant voltage and current charging method in order to have safe charging process[51], [52].

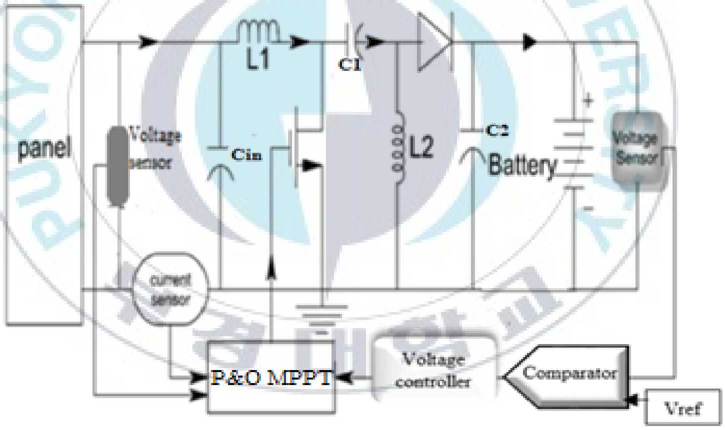

Figure 16 Model of MPPT Battery Charging System

This power conversion stage which is connected in the middle of a PV module and a battery storage system is called DC-DC SEPIC operating in continuous current mode.

On this control method, the output of the DC- DC converter is the feedback of PWM controller and adjusts the duty cycle[53]. This type of controller is designed by step-up/step-down voltage and has single loop control method. The parameters of this control system are measured voltage, reference voltage and comparator. So that on this mixed control system both voltage control mode and MPPT charging controller are used for charging the battery storage system.

On this charging level as shown is Figure 16 above the output voltage of single-ended primary inductance converter (SEPIC) charges the battery and sense by the voltage sensor to regulate the charging battery voltage. Hence, the output voltage from the battery compares with the reference voltage of the system. The Algorithms of the SEPIC MPPT and voltage mode battery charging controllers are operates as;

1st measure the current and voltage of the panel

2nd calculate the power from the measured current and voltage

3rd calculate the change in power

If the change in power is zero send the signal to the gate terminal of the switch (MOSFET or IGBT)

If the change in power is greater than zero increase the voltage difference of the reference voltage and measured output voltage of the battery then send the signal to the switch.

If the change in power is less than zero decrease the voltage difference of the reference voltage and measured output voltage of the battery then send the signal to the switch.

Chapter 4: The Hybrid Charging System

Hybrid energy storage systems is characterized by a valuable combination of two or more energy storage technologies with complementary operating characteristics, which are power density and energy, self-discharge rate, life-time, efficiency[54][55][56].Hence, on this chapter we present optimization framework and complete design of the maximum power point tracking (MPPT), super capacitor and battery storage system in cascade method. The regular MPPT technique maximizes the PV panel output power without taking into consideration the loss of power in the charger, while we consider loss of power in the charger and introduce a maximum power that transfers into storages. The maximized charging power used to charge the super capacitor, which charges the battery without loss of power by self-discharging process of super capacitor.

On this work, management of battery Storage System (BSS) connected with supercapacitor in series is designed using switch-mode DC-DC boost converter with a feedback controller. This design of a feedback controller for such converters is preferred to ensure an output voltage and current with zero steady state error and fast response to the input. To achieve these characteristics, a fixed frequency compensated voltage-mode controller and current mode controllers are designed[57]. The detail of MPPT super-capacitor charging system and boost battery charging controller are designed as follow.

4.1 MPPT Supercapacitor Charging System

This power conversion stage is the same as MPPT battery charging system except the storage system is supercapacitor unlike the previous one, which is battery. Hence, on this stage we have PV module and super capacitor storage system with DC-DC SEPIC in between that operates in continuous mode of operation.

On this charging level the output voltage of single-ended primary inductance converter (SEPIC) charges the super capacitor and sense by the voltage sensor to regulates the overall charging super capacitor voltage. Hence, the output voltage from the super capacitor compares with the reference voltage of the system.

The disadvantage of this system is only having fast self-discharging and low energy storage system. However, it has much more advantages over SEPIC MPPT and voltage mode battery charging control such as its constant voltage, current and constant power charging mode performance with adaptive properties to irregular solar irradiance and temperature[58].

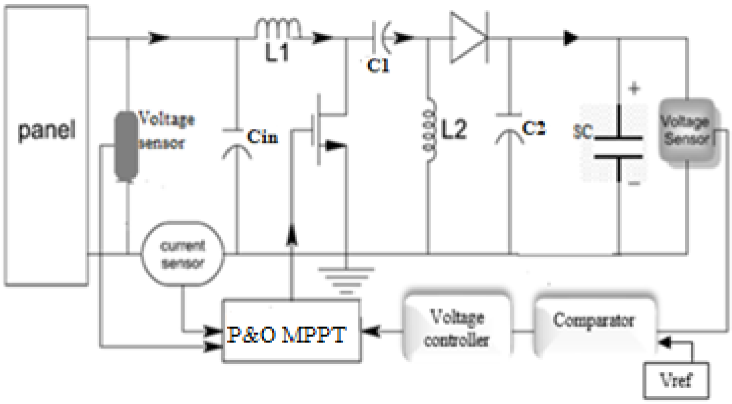

Figure 17 Model of MPPT Supercapacitor Charging System

The Algorithms of the SEPIC MPPT and voltage mode supercapacitor charging controllers are;

1st measure the current and voltage of the panel

2nd calculate the power from the measured current and voltage

3rd calculate the change in power

If the change in power is zero send the signal to the gate terminal of the switch (MOSFET or IGBT)

If the change in power is greater than zero increase the voltage difference of the reference voltage and measured output voltage of the supercapacitor then send the signal to the switch.

If the change in power is less than zero decrease the voltage difference of the reference voltage and measured output voltage of the supercapacitor then send the signal to the switch.

4.2 Boost Battery Charging Controller

This method has two (Parallel) terms to have voltage and current controller in parallel, which are current term and voltage term controllers at the same time[53]. Those control terms are constructed based on the reference output current, output battery voltage, input voltage and the inductor current of DC-DC boost converter. Hence, in our case those parameters are used to control the battery voltage and current by regulating the battery voltage and inductor current respectively.

The calculation of this control system is derived in the equation below and the block diagram of the system is shown in Figure 18[59].

$$D = \frac{L}{T_s}\frac{i_{ref} - i_L}{V_{ref}} + \frac{V_{ref} - V_{SC}}{V_{ref}} \qquad (21)$$

Where L is the inductor of the converter, T_s is the switching period, i_{ref} is reference current, i_L is an inductor current, V_{ref} reference voltage and V_{SC} the input voltage of the convertor. Note that Ro on the boost convertor model bellow is battery in our real simulation model.

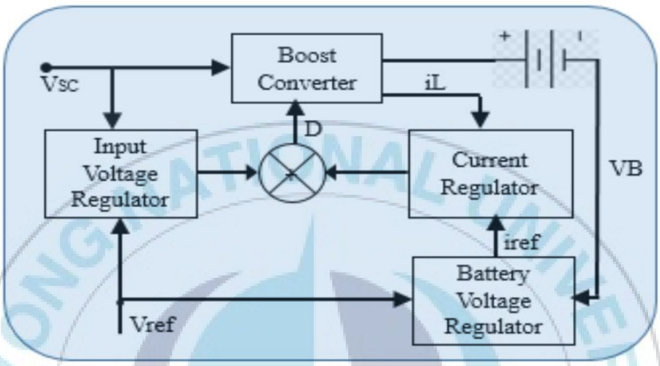

Figure 18 Topology of boost converter with its controller

4.3 The Hybrid System Topology

This system is a combination of MPPT supercapacitor charging system and boost battery charging system. This compensates the disadvantage of MPPT supercapacitor charging system and the existing MPPT battery charging system.

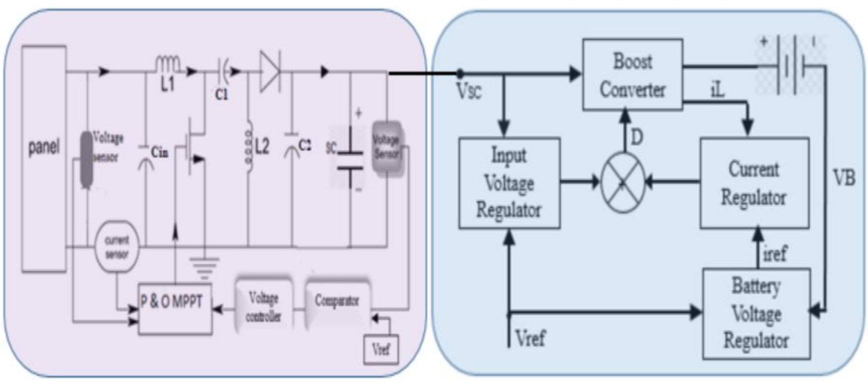

Figure 19 Model of hybrid charging system

The Algorithms of the combined charging system controller has two steps, which are super capacitor controller (1st step) and battery controller (2nd step).

1st step:

1st measure the current and voltage of the panel

2nd calculate the power from the measured current and voltage

3rd calculate the change in power

If the change in power is zero send the signal to the gate terminal of the SEPIC switch (MOSFET or IGBT)

If the change in power is greater than zero, increase the voltage difference of the reference voltage and measured output voltage of the supercapacitor then send the signal to the switch of the SEPIC.

If the change in power is less than zero decrease the voltage difference of the reference voltage and measured output voltage of the supercapacitor then send the signal to the switch of the SEPIC. This step was designed by PSIM power electronics software.

2nd step:

This 2nd step is called battery charging controller which has voltage and current mode controllers. This parallel controller is used to control the voltage and current values of the battery storage system by regulating the battery voltage and inductor current at the same time.

1st Measure the output voltage of the battery

2nd Compare the output voltage and the reference voltages

3rd Regulate it based on the required output

4th Measure the inductor current and compare it with the reference current

Finally, regulate the current and voltage and send the signal to the DC-DC boost convertor switch terminal. This part of the system was designed by using both Matlab/Simulink and PSIM software tools.

The Matlab/Simulink and PSIM connection of the system is show bellow in Figure 20.

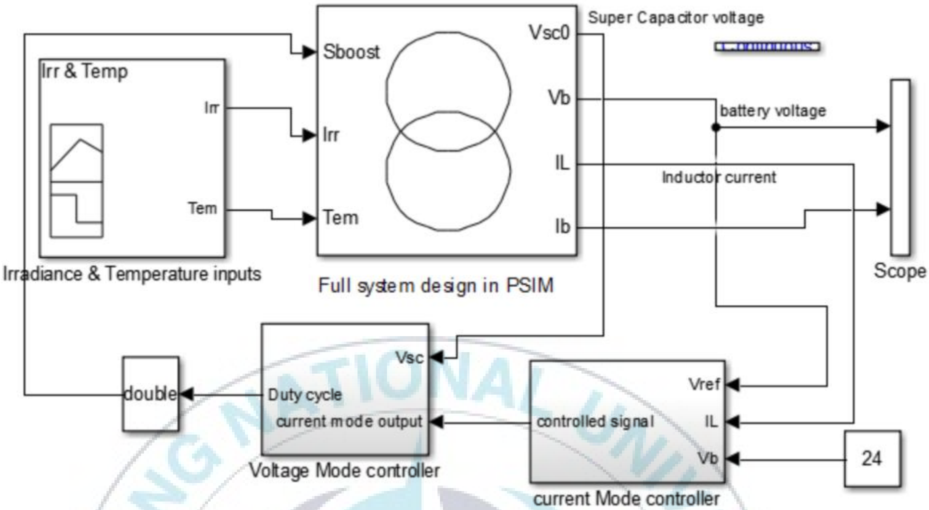

Figure 20 Matlab/Simulink and PSIM model of the hybrid system

Chapter 5: Simulation Results and Discussion

To demonstrate the validity of hybrid energy storage charging system for dynamic renewable energy, the simulation has been implemented by using both PSIM and Matlab software. The parameters used to design convertors and the output values from the solar panel are listed in graphs and tables as below.

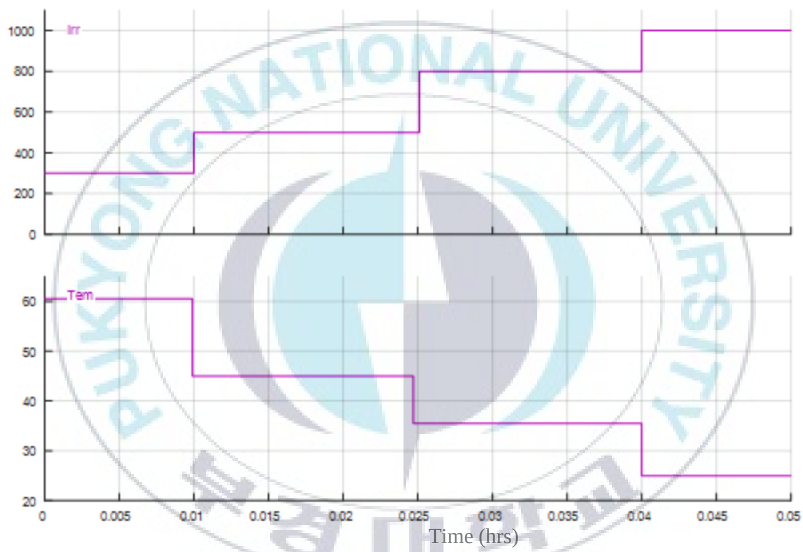

Figure 21 Irradiance (Irr) and Temperature (Tem) inputs

Table 1 SEPIC design parameters

Parameters	Values
Input voltage	0.5~17V
Inductor L1	500µH
Inductor L2	500µH
Input Capacitor C_{in}	1000µF
Capacitor C1	4.7 µF
Capacitor C2	47 µF
Frequency	5KHz
Output voltage	8~17V

Table 2 Boost convertor design parameters

Parameters	Values
Input voltage	0~17V
Indictor	100μH
Capacitor	33μF
Frequency	200KHz
Output voltage	24~25V

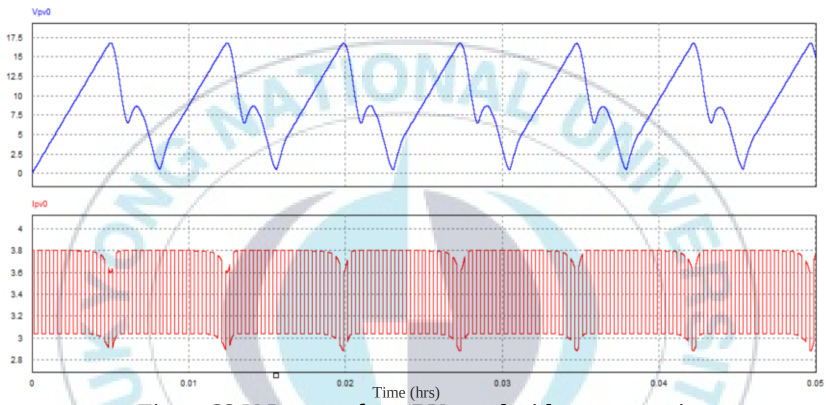

Figure 22 V-I output from PV panel with respect to time

Figure 23 Global maximum power from the PV panel

Where Vpv0 and Ipv0 are the voltage and current that generates from the PV (photovoltaic) panel.

5.1 The I-V and P-V Characteristics of PV Panel

The I-V and P-V characteristics have difference values based on the generation of solar irradiation and temperature.

On the user defined module data we have 36 cells per module and we have one module only. From that module we expect maximum power of the panel 60.8W, open circuit voltage 18V, short circuit current 4A, voltage at the maximum power point 16V and current at the maximum power point 3.8A at shown from the PV module in Table 3.

Table 3 User define data of PV Module

parameters	Parameter values
Number of cells	36
Maximum power	61W
Open circuit voltage	18V
Short circuit current	4A
Maximum voltage(Vmax)	16V
Maximum current(Imax)	3.815A

In the Figures 25 and 26, the simulation results are based on variable irradiance (0.3, 0.5, 0.8 and 1kW/m^2) and constant temperature (25^0C), which is as shown Figure 24.

Power generated from the panel is difference based on the changing solar irradiance from 300 to 1000 W/$m^{2.}$ The maximum power is occurred in 1000 W/m^2 which is approximately 60W and the minimum power is occurred at the 300 W/m^2 irradiance which is around 15W.

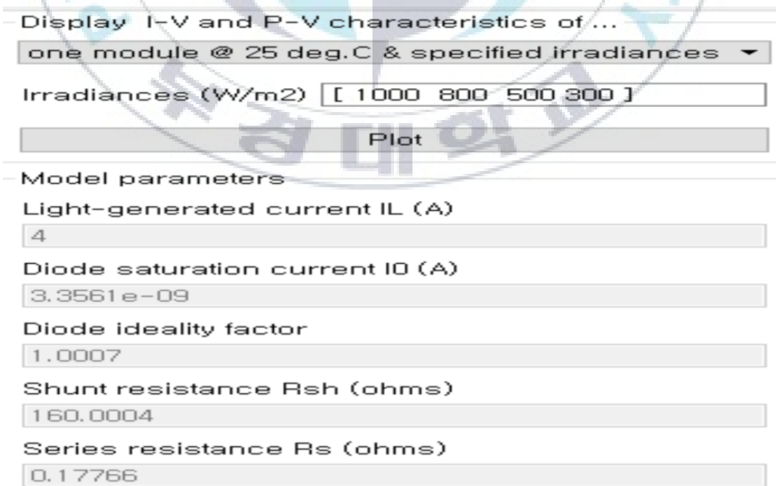

Figure 24 Inputs of variable irradiance with constant temperature

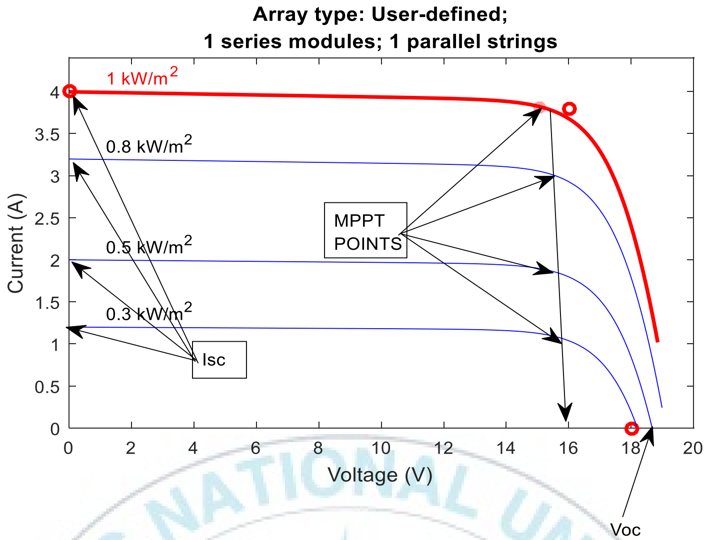

Figure 25 I-V curve of solar module on variable irradiance

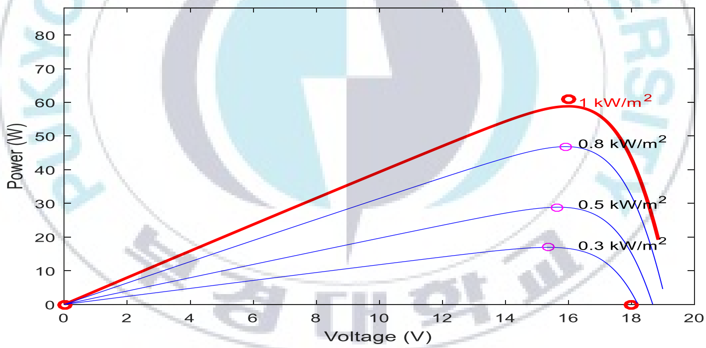

Figure 26 P-V curve of solar module on variable irradiance

The same is true power generated from the panel is difference based on the changing solar panel temperature from 25 to 60^0C. The maximum power is occurred in 25^0C which is approximately 60W and the minimum power is occurred at the 60^0C temperature which is around 45W. When we compare the effect of temperature and solar irradiance the temperature has less impact on the output power as we can observe from the results.

Figures 28 and 29 are simulation results based on variable temperature (60, 45, 35 and 25^0C) and constant irradiance (1000W/m^2), which is shown in Figure 27.

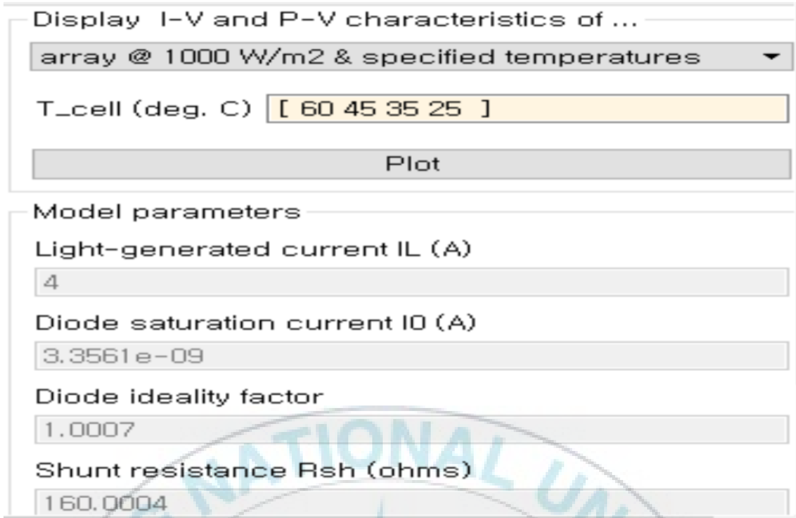

Figure 27 Variable temperature input with constant irradiance

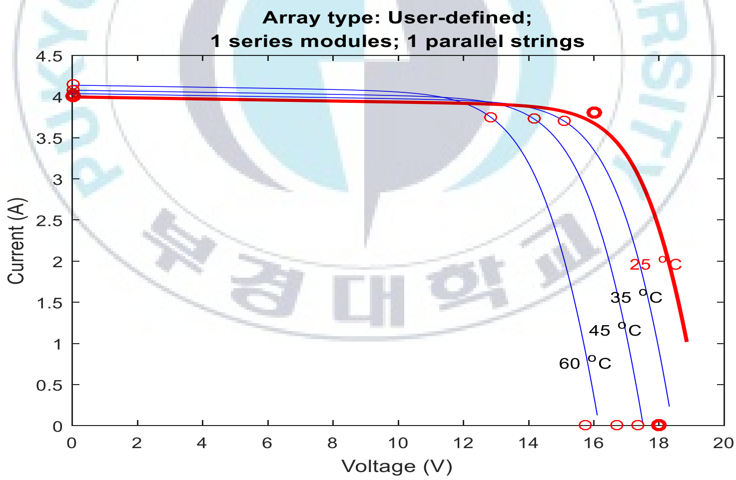

Figure 28 I-V Curve of solar module on variable temperature input

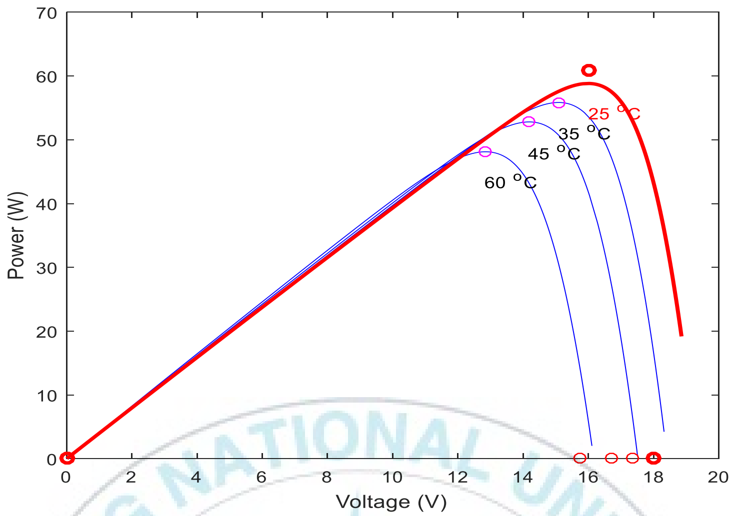

Figure 29 P-V curve of solar module on variable temperature input

5.2 Existing MPPT Battery Charging System Output

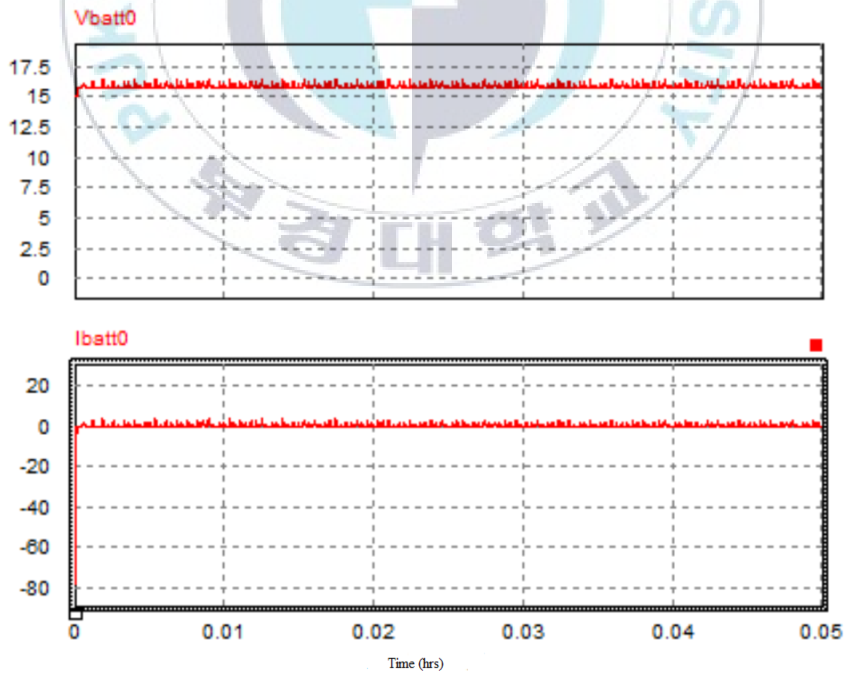

Figure 30 Output of MPPT battery charging system

Measure

Time	4.5790050e-002
Vbatt0	1.6279245e+001
Ibatt0	2.4405948e+000
Ibatt0*Vbatt0	3.9731040e+001

Figure 31 Global maximum value of MPPT battery charging system

As it is depicted in Figure 30 the output voltage and current of the battery is non constant because of the irregularity output of the solar system.

In addition, the maximum power generated from the solar panel was not harvested smoothly and it was very small in magnitude. As we can observe from the product of battery current and voltage (I_{batt0}*V_{batt0}) respectively in Figure 31, the global maximum power is approximately 39.7W, which is less than half of the required maximum power. Therefore, a compensator system must be designed to have the desired system output.

5.3 The Proposed System Simulation Outputs

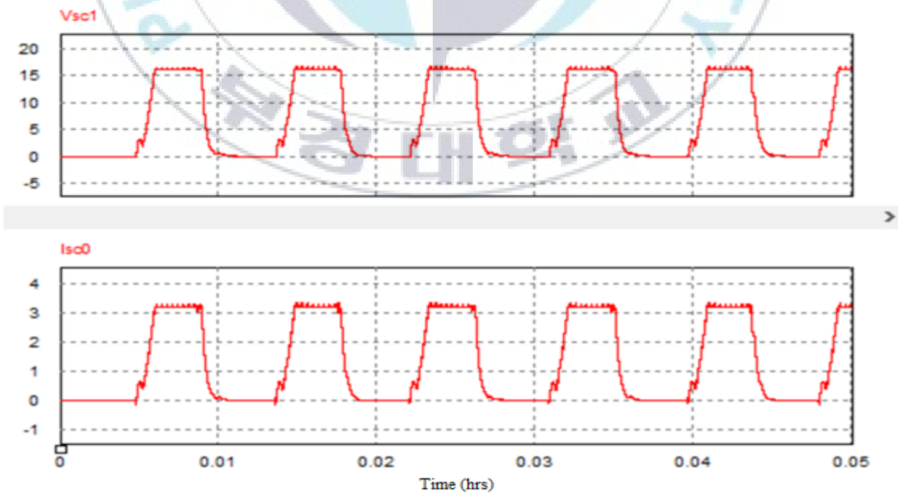

Figure 32 Output of MPPT supercapacitor charging system

Figure 33 Global maximum (max) value of MPPT supercapacitor charging system

The simulation results in Figure 32 and 33 are output of SEPIC MPPT and voltage mode supercapacitor charging system. As we are looking from the result the output voltage and current of the supercapacitor are better than the out puts of MPPT battery charging system. Because, super capacitor has the ability to resist the irregularity output of the solar panel and it has adaptive property. The product of supercapacitor voltage and current (V_{sc1}*I_{sc0}) has been approximately **60W**, which is the maximum power required from our system. From this point of view we have been harvested almost **99%** of energy that generated from our system. However, super capacitor also has drawback which is fast self-discharging and less energy storing properties. Hence, we have to design a new hybrid system which can compensate the disadvantage of this system and MPPT battery charging system.

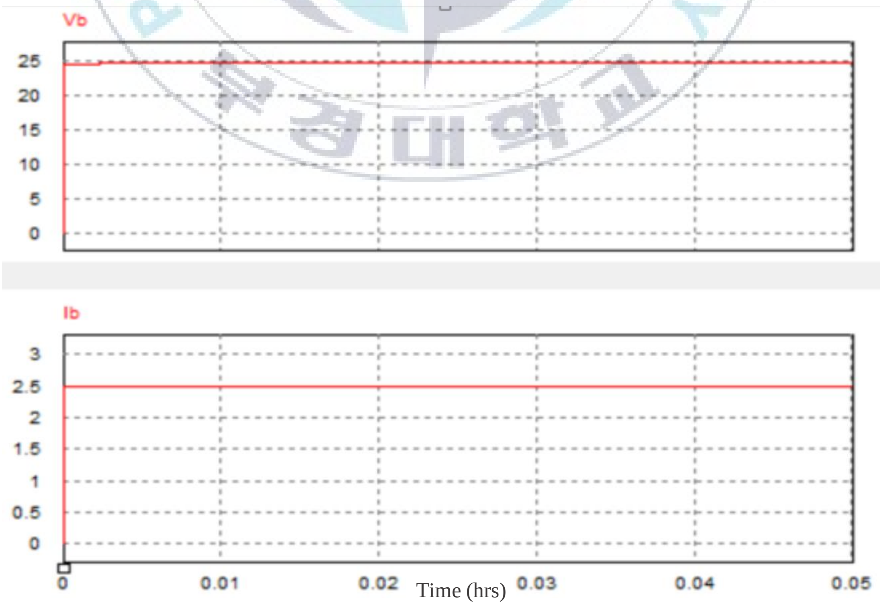

Figure 34 Hybrid charging system output

Measure

Time	4.9995605e-001
Vb	2.4564023e+001
Ib	2.4800000e+000
Vb*Ib	6.0918777e+001

Figure 35 Global maximum value of hybrid charging system

This simulation result is the compensation of both MPPT super capacitor charging and boost battery charging system.

On this simulation result we can observe that the output of the hybrid system has constant voltage and current output with in very short period of time. When we use the hybrid system it reduce the delay time of charging battery, maximizes the harvesting maximum power, reduce self-discharging property of the super capacitor and maximize the energy stored in the system. Hence, on Figure 35 simulation result the output maximum power is the ideal required maximum power from the system which is **60.9W** (Vb*Ib) almost 99.9% of the maximum power from the solar panel. Where Vb is battery voltage, Ib is battery current, Vsc1 is supercapacitor voltage and Isc0 is supercapacitor current.

5.4 Comparison of the Existing and Proposed System

The effect of our proposed model and control system can be seen on Figure 35. As we can compare the proposed battery charging controller and the existing battery charging control system, the proposed battery charging system has smooth charging process and excellent maximum output power. From Figure 31 we can observe that the global maximum of the existing MPPT battery charging has 39.7W which is less than the required power output. In addition, in Figure 30 the charging system of the battery has non constant current and voltage charging modes. But, the output power of the proposed charging system which is in Figure 35 has the global maximum power 60.9W, which is the same as input power from the source. Hence, our proposed charging system has high efficiency over the existing battery charging system.

Chapter 6

Conclusion

This thesis presented a hybrid energy storage system for renewable energy harvesting, which includes MPPT supercapacitor charging and DC-DC boost battery charging system in a cascaded technique.

In the MPPT supercapacitor charging method, P&O(Perturb and Observe) MPPT algorithm executes to track the maximum power point from the PV panel according to the temperature and solar irradiation and the maximum power is transferred to the super-capacitor by using voltage mode PI(proportional and integral) controller. The boost battery charging technique is the 2^{nd} part of the proposed system, which is the permanent storage system of our hybrid system model. This hybrid storage system is used to harvest solar energy by taking in to consideration of the charging system efficiency, by assuring safe and fast battery charging process. The SEPIC converter and boost converters have been advantageous for implementation, since there are easily adapted according to PV output voltage conditions.

We have developed a program by using Matlab/Simulink and PSIM (Software for power electronics) simulations, which helps to design the control systems and main circuits of the system respectively. From the simulation results we can conclude that the system has very high efficiency and has very fast charging process.

Even though we establish our research techniques by combination of PV panels, super capacitors and battery; the proposed energy optimization approach is not restricted to solar harvesting system only.

Future Work

By using this design, the hardware implementation of the system should be made and analyzed. According to hardware implementation and analysis, this system will be compared with the previous implemented systems for future.

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