

**Study Super-Capacitor Energy Storage System for Improving
Power Quality in Standalone PV System**

Melaku Shewalem G/Tsadik

ID - GSR 0043/09



A Thesis Submitted to

The department of Electrical Power and control Engineering

School of Electrical Engineering and Computing

**Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Electrical
Power (Power System Engineering)**

Office of Graduate Studies

Adama Science and Technology University

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Advisor: Getachew Biru Worku (DR.-ING)



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APPROVAL SHEET

We, the undersigned, members of the Board of Examiners of the final open defense by Melaku Shewalem has read and evaluated his thesis entitled “Study Super-Capacitor Energy Storage System for Improving Power Quality in Standalone PV System” and examined the candidate. This is, therefore, to certify that the thesis has been accepted in partial fulfillment of the requirement of the Degree of Master.

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DECLARATION

I, the undersigned, declare that this MSc thesis is my original work, has not been presented for a degree in any other university, and all sources of materials used in this thesis have been fully acknowledged.

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This MSc Thesis has been submitted for examination with my approval as thesis advisor.

Getachew Biru (Dr. - Ing)

Advisor

Signature

Date of submission: ____ / ____ / ____

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ACRONYMS

Ah	Ampere Hour
CSP	Concentrated Solar Power
DC	Direct Current
DoA	Days of Autonomy
EMS	Energy Management System
EPR	Equivalent Parallel Resistance
HESS	Hybrid Energy Storage System
IC	Intermittent Charging
ICC	Interrupted Charge Controller
KG	Kilogram
KW	Kilowatt
LRV	Load Reconnects Voltage
LVD	Low Voltage Disconnect
PV	Photo Voltaic
RES	Renewable Energy Source
SC	Super Capacitor
SOC	State of Charge
TSC	Three States Charging
UPS	Uninterruptable Power Supply
VR	Voltage regulator
VRLA	Valve Regulated Lead Acid
V	Voltage

ABSTRACT

Recently the demands on various sources of energy especially renewable energy sources have significantly increasing. Demand escalation and technology implementation is accompanied with some issues. One of the major drawbacks of renewable energy generation is the change in energy production due to its variable in nature which adversely impact local loads that are sensitive to poor power quality. To mitigate large swings in power, the renewable energy source output conditioned by using energy storage systems and a small energy buffer. The best known storage was batteries, flywheels (FW) and pumped hydro power. The research for new storage systems is still going on. As a result, new storage systems like hydrogen and compressed air were proposed. Most systems store electrical energy in another type of energy. Their cost, limited lifetime and the power injection capacity are serious disadvantages. To solve these problems, an improvement system is developed to smooth the renewable source power output by utilizing the energy of supercapacitor for high energy density with a high power performance storage system. In this thesis, a hybrid battery-supercapacitor based power storage and injection system capable of integrating a PV system as a manageable generation system to moderate fluctuations in the energy generated will be introduced and studied. A sample load is taken for analyzing the reliability of the power supply with PV system and the storage system with and without Supercapacitor compared finally, hybrid Battery-Supercapacitor storage system analyzed. The simulation is carried out using detailed model of MATLAB®/Simulink model and for economic analysis Homer software and Microsoft excel used. This work can reduce charge discharge property of battery and battery states of discharge were reduced by 50.5%. The battery replacement cost decrease up to 40-50% by using this hybrid storage system.

Keywords: *Renewable energy sources (RESs), PV (Photo Voltaic), Hybrid Energy Storage System (HESS), Energy Storage System, Super-Capacitor, Power Quality, MATLAB®/Simulink, Homer Software.*

CHAPTER ONE

Introduction

1.1 Motivation and Background

The goal of any power system is to deliver electricity to its customers in an economical and reliable manner. Unless this power is planned and maintained reliable, it causes adverse economic effect due to interruption costs and power outages. The importance of power quality issues is one of the most important aspects of future smart power system design and operation. The reason is that more active consumer participation in the power sector and introduction of renewable sources which has risen very considerably over the last two decades, having a great impact on voltage variation because its intermittency. Now a day, consumers require high quality power supply especially for operating their sensitive loads.

In modern industries, load equipment uses electronic controllers, which are sensitive to poor voltage quality and will shut down if supply voltage is depressed or if harmonic distortion of the supply voltage is excessive. Due to variation in energy obtained renewable sources, it became difficult in generating power and connecting it directly to the load adversely affect and frequency at the customer end.

Due to a marked increase in the number of equipment which is sensitive to adverse power quality environments, the disturbances introduced by nonlinear loads and the proliferation of renewable energy sources among others makes this thesis very essential. The power quality in the renewable energy sources (RESs) is widely studied due to the compliance with power quality standards on integration of renewable energy systems to the customer's accurate power need and its impact on some sensitive loads.

In order to maintain smooth power flow with constant voltage and frequency, the system should be integrated with properly designed Energy Storage System (ESS). In standalone photovoltaic systems the electrical energy produced by the PV array cannot always be used when it is produced because the demand for energy does not always coincide with its production but batteries are commonly used. The primary functions of a storage battery in a PV system are to:

- ✓ Store electrical energy when it is produced by the PV array and to supply energy to electrical loads.
- ✓ Supply power to electrical loads at stable voltages and currents, by suppressing or smoothing out transients that may occur in PV systems.
- ✓ Supply high peak operating currents to electrical loads or appliances.

In energy storage systems, lead acid, Li ion and Ni-Cd battery are usually used. Even if these storage systems comparably good there are some disadvantages like short service life, weight,

maintenance, the level of discharge and the impact on the environment due to battery deteriorate. One solution is to use supercapacitors. The unique property of Supercapacitors is they have high power densities that enable them to handle fast fluctuations in energy levels [4, 8] in which the renewable energy complained with. In comparison, commercially available supercapacitor has the lowest energy density but it is unmatched in power density as well as recharge cycles. These characteristics brought a new role onto supercapacitor as an electric storage device. The capacitance is related to the concentration of ions near the electrodes, thus when voltage increases, electric field attracts more ions. The highest capacitance is always found when low currents are used and vice versa.

This thesis will review and explains the various features and potential of supercapacitor hybridized with battery for improving quality and reliability of model resident in which the power faded with PV renewable energy. Modeling is made based on the load type and the impact of solar irradiance. Therefore in this thesis detail of supercapacitor and cost effective battery-supercapacitor hybrid storage system for renewable standalone system will be studied. The model simulation tested with the help of Mat lab/Simulink.

1.2 Statement of the Problem

Nowadays, Renewable energy sources (RESs) are increasingly present in electrical networks. One of widely used RES is photovoltaic technology. The increasing penetration rate of RES in the power systems is raising technical problems, as voltage regulation, harmonics, network protection coordination, loss of mains detection, and RES operation following disturbances on the grid network in addition production capital is also the biggest challenge .

Unlike utility power plants which produce electricity constantly, variations of PV output power due to the time of day and year or the weather, the output of PV modules is directly related to voltage and frequency fluctuations. Distribution system, sensitive customer loads and critical commercial operations suffer from outages and service interruptions which can cost financial losses to the consumers. Thus it has been pivotal in making these processes more productive, efficient, and safe.

However, this trend also makes manufacturing processes and equipment more vulnerable to real world power quality condition. Power quality is related to fluctuations in the electrical supply in the form of momentary interruptions, voltage sags or swells, transients, harmonic distortion, electrical noise, and flickering lights, among others. Thus an energy storage system is required for energy buffer for a photovoltaic source and plays an important role in improving the performance of operational stability and power quality of a power system. The ultimate reason that we are interested in power quality is economic value [4].

Battery energy storage is used in many locations but its disadvantages are the limited discharge rate and the degradation with time, resulting in a low battery state of charge (SOC). Low battery SOC leads to sulphation and stratification, both of which shorten battery life.

Supercapacitor are property long life (more than 300000 charging and discharging, good reversibility, high rates of discharge-charge, very low internal resistance, high efficiency, high power output, it is safe, possibility of use in remote locations (no maintenance), simple loading methods, maintenance free operation[8].

One of the feasible solutions for photovoltaic renewable energy sources is hybridization of high energy batteries with supercapacitors. This thesis studies cost effective storage system and power quality problem mitigation using battery-supercapacitor hybrid storage system. The systems interfaced to the stand alone photo voltaic source with the help of buck boost converter to inject and remove unwanted harmonics and investigate the impact of renewable sources on power quality. The voltage fluctuations generated by PV system are analyzed, during continuous operation as well as for generator interconnection if available.

1.3 Significant of the Study

This study will be so important due to

- ✓ The disadvantages of using batteries adverse impact on the environment, short life service, weight and need to maintain the level of charge.
- ✓ Need for very high energy density device with a high power performance and a long lifetime on PV system.
- ✓ The economic impacts of standalone PV system on customers and load equipments.
- ✓ Reducing distribution network power fluctuation when used with power improvement units.
- ✓ Power quality (PQ) and reliability of a power system
- ✓ Reducing equipment damage in both supplier and customer side.
- ✓ Voltage notches may come sufficiently close to zero to cause errors in instruments and control systems, can be maintained.
- ✓ Supporting the penetration of renewable energy sources through reducing the intermittency of the supply.

1.4 Objective

1.4.1 General Objective

- The general objective of this thesis is to Study hybrid battery-supercapacitors storage for improving the storage system of standalone PV system.

1.4.2 Specific Objective

- Identify alternative energy storage for PV system other than battery and fuel cell.
- Study hybrid battery- supercapacitor storage system to increase the lifetime of the devices with best power quality and reduce environmental impact.
- Study the potential of supercapacitors in improving quality and reliability of electric energy supply.

- Reviews the current trends of battery-supercapacitor HESS used in standalone PV system.
- Evaluate the capability of supercapacitors in mitigating voltage variations and with solar radiation.
- Propose various battery-supercapacitor HESS topologies and system should also provide the best orientation for the HESS to serve demand load with appropriate control system.
- Design storage system with high energy density device with a high power performance.
- Mitigate power fluctuation and analyze the effects of the power quality for PV system.
- Compare the performance of the system with and without the proposed solution.
- Evaluate energy management controller to determine the cost saving of the battery supercapacitor HESS for the complete system.

1.5 Scope of the Thesis

The scope of this thesis is mainly focused on studying the applicability and effectiveness of supercapacitor and battery-supercapacitor hybrid energy storage system for PV power system. In this thesis the hybrid energy storage system can be modeled using math lab Simulink for monitoring the supercapacitor's operation. The detail system cost analysis have been done using homer and excel.

1.6 Research Hypothesis

Photovoltaic (PV) power systems convert sunlight directly into electricity. A residential PV power system enables a home owner to generate some or all of their daily electrical energy demand on their own roof. Stand alone or autonomous systems are not connected to the grid. Some stand-alone systems known as PV-hybrid systems or island system may also have another source of power, wind turbine, bio-fuel or diesel generator, etc.

A stand-alone system varies in size and type, but 20Wp-1kWp is quite common. The stand-alone system is also known as an off grid system. Off-Grid systems (standalone) use a photovoltaic system to supply electricity to a consumer unit directly or via a battery, independently of other energy sources. These systems are suitable for small devices and equipment not close to an electricity supply (e.g. street lighting, water pumps, and radio signal equipment).

PV panels are continually improving and becoming more efficient but remain an intermittent power generator. A storage system is required in an autonomous PV system to consistently meet the load requirement. In general, lead acid batteries are the chosen storage technology. As can be seen from the literature PV batteries have a number of failure modes which reduce the battery lifetime, increasing the system cost. The runtime of the battery is also affected by the voltage drop which occurs during high current discharge.

A number of PV power applications require relatively low average power but a relatively high peak power. From the technical review it becomes apparent that combining an supercapacitor and a battery to form a HESS reduces the strain of high discharge currents from the battery. This results in extended battery runtime and lifetime. The battery SOC limit will have an impact on the effectiveness of the supercapacitor in the system; this should be further investigated when comparing a HESS to a system with battery only storage. The system cost difference between a HESS and a battery storage system has not been discussed in the literature. The cost of the storage system will always have an impact on the chosen configuration.

This work focuses on a battery supercapacitor HESS for PV applications that require high peak to average power or pulse power. A methodology to optimally size the combination of batteries and supercapacitor in the HESS is required to prevent excess system cost and to prevent loss of load.

Unlike a battery only storage system the charge/discharge power to/from the HESS must be split between the battery and the supercapacitor. The priority or ratio of the power split between both components for charging and discharging should be examined to develop a control strategy that best utilizes the available energy and maintains the battery at a high SOC to prevent premature failure to meet the load requirement.

1.7 Thesis Organization

The study and design of supercapacitor and battery supercapacitor HESS for an autonomous PV system is the focus of this thesis. The thesis is organized into the following chapters: Chapter 2 describes the components of the PV system and provides models for each of the components. The lead acid battery is compared to the supercapacitor, to investigate the strengths and weakness of each technology. The different hybrid configurations for the system are explored, to obtain the best arrangement for the system. Recent related documents presented as literature review.

Chapter 3 describes the development of modeling and simulation of the standalone PV system. The required inputs load profile and the solar radiation on a horizontal plane at the site location. Materials required for the PV system and their characteristics with proper design calculations and possible arrangement presented in this chapter. The sampling rate is set to enable the peak power requirements of the load to be taken into account.

Chapter 4 describes the design of the PV system and the model developed for the simulation of domestic load. The component values and Mat lab simulation out come with proper description obtained for the battery and supercapacitor displayed.

Finally, the conclusions, recommendations and future researches are discussed in chapter five. Results obtained from this thesis work are summarized and relevant conclusions have been drawn. Possible solutions to the problems faced during the thesis work have been recommended and future works in the area of supercapacitor are proposed.

CHAPTER TWO

Theoretical Background and Literature Review

2.1 Theoretical Background

2.1.1 Overview of Standalone PV System

Continuous and reliable electric power supply is important for power systems. The world's population continues to grow, with increased reliance on technology, resulting in an increase in the demand for energy. Sometimes, unwilling outages or using an energy source with low reliability can be harmful for electrical systems. Currently the main source of energy is from finite resources such as coal, oil and natural gas. The world's resources of fossil fuel are declining, with the ability to produce high quality, cheap and economically extractable oil on demand shortly running out. The utilization of fossil fuels is also harmful to the environment. When fossil fuels are burned to produce energy they emit greenhouse gases, carbon dioxide and sulphur dioxide. The release of these gases into the atmosphere is contributing to climate change and the production of acid rain. The emission of certain greenhouse gases also has a harmful effect on the ozone layer, which is being depleted. Due to incremental fuel cost, shortage of reliability in power sources, increasing demand, and inappropriate effects of fossil fuels on environment, demands for using renewable energy sources have been increasing. Power generated by photovoltaic cells is a function of different parameters such as radiation intensity and temperature.

The increase in energy demand, the decline in fossil fuel resources, along with the environmental issues involved with burning fossil fuels has increased the need for alternative energy resources. Renewable resources that will not diminish from their utilization include sun, wind, earth and water. There has been a growth in the level of research being conducted in the development of technologies to utilize these resources, to obtain the maximum output energy.

Renewable energies are harnessed in different ways in the various regions of the world. The ranges of renewable resources that are being utilized include biomass, geothermal energy, wind power, hydropower and solar energy. Each of these renewable technologies has their advantages and disadvantages. Hydropower and geothermal energy are location specific limiting their utilization. The development of biomass has had implications on food production, as food crops are displaced to grow crops with a better yield for biomass. Wind turbines require regular maintenance due to moving parts and are not considered aesthetically appealing. Solar power has its disadvantages; however, photovoltaic (PV) panels require minimal maintenance, generate no noise and are being developed to be integrated into building designs. The cost of PV panels is also falling dramatically.

In recent years, using Hybrid Electric Energy Storage (HEES) systems have become more important and different models have been proposed.

2.1.1.1 History

In 1839, a French physicist Edmund Becquerel proposed that few materials have the ability to produce electricity when exposed to sunlight. But Albert Einstein explained the photoelectric effect and the nature of light in 1905. Photoelectric effect state that when photons or sunlight strikes to a metal surface flow of electrons will take place. Later photoelectric effect became the basic principle for the technology of photovoltaic power generation. The first PV module was manufactured by Bell laboratories in 1954.

As outlined by Thomas Edison solar energy is a powerful resource, with the earth's surface receiving a total annual amount of solar energy that is nearly 10,000 times the world's total primary energy requirement [16]. Significant growth has been seen by the PV industry in recent years. In 2010 the global installed capacity grew by 17GW from 23GW in 2009 to 40GW in 2010, in 2010 in the EU it was the number one renewable technology in terms of capacity growth. Figure 2.1 outlines the growth that occurred in the PV industry between 2000 and 2010, along with the predicted growth going forward to 2015. Two predicted growth outlooks are included, a moderate outlook and a higher policy driven outlook [18].

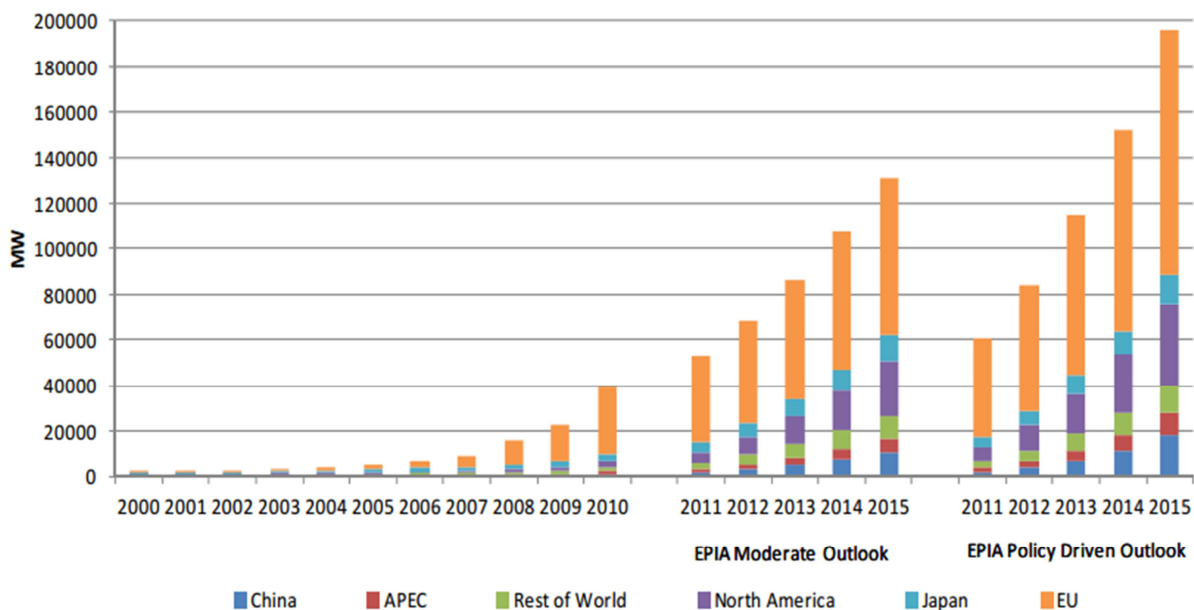


Figure 2.1: Evolution of the global installed PV capacity 2000-2015: [23]

The PV panel is an intermittent sustainable energy source whose output is time and weather dependent. There are two forms of PV systems, grid connected and autonomous. In grid

connected systems, excess energy can be provided to the electricity grid, at a set Feed in Tariff, with the grid providing the required energy at night and in times of low solar radiation. In this form the PV system does not require any energy storage. The same is not true for autonomous PV system, which requires energy storage to balance the generation and demand.

2.1.1.2. Present Situation of Solar Photovoltaic Production

Nowadays, there are two big types of solar power production. One of them is Solar Photovoltaic (PV) Systems, which uses solar panels to convert sunlight directly into electric power. The other one is Concentrated Solar Power (CSP) also known as “concentrated solar thermal”, this method uses solar thermal energy to make steam that is converted into electricity by a turbine thereafter.

During the last years, the growth of photovoltaic has been very strong worldwide. With the aim of moving towards a low carbon economy, each country has its target and even the European Commission has its own, for example, the Renewable Energy Directive sets rules for the EU to achieve its 20% renewable target by 2020 [17]. In 2015, global Solar PV capacity achieved 227 GW while CSP capacity reached 4.80 GW among 785 GW of total renewable power capacity (not including hydro) [23]. By the end of 2016, installed global photovoltaic capacity increased to at least 303 GW, which equals to 1.80 % of the electricity demand of the planet. The covered demand percentage might seem low, however, back in 2000 the total amount of PV installed was only 170 MW, compared to now the growth is considerable [17]. Top countries installing PV system during the last years are observed in Figure 2.2.

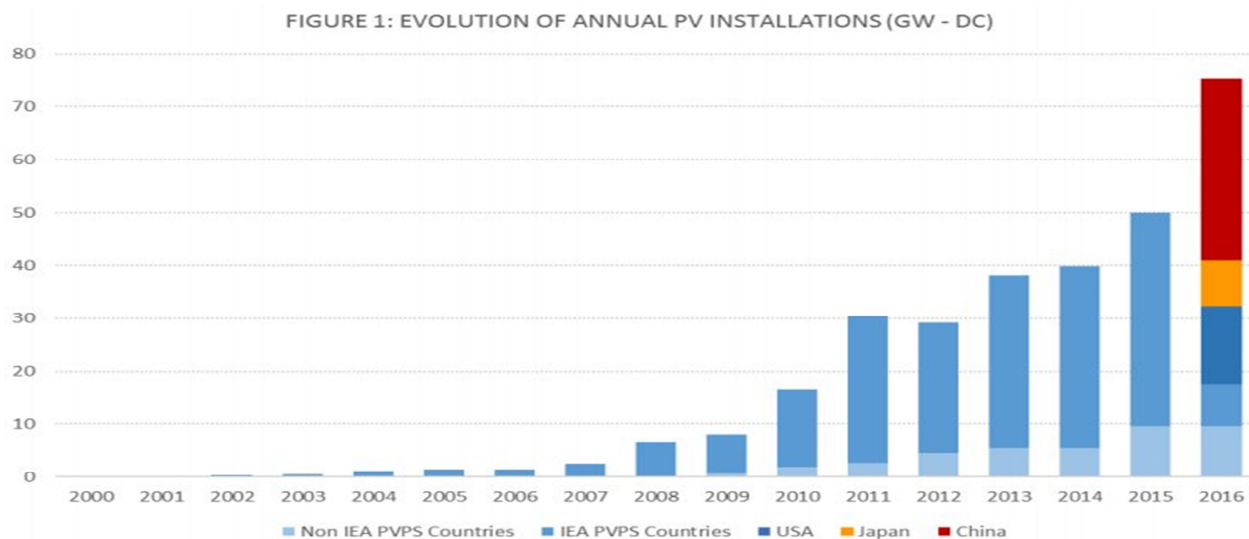


Figure 2.2: Evolution of annual PV installations from top countries. Source: [23]

2.1.2 Working Principle of Solar PV

Standalone PV systems produce power independently of the electricity grid and are most common in remote areas that are outside the reach of the electricity grid, due to the large expense

involved in extending the grid. Applications of standalone PV systems in remote areas include lighthouse operation, remote communication stations, rural housing and water irrigation systems. For rural housing, the development of building integrated PV systems means the cost of the PV can be offset against the cost of the material being replaced, for example the roof tiles. An important consideration when designing standalone PV systems is the use of low energy and energy efficient appliance, to ensure the electricity demand of the building is as low as possible. This will lead to a reduction in the PV system cost. Figure 2.3 illustrates the topology of a typical standalone PV system incorporating a PV panel, regulator, energy storage system, and load.

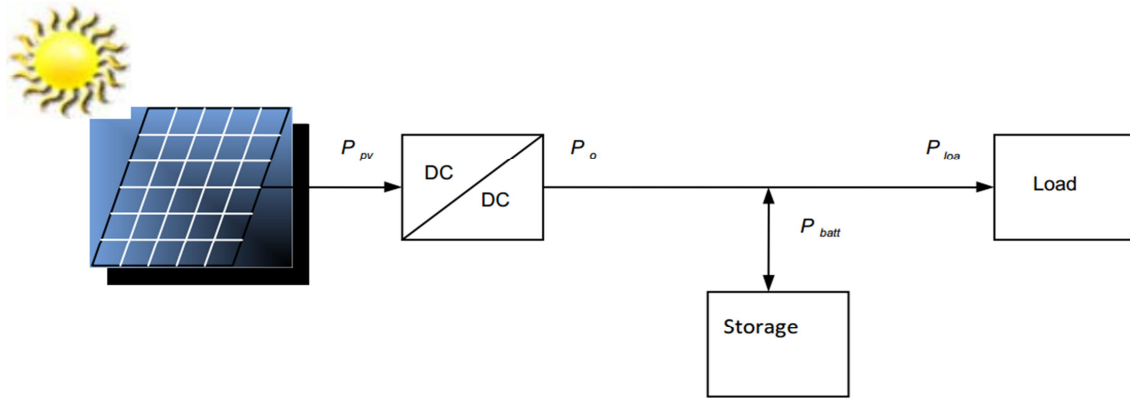


Figure 2.3: Stand-alone PV system topology: [2]

The following section will explain how a solar cell works and how is its equivalent circuit model.

2.1.2.1 Solar Cell Structure

A solar cell is an electronic device which directly converts sunlight into electricity. The mechanism in which solar light is directly converted into voltage or current is called the photovoltaic effect.

Basic steps in the operation of a solar cell are:

- a)*** The generation of light generated carriers (electrons and holes): due to the absorption of incident photons by the material (semiconductor, typically silicon: Si) to create electron-hole pairs provided that the incident photon has an energy greater than that of the band gap.
- b)*** The collection of the light-generated carriers by the p-n junction to generate a current: due to the existing electric field at the p-n junction, the p-n junction spatially separates the electron (to the n-type zone) and the hole (to the p-type zone) to prevent its recombination.
- c)*** The collection of the charge carriers at the contacts and the generation of a large voltage across the solar cell.
- d)*** The dissipation of power in the load and in parasitic resistances. A representation scheme of the solar cell operation can be observed in Figure 2.4.

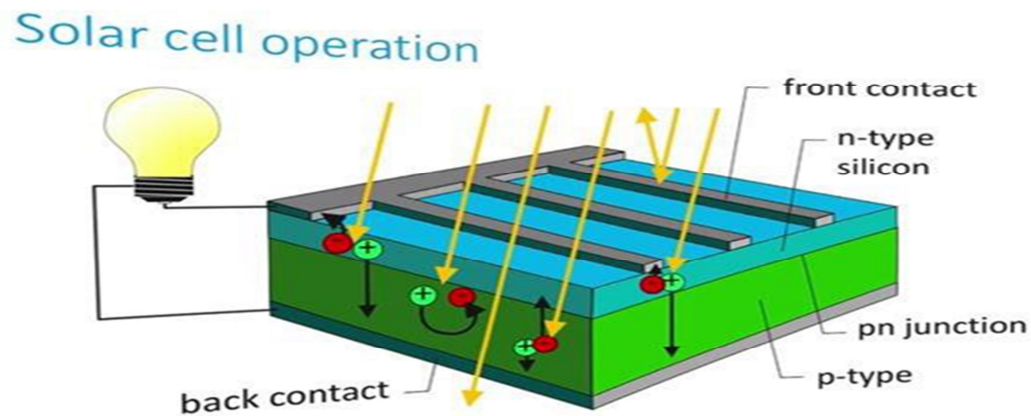


Figure 2.4: Simplified representation of a silicon based solar cell and its operation:[1].

A) PV Cell

Photovoltaic cell is the building block of the PV system and semiconductor material such as silicon and germanium are the building block of PV cell. Silicon is used for photovoltaic cell due to its advantages over germanium. When photons hit the surface of solar cell, the electrons and holes are generated by breaking the covalent bond inside the atom of semiconductor material and in response electric field is generated by creating positive and negative terminals. When these terminals are connected by a conductor an electric current will start flowing. This electricity is used to power a load.

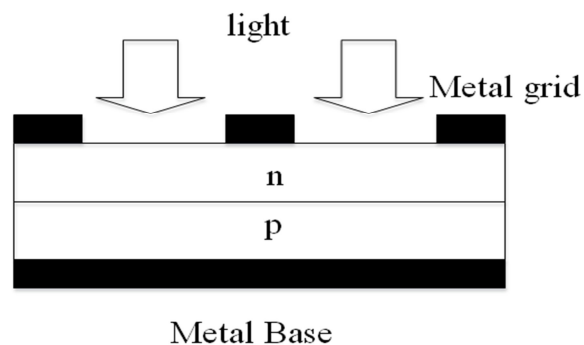


Figure.2.5: Structure of PV cell:[5]

B) PV Module

It is used for solar energy harvesting which is the main source of energy for the sensor node. The output power from PV is not stable and depends on the irradiance and temperature. The output power from PV array is different at different irradiance and temperature level [1]. A single cell generate very low voltage (around 0.4), so more than one PV cells can be connected either in serial or in parallel or as a grid (both serial and parallel) to form a PV module as shown in Figure2.5. When we need higher voltage, we connect PV cell in series and if load demand is high current then we connect PV cell in parallel. Usually there are 36 or 76 cells in general PV modules. Module we are using having 54 cells. The front side of the module is transparent usually buildup of low-iron and transparent glass material, and the PV cell is encapsulated. The efficiency of a module is not as good as PV cell, because the glass cover and frame reflects some amount of the incoming radiation.

C) PV Array

A photovoltaic array is simply an interconnection of several PV modules in serial and/or parallel. The power generated by individual modules may not be sufficient to meet the requirement of trading applications, so the modules are secured in a grid form or as an array to gratify the load demand. In an array, the modules are connected like as that of cells connected in a module. While making a PV array, generally the modules are initially connected in serial manner to obtain the desired voltage, and then strings so obtained are connected in parallel in order to produce more current based on the requirement.

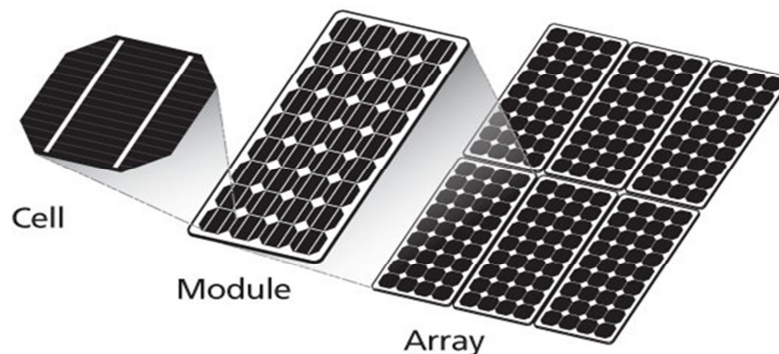


Figure.2.6: Photovoltaic system: [5]

A method of sizing a PV array is described in the IEEE guide for array and battery sizing in standalone PV systems [5]. The number of PV panels required is based on the solar radiation, array to load ratio, system losses and load. If the load is constant the solar radiation for the worst month is used in the calculations. For changing loads the worst case is selected as the month with the lowest array to load ratio. The number of batteries required is determined based on the Days of Autonomy (DOA), assuming no power is supplied by the PV array.

2.1.2.2 Storage System

An autonomous PV system utilizes an Energy Management System (EMS) to control the flow of power throughout the system. The EMS is generally responsible for controlling the converters in the system with the charging/discharging protocol of the storage system.

2.1.2.3 Battery

Another important element of a stand-alone PV system is the battery. The battery is necessary in such a system because of the fluctuating nature of the output delivered by the PV arrays. Thus, during the hours of sunshine, the PV system is directly feeding the load, the excess electrical energy being stored in the battery. During the night, or during a period of low solar irradiation, energy is supplied to the load from the battery.

I. General notions for battery

Some of fundamental concepts of the battery are

- ✓ **Nominal capacity** q_{max} - the number of ampere-hours (Ah) that can maximally be extracted from the battery, under predetermined discharge conditions.
- ✓ **State of charge SOC** – the ratio between the present capacity and the nominal capacity q_{max} : $SOC = q / q_{max}$, obviously $0 \leq SOC \leq 1$. If $SOC=1$ the battery is totally charged, otherwise if $SOC=0$ the battery is totally discharged.
- ✓ **Charge (or discharge) regime** the parameter which reflects the relation-ship between the nominal capacity of a battery and the current at which it is charged (or discharged). It is expressed in hours; for example, discharge regime is 30 h for a battery 150 Ah that is discharged at 5A.
- ✓ **Efficiency** – the ratio of the charge extracted (Ah or energy) during discharge divided by the amount of charge (Ah or energy) needed to restore the initial state of charge. It is depending on the state of charge SOC and on the charging and discharging current.
- ✓ **Lifetime** – the number of cycle's charge/discharge the battery can sustain before losing 20% of its nominal capacity.

In general, the battery models view the battery as a voltage source E in series with an internal resistance R_0 , as shown in Figure 2.7.

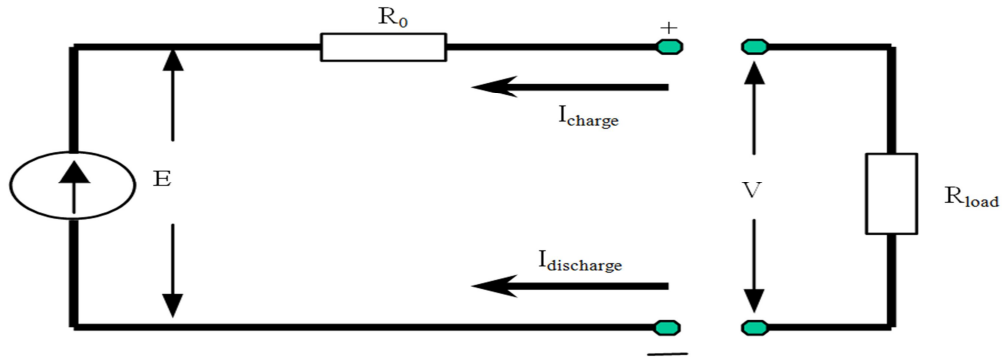


Figure 2.7: Schematic diagram of the battery: [47]

A number of different technologies can be utilized for energy storage in PV systems, the Valve Regulated Lead Acid (VRLA) battery being the most common choice. The influence of combining a supercapacitor with the battery bank in a hybrid system for pulse and peak current loads is assessed in this work. When designing the standalone PV system it is important that the system is optimized to ensure that the load can be maintained to the system specifications.

This chapter reviews the failures incurred by batteries in autonomous PV systems and the advantages of including supercapacitor in combination with the battery [47]. A number of optimization programs for PV systems currently exist; these programs are compared, to obtain their advantages and disadvantages. Finally an evaluation of the control systems for autonomous PV systems is performed. PV systems adopt a control system to monitor the state of the storage system, the load requirement and the output power from the PV panels, to control the power flow throughout the system.

II. Lead Acid Battery

The lead acid battery is a mature technology which is chosen for many applications because it is reliable, low cost and low maintenance. The battery produces electrical energy through chemical reactions. There are different types of lead acid batteries - flooded lead acid and VRLA batteries. VRLA batteries (Gel and Absorbed Glass Mat (AGM)) are lower maintenance. The hydrogen and oxygen are recombined back into water inside the battery, negating the need to refill the electrolyte. Valves allow excess pressure to be released from the battery preventing damage. Battery charging is a very important factor for prolonging battery life.

PV panels are not an ideal source for charging as their output is unreliable and heavily dependent on weather conditions. An optimum charge/discharge strategy cannot be guaranteed, which may result in prolonged periods of low battery SOC. The SOC is a measure of the available capacity remaining in the battery, calculated as a function of the rated capacity. Typically charge controllers are utilized in PV systems to protect the battery from over discharge and over charging. Set points are employed by the charge controller as illustrated in Figure 2.8 [41].

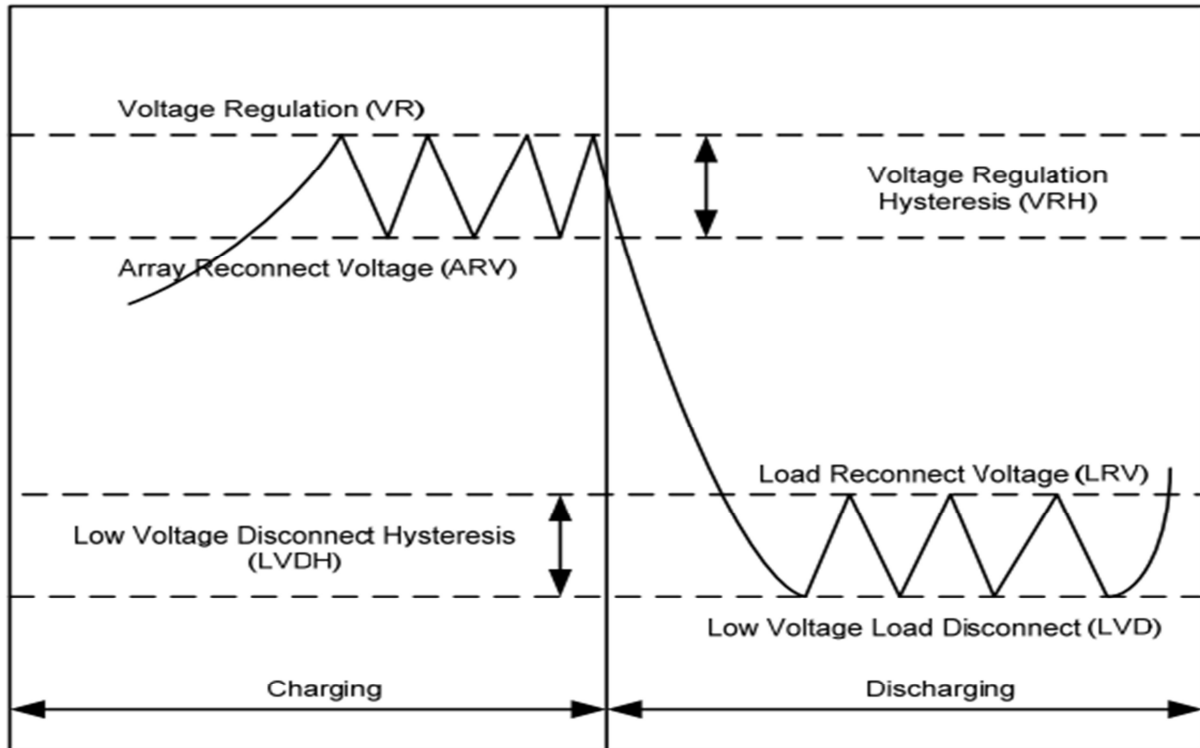


Figure 2.8: Battery charge controller set points: [41]

The Voltage Regulation (VR) set point limits the maximum voltage the battery can reach before being disconnected from the PV array during charging, to prevent overcharging. The battery voltage must then drop to the Array Reconnect Voltage (ARV) set point before being reconnected to the PV array for charging. Similar limits are employed during battery discharge. The Low Voltage Disconnect (LVD) set point gives the minimum voltage the battery can be discharged to before it is disconnected from the load to prevent over discharge. The Load Reconnect Voltage (LRV) set point indicates the voltage at which the load can be reconnected to the battery.

Various battery charging methods can be utilized in PV systems, including Intermittent Charging (IC), Three Stage charging (TSC) and Interrupted Charge Control (ICC). IC is the most commonly used method in commercial chargers. The battery is charged with MPPT between the predefined voltage thresholds VR and ARV. When the battery reaches the VR set point, the charging is stopped; the battery voltage is monitored until it drops to ARV at which point charging recommences [29]. TSC delivers power to the battery in three steps. The first step (bulk charging) charges the battery with maximum current until the battery reaches its final charging voltage, known as the absorption voltage. This step replaces 70-80% of the battery's capacity.

The second step is absorption charging. The charging current is steadily decreased while the battery voltage is maintained at the absorption voltage. This step replenishes the remaining 20-30% of the capacity. The final stage is float charging, where a small current is supplied to the

battery to maintain the battery voltage [10]. ICC is a variation of IC. ICC avoids the potential undercharging problem faced by IC. ICC charges the battery in four modes. Mode 1 - the battery is charged with constant current with a charge rate of $0.1C$ to an upper threshold. Mode 2 - The battery is then left in open circuit until the lower threshold limit is reached. In Mode 3 the battery is pulse charged with a charge rate of $0.05C$ until the upper voltage limit is reached again. In Mode 4 the battery is at full capacity and is disconnected. Modes 1-3 are repeated when the battery voltage falls to 97% SOC [20]. The voltage and current profiles implemented for each of these charging methods is given in Figure 2.9.

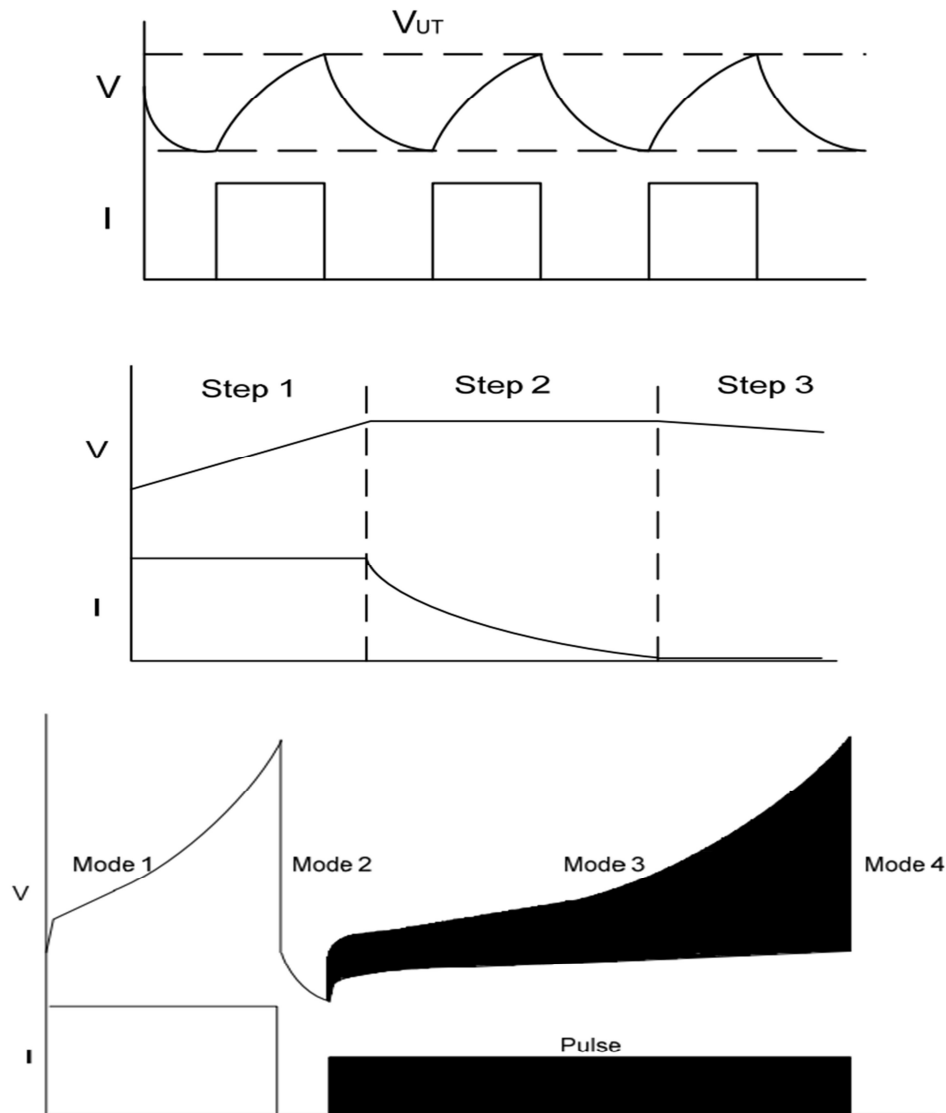


Figure 2.9: Battery charging voltage and current profiles for (a) IC (b) TSC and (c) ICC: [20]

The batteries used for PV energy applications are cycled regularly. They are required to supply power to the load during night time or under low solar radiation conditions, and are charged

during daylight hours. A battery model is utilized to assist with the design and optimization of the PV storage system. The model represents the storage capability of the battery under various operating condition.

III. VRLA Battery Model

Battery models fall into different categories which include mathematical, electrochemical, thermal and electrical models. An electrical equivalent circuit model is utilized to represent the battery in this situation. Various electrical models exist ranging from the simple to more accurate complex models. The simplest model consists of an ideal voltage source with a series resistance to model the internal resistance of the battery. Both the voltage and internal resistance are functions of the battery SOC. Monitoring of the SOC is important in PV systems as it gives an indication of the remaining battery run time. When periods of low battery SOC is known certain loads may be prioritized.

The model selected to represent the battery for system analysis is a resistance capacitance (RC) model shown in Figure 2.10 [47].

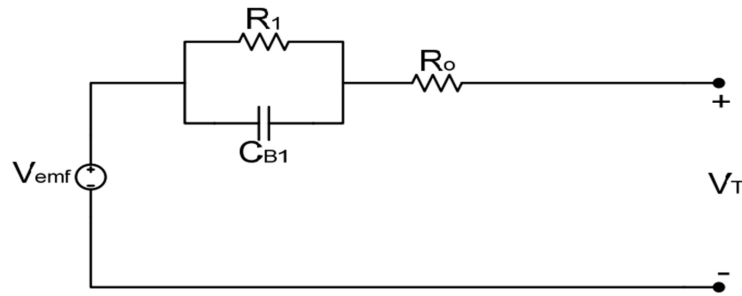


Figure 2.10: RC electrical equivalent battery model: [47]

R_0 is the ohmic resistance which causes the initial voltage drop due to the cell connectors, connectors, electrodes and the ionic path through the electrolyte. R affects the performance or rate capability of a cell. It causes a voltage drop during operation and also consumes part of the useful energy as waste heat. A charge separation exists between them solid electrodes and the electrolyte. A positive/negative ionic layer absorbed onto the electrode surface is balanced by an equal quantity of negative/positive charge in an adjacent layer in the electrolyte. This may be considered as the structure of a plate capacitor and is known as a double layer.

The electrical characteristics of the double layer are described in the model. The capacitor C_{B1} represents the charge shifting within the double layer and accumulating at the phase boundary between the active material and the electrolyte. The resistor R_1 represents the energy losses of the charge transfer within the double layer.

An improvement to the RC model is an RC model with parasitic or self-discharge resistance. Self-discharge is usually down to gassing, which results from battery overcharging [14]. PV

batteries can frequently be left undercharged and an energy management system is implemented to prevent battery over charging, therefore the parasitic branch is omitted from the model.

IV. Lead Acid Battery Failures

Energy storage is an important part of an autonomous PV system. Generally lead acid batteries are the most common storage technology, due to their wide availability, low cost, and low maintenance. PV panels are not ideal for battery charging since they are time and weather dependent. An optimum charge/ discharge strategy cannot be guaranteed resulting in poor battery life. Batteries have a very limited life cycle under extreme discharging conditions and need to be continuously replaced. The cost associated with the purchase of new batteries and the disposal of old ones is cumulative. Batteries are not environmentally friendly and thus cannot be easily disposed [39].

As a solution to this problem, manufacturers parallel many batteries to increase the power characteristics of the battery pack. This practice increases the weight and cost. Since the weight has been increased, the demand higher currents from the batteries and therefore once again more batteries are needed. Clearly this is not the best solution to the energy storage problem. Therefore, the batteries are regularly replaced making them the main contributor to the system lifetime cost [39].

1. Stratification affects the operating characteristics of the battery, reduces the battery capacity, and causes other forms of aging to occur.
2. Sulphation is caused by extended periods of low battery SOC. Increased sulphation occurs at the lower part of the electrodes due to stratification and eventually this region of the electrodes become unusable.
3. Corrosion of the lead grid occurs due to high positive potential at the positive electrodes. The cross section of the grid is decreased, increasing the grid resistance. A layer of lead oxides and sulphates is formed between the grid and the active material, increasing the contact resistance. These result in an increased ohmic voltage drop.
4. Erosion is the result of loosening of the active material of the electrodes due to mechanical loads incurred during cycling operation. The loosened material can be separated from the electrode and collected as sludge at the base of the battery. If the volume of the sludge is large it can result in a short circuit of the electrodes.
5. Short circuits can also occur from the growth of dendrites from the positive to the negative electrode through the separator. Prolonged time at a low SOC, low acid concentration, increases the dendrites growth rate.
6. Reverse charging of a single cell can occur when a cell within the string has a lower capacity and becomes overcharged.
7. Oxidation of additives to the lead sponge of the negative electrode results in large lead crystals forming on the negative electrode resulting in the loss of internal surface area and capacity.

8. Ice formation prevents battery operation and can also damage the battery casing while high temperature reduces battery lifetime. Increasing battery temperature accelerates corrosion, sulphation, gassing, and self-discharge.

Incorrect sizing and poor battery management can lead to overcharging of the PV battery in periods of high solar radiation.

2.1.3 Supercapacitor

Supercapacitors also known as electrical double layer capacitors are electrochemical storage devices developed in 1957. supercapacitor utilizes a physical reaction to produce power unlike batteries which depend on chemical reactions, therefore supercapacitor allow faster charge and discharge rates compared to batteries of similar volume. Supercapacitors have a greater power density than batteries by a factor of 10, allowing the supercapacitor to provide more power over a shorter period of time. Conversely, batteries have a higher energy density compared to the supercapacitor also by a factor of 10. For this reason supercapacitor are not substituted for batteries but often employed as a complementary technology in HESS to increase power density.

The supercapacitor employs the same principals as normal capacitors but its capacitance is in the thousands of farads range. The supercapacitor is constructed of two electrodes immersed in an electrolyte with anion permeable separator placed between the electrodes to prevent electrical contact, but to still allow ions from the electrolyte to pass through. Figure 2.11 shows the basic cell structure of the supercapacitor [33].

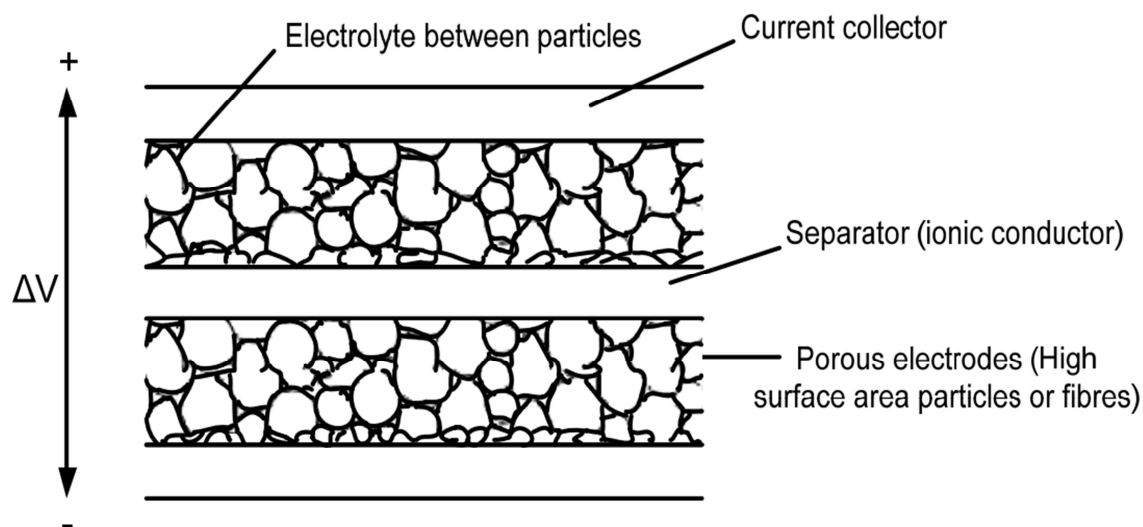


Figure 2.11: Supercapacitor basic cell structures: [33]

In the supercapacitor the charge is stored in the ionic layer that forms at the interface between each of the electrodes and the electrolyte, hence the accumulated charge forms an electric double layer. The large capacitance of the supercapacitor is as a result of the high surface area of the

electrodes. The most common electrode material used is highly porous activated carbon with a surface area of $2000\text{m}^2/\text{gram}$ due to its low cost, high surface area and availability. The development of the carbon electrode material influences its porous structures. It is the accessibility of the pores to the electrolyte that is important, if the pores are too small for access by the electrolyte ions they will not contribute to the electric double layer. Alternative electrode materials such as metal-oxides and conducting polymers are also being investigated.

The thickness of the dielectric also influences the capacity of the capacitor. For the supercapacitor the dielectric thickness is based on the size of the ionized electrolyte molecules and, therefore, is of the order of $10\text{\AA}$ (approximately 1.0nm). The voltage of the supercapacitor is determined by the type of electrolyte utilized, organic or aqueous. The organic electrolyte is the most common due to its high cell voltage range ($2\text{--}2.7\text{V}$) while the aqueous electrolyte has a breakdown voltage of approximately 1V . The separators are chosen depending on the type of electrolyte utilized. Polymer or paper separators are used with organic electrolytes while ceramic or glass fiber separators are employed with aqueous electrolytes.

The supercapacitor has a low electrical series resistance making it capable of delivering high currents. Supercapacitor also has a low operating voltage of $2\text{V} - 2.7\text{V}$. To increase the operating voltage of the supercapacitor bank to the required application voltage a number of supercapacitor cells are connected in series.

Connecting the cells in series reduces overall capacitance while parallel connection of the cells can be employed to increase capacitance. Since the series connected cells may not behave identically the voltage applied to the bank may not divide equally among the individual cells resulting in overvoltage of an individual cell, which could cause the cell to fail [37]. Cell balancing is employed to maintain individual supercapacitor s within their rated voltage. Cell balancing circuits can be either active or passive.

The simplest method of cell balancing is a passive circuit utilizing resistors in parallel with the supercapacitor s, illustrated in Figure 2.12. Resistors are generally ten times the average leakage current of the cell. Passive cell .balancing is simple and low cost, but it has a slow response due to the linearity of the leakage current with voltage and high parasitic losses due to ten times additional leakage current.

Therefore, passive cell balancing is suited to low duty cycle applications which can tolerate higher leakage e.g. backup power supplies.

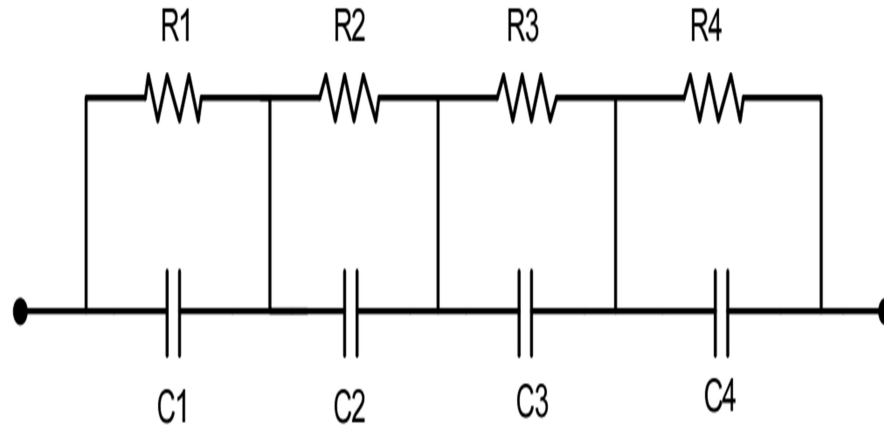


Figure 2.12: Passive resistor cell balancing circuit: [34]

Active cell balancing circuits shown in Figure 2.13 are utilized in application with high duty cycles and where low parasitic losses are necessary. The circuits use active switching devices; a voltage detection circuit controls the switches turning the switches on when the voltage across the cell approaches the bypass threshold voltage. Active balancing is fast, provides accurate equalization of the voltage distribution and has minimal parasitic losses but is more expensive than passive cell balancing.

Examples of active cell balancing circuits include switched resistors in parallel to each other. The resistor bypasses the main circuit when the switch is on. Each cell voltage is measured in this method. DC-DC converters connected across two neighboring cells can actively equalize the cell voltages. There are power losses due to the converters. This method has higher efficiency than other methods, but the hardware control is costly.

An alternative method utilizes zener diodes in parallel to the cells. The cell voltage is held constant as soon as the zener voltage is reached and the diode is used to bypass the main circuit. There are high power losses in the diode and the zener voltage has a strong temperature dependency. Another example of an active balancing circuit uses a comparator across two cells, comparing their voltages and moving charge to equalize the two cells. Maxwell technology adopts a linear voltage balancing system which always attempts to balance two adjoining supercapacitors based on the variation in voltage between the cells [34].

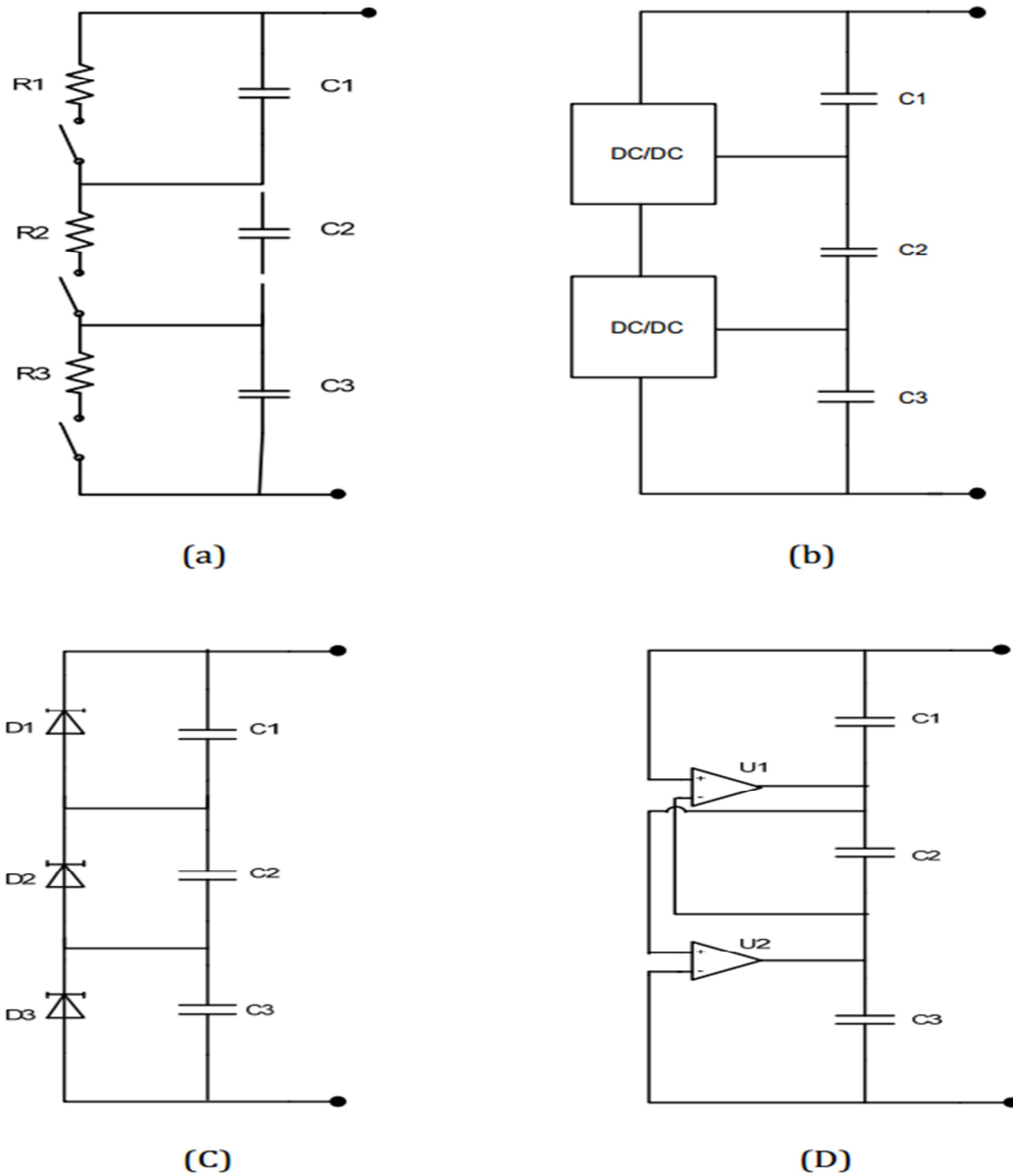


Figure 2.13: Active cell balancing circuits (a) Switched resistors (b) DC-DC converters (c) Zener diodes (d) Comparators: [34]

2.1.3.1 Supercapacitor Technology

Supercapacitor technology has been commercially available for over the past decade. They can store much more energy than conventional capacitors and are available in sizes up to 4000F with voltage ratings of up to 3V per cell. They can be discharged or charged faster than batteries and can deliver 10-20 times more power e.g. supercapacitors typically have 10 times the specific power (W/kg) as well as a much lower charge time when compared to lead acid batteries. They also offer 10 to 100 times the energy density (Wh/Kg) of conventional capacitors. In terms of energy and power density, supercapacitors can therefore be placed between batteries and

conventional capacitors [11-12]. A comparison of conventional storage technologies is shown in Table 2.1.

Supercapacitor can be used as a temporary power source for backup purposes. Batteries were first used for this application; however the large energy storage capability of supercapacitors makes them an alternative to batteries. In these applications the supercapacitor is charged from the mains and provides temporary power during a power failure.

The second application of supercapacitor is important in the field of energy storage in hybrid electric vehicles. Supercapacitor can be used to provide the short bursts of energy needed by hybrid electric vehicles during acceleration. Supercapacitors do not need regular replacement like batteries because they are not as adversely affected during repetitive deep charging and discharging. This also implies that supercapacitors are more environmentally friendly since they don't need to be frequently discarded. Supercapacitors can be fully charged from a total discharge within a few seconds. This makes them ideal for use in regenerative braking systems. Supercapacitors are not prone to temperature effects as are batteries and can operate in temperatures as low as -40°C [13].

Supercapacitors cannot replace batteries completely; however they can be used to complement each other. In the hybrid electric vehicle, the supercapacitor can be used during vehicle operation. During standstill a downsized battery can be used to power the auxiliary systems. A slow charge time can be used to charge the batteries and thus extending their lifetime. Although batteries cannot deliver large currents at extremely low temperatures, they can deliver enough current to slowly charge the supercapacitor, which can be used to start the vehicle. This could prompt the use of longer lasting batteries rather than large batteries designed to deliver hundreds of amps during a cold start.

Table 2.1: Comparison of conventional storage technologies [11]

Available Performance	Lead Acid Battery	Supercapacitor	Conventional Capacitor
Charge Time	1 to 5 hrs	0.3 to 3 s	10^{-3} to 10^{-6} s
Discharge Time	0.3 to 3 hrs	0.3 to 3 s	10^{-3} to 10^{-6} s
Energy(Wh/Kg)	10 to 100	1 to 10	< 0.1
Cycle Life	1000	> 500,000	> 500,000
Specific Power(W/Kg)	<1000	< 10,000	< 100,000
Charge/Discharge Efficiency	0.7 to 0.85	0.85 to 0.98	> 0.95

2.1.3.2 Modeling of Supercapacitors

When sizing the supercapacitor it is necessary to understand the implications of the various factors that not only affect the capacitor, but will also affect the design of the interface power electronics.

These factors affecting the choice of capacitor include:

- The peak capacitor voltage,
- Allowable maximum percentage discharge,
- Peak current flowing through the capacitor,
- Capacitor time constant (τ),
- Capacitance per cell,
- Cell voltage,
- Number of cells needed,
- Mass of the cell array,
- Cost of the cell array.

The electrical behavior of a supercapacitor is characterized using an electrical equivalent circuit model. Several different modeled in a similar manner to conventional capacitors. The simplest of the supercapacitor models is the classical equivalent circuit model of Figure 2.14; it's comprised of three ideal circuit elements: a capacitance C in parallel with an ESR, which models resistance contributes to the energy loss component of the supercapacitor during charging or discharging and an equivalent parallel resistance (EPR) which models the current leakage found in all supercapacitors. This leakage current varies from a few milliamps to tens of milliamps in large supercapacitors. This model can give an approximation of the supercapacitor operation

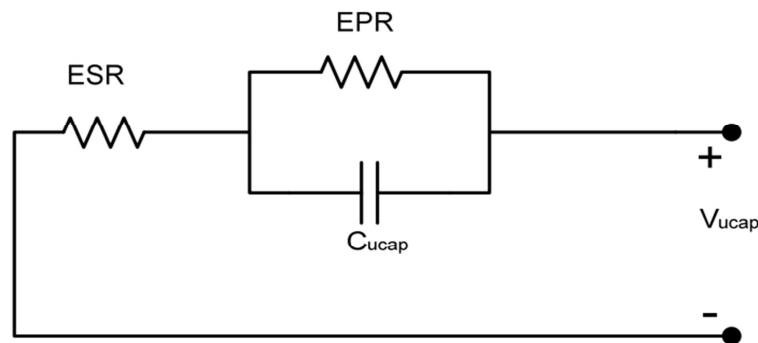


Figure 2.14: Supercapacitor classical equivalent circuit model.

Zubieta and Bonert [38] proposed a more detailed three branch model of the supercapacitor described in Figure 2.15. The model consists of three RC branches each having a different time constant. The first branch labeled the “immediate branch” contains the ESR and represents the behavior of the supercapacitor in the seconds range. The second branch or “delayed branch” contains R_2 and represents the behavior of the supercapacitor in the minute range. The final branch or “long term branch” represents the long-term behavior of the supercapacitor after

approximately ten minutes. The capacitor KV reflects the voltage dependency of the supercapacitor and the EPR models the leakage current.

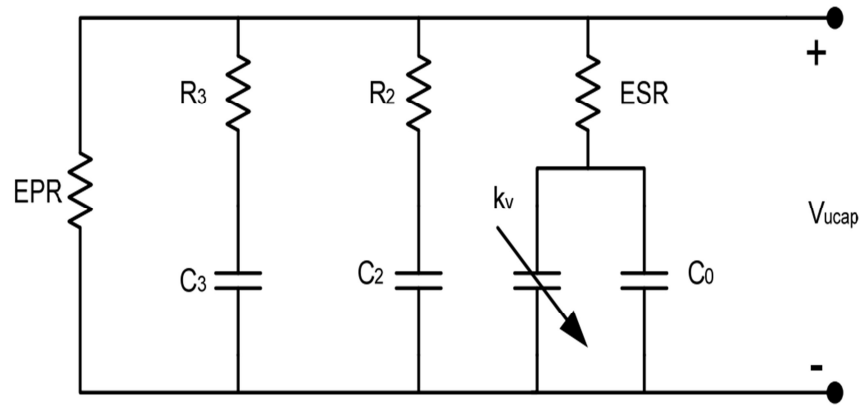


Figure 2.15: Three branch supercapacitor model: [38]

The three branch model was reduced to a two branch model in this work as the supercapacitor is utilized to provide short peak loads; the long term branch was removed from the model of Figure 2.15.

The component parameters are determined from the constant current charge and self-discharge characteristics of the supercapacitor. Equation utilizes to determine the model component values, based on the topology discussed in [40]. The supercapacitor is left to self-discharge after full SOC is achieved. Increasing the number of branches in the model will increase the model accuracy, reducing the percentage error.

The voltage rating of supercapacitors is typically less than 4V. When higher voltage ratings are required, many supercapacitors are connected in series to form a string of cells. Supercapacitors, like conventional electrolytic capacitors, suffer from large deviations in their capacitance.

These deviations can be as high as 20% from the nominal cell capacitance value. When connected in series, common current flows through all the cells and since the cell capacitances differ, the cell voltages will vary. This could result in individual cells being overcharged and thus exceeding their voltage limits. For this reason, an active or passive voltage balancing circuit is employed to regulate the cell voltage.

The discharge profile for a supercapacitor under constant current is shown in Figure 2.16. A constant current discharge is particularly useful when determining the parameters of the supercapacitor. These parameters include the equivalent series resistance, specific power and specific energy.

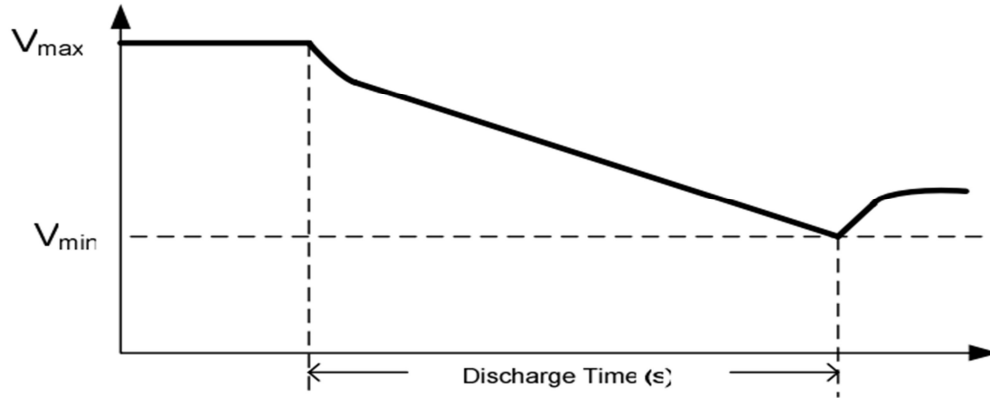


Figure 2.16: The voltage discharge profile for an SC under constant current discharge [24].

It is common to make the mistake of choosing a specific voltage and thus calculating the capacitance required, which often results in an over sizing of the supercapacitors. The aim when sizing any string of capacitors is to minimize the mass, which implies using the least amount of capacitors. The voltage function, $V(t)$, and current waveform, $I(t)$, is shown in Figure 2:17. It is important to note that the variables V_{max} and C are in fact related by the common variable n , which is the number of cells. The assumption is that the capacitors will never be charged above the combined maximum voltage rating of all the cells.

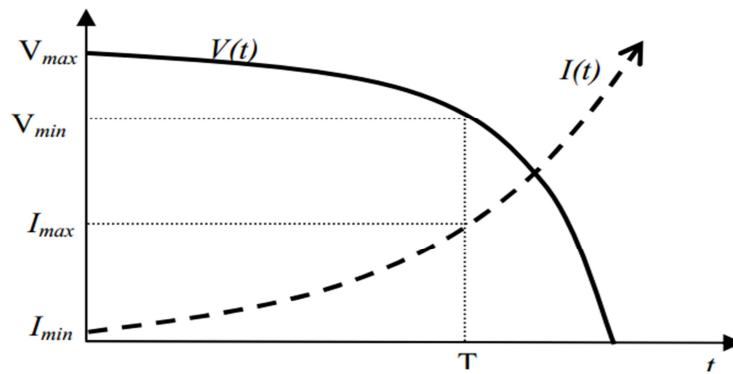


Figure 2.17: The voltage and current waveforms for a constant power discharge.

2.1.3.4. The Effect of Super Capacitor Sizing On Power Electronics

In the previous section we illustrated how the number of capacitors, and consequently the mass, can be determined using an iterative numerical method. This reduction in capacitor mass has implications on the rating of the power electronics used to interface between the capacitors and the constant power application. The power electronic converter needs to be rated at the maximum voltage as well as the maximum current as indicated by [6].

In the next illustration we will examine how the choice of capacitor and maximum operating current affects the sizing of the overall system. The commercially available capacitors that will

be analyzed are from Maxwell, Panasonic, Montena and Ness. The latest technology in supercapacitors is from Jeol Ltd, Japan. These capacitors are not yet available commercially; however prototype specifications have been made available. The specifications for the supercapacitors are shown in Table 2.2.

The assumption made in the calculations is that there is no limit on the current conducting capability of the supercapacitors. Although this is not practical, knowing that all capacitors have a practical limit, it gives an insight into the sizing if manufacturers are able to design them with higher current ratings. The current limit for large supercapacitor cells is about 400A-600A.

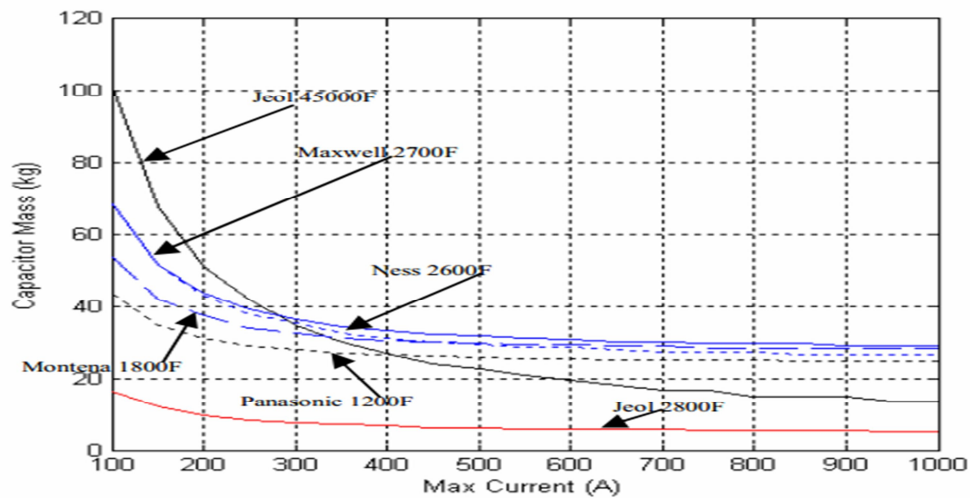


Figure 2.18: The mass of the capacitors versus the maximum allowable current.

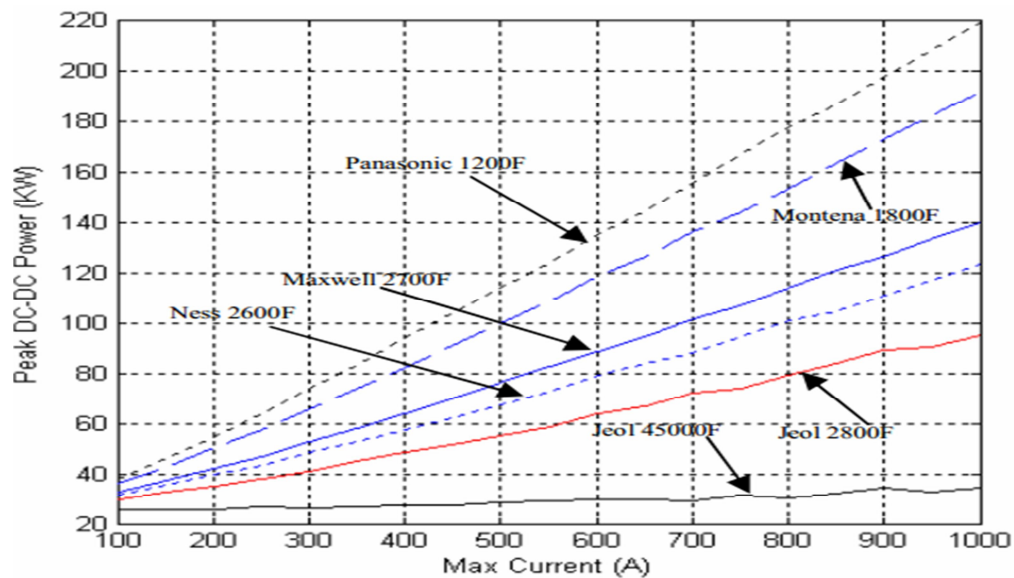


Figure 2.19: The rating of the power electronics versus the maximum allowable current.

Table 2.2: Specifications for the supercapacitors

	Weight Per cell (Kg)	ESR (m Ω)	Specific energy (Wh/kg)	Specific power (W/kg)	Cell voltage (V)	Time constant ($\tau=RC$)
Ness 2600F	0.65	0.25	2.31	7284	3	0.65
Panasonic 1200F	0.34	1	1.3	6618	3	1.2
Maxwell2700F	0.52	0.6	2.5	8929	2.5	1.6
Montena 1800F	0.4	0.6	2.49	7812	2.7	1.8
Jeol 2800F	0.21	2.1	27	8000	3.8	6
Jeol 45000F	1.5	4.4	60	540	3.8	200

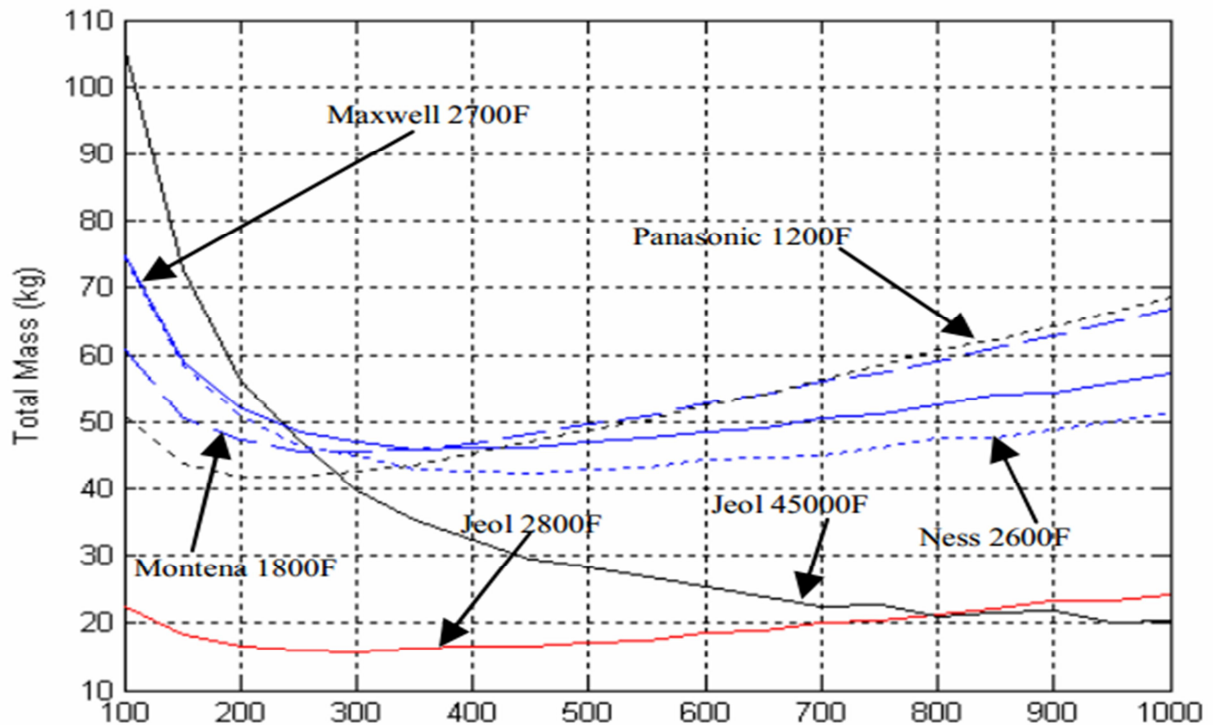


Figure 2.20: The mass of the system versus the maximum allowable current

2.4 Battery Supercapacitor Comparison

The lead acid battery and supercapacitor were described in the previous sections. These are complementary technologies which benefit from being combined in hybrid systems. The two

main characteristic taken into consideration when comparing both technologies is the energy and power density of each device.

The supercapacitor has a greater power density than the battery, allowing the supercapacitor to provide more power over a shorter period of time. Conversely, the battery has a higher energy density compared to the supercapacitor to supply the lower power for a longer period of time. The ragone chart in Figure 2.21 shows the energy and power comparison of different storage technology. Table 2.3 compares the supercapacitor and battery characteristics.

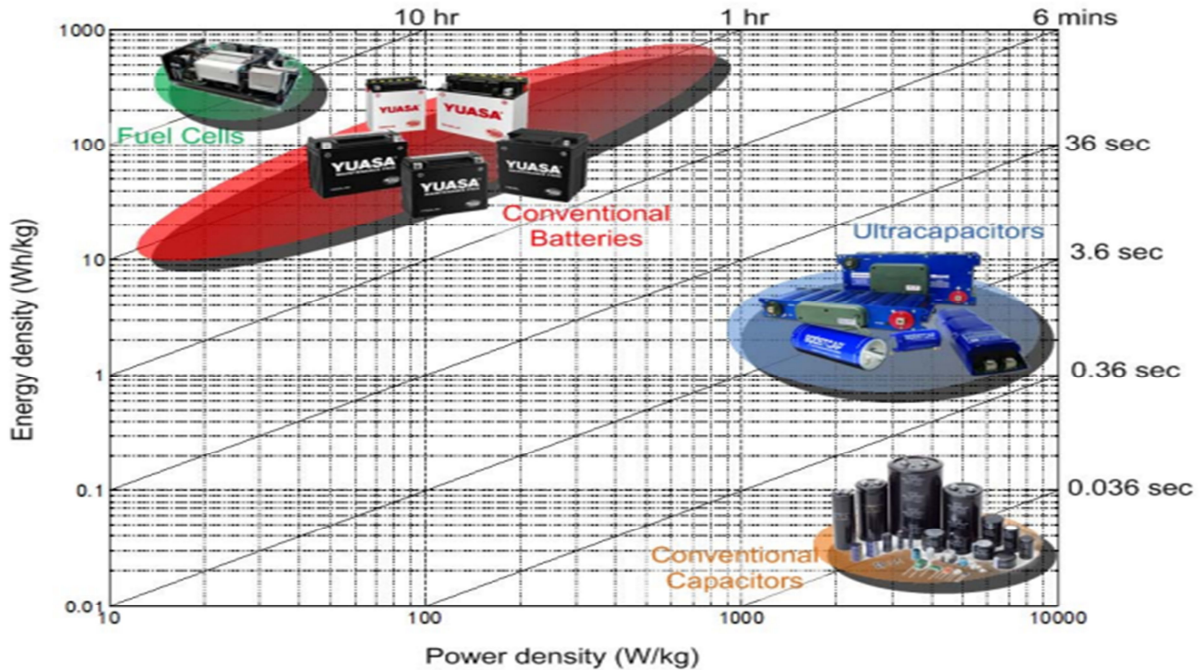


Figure 2.21: Ragone chart for storage technology

Table 2.3: Battery supercapacitor comparison

	Supercapacitor	Battery
Voltage	2.7v/cell	2v/cell
Temperature	-40°C-+65°C	-20°C-+50°C
Efficiency	0.85-0.98	0.-0.85
Life cycle	>500,000	1000
Power density	<10,000W/Kg	<1000W/Kg
Energy density	1-10Wh/Kg	10-100Wh/Kg
Charge time	0.3 – 30 sec	1-5 hrs
Discharge time	0.3 – 30 sec	0.3 – 3 hrs

2.1.4.1 Role of Battery and Supercapacitor

The system load profile and operating conditions of PV system influences the battery life. Li-ion battery and ELDC are used for electric storage. In which battery is used as primary storage and supercapacitor is used as secondary storage. This hybrid storage technique offers increased lifetime [3]. Due to low leakage charge battery is used for holding the charge for a long time and is discharged only when solar energy is not available and supercapacitor storage is exhausted. The role of supercapacitor changes in accordance with the mode of operation, when solar power is available it smoothens the energy flow to match the charging profile of the battery and keep the voltage of the DC bus constant. During unavailability of solar power, the supercapacitor is dripped charged from the battery to supply the peak power. To check the inefficiency caused due to leakage charge supercapacitor is charged just before the arrival of the peak demand.

2.1.4.2 Hybridization of Energy Storage Technologies

The main purpose of a hybrid energy system is to achieve a power source with both high power density and high energy density. With hybridization of different energy storage technologies, one can have all advantages of them together and increase the system's reliability and optimization. A hybrid energy system should be carried out for some special applications such as operating regenerative braking energy in electric vehicles or metros, because an energy storage source with high power density and high energy density is required. Table 2.4 compares these parameters [2].

Table 2.4: Qualitative comparison of energy storage devices

Device	Specific Energy	Specific Power
Chemical battery	High	Low
supercapacitor	Low	High
Flywheel	Low	High
Fuel cell	High	High

2.1.4.3 Hybrid Configuration

Different configurations can be employed to combine batteries and supercapacitors in the HESS. The simplest configuration is a passive HESS, the battery and supercapacitor directly connected in parallel to the load as shown in Figure 2.22. The power supplied by/to the battery and supercapacitor is determined by the components internal resistance limiting the power enhancement of the HESS. This configuration utilizes a common voltage bus which is not controlled. The voltage is set by the battery leading to under utilization of the supercapacitor [4].

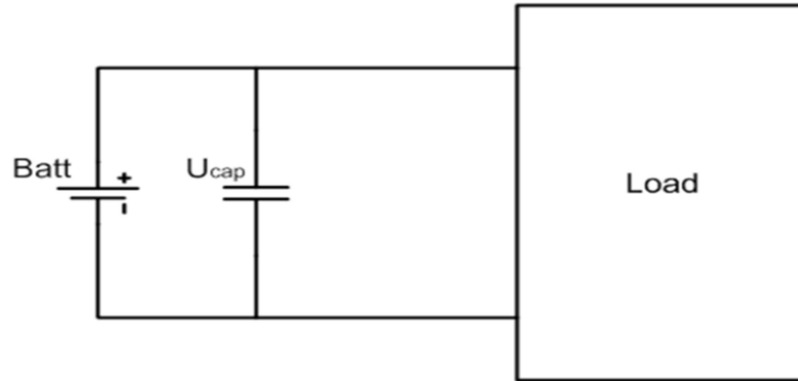


Figure 2.22: Passive HESS configurations: [19]

Active HESS enables better utilization of the supercapacitor by including dc/dc converters. The converters actively control the power to/from the battery and supercapacitor, allowing more efficient utilization of the supercapacitor leading to increased power capability. The HESS with dc/dc converter can adopt different forms. The first layout of the active HESS places a dc-dc converter between the battery and supercapacitor as illustrated in Figure 2.23. In this configuration the dc-dc converter controls the power from the battery to the supercapacitor and load, which improves the power density of the storage system. Other advantages to the active hybrid system include smaller battery ripple current and wider operating voltage range [19].

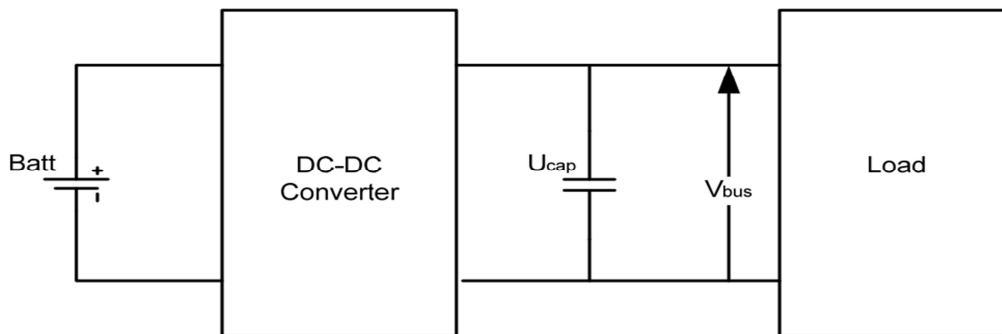


Figure 2.23: HESS with a bidirectional converter between battery and supercapacitor: [19]

An alternative with two dc/dc converters is illustrated in Figure 2.24. The first converter allows the supercapacitor and battery to be operated at different voltage levels, giving greater flexibility in the design of the battery and supercapacitor banks. The current output of the battery is controlled with the remaining load power requirement met by the supercapacitor. The supercapacitor voltage becomes the bus voltage, which varies with SOC. The second dc-dc converter is required to maintain the load voltage. There is a large voltage swing on the converter input due to the large voltage range of the supercapacitor. High input current for low supercapacitor SOC leads to high IR losses [9].

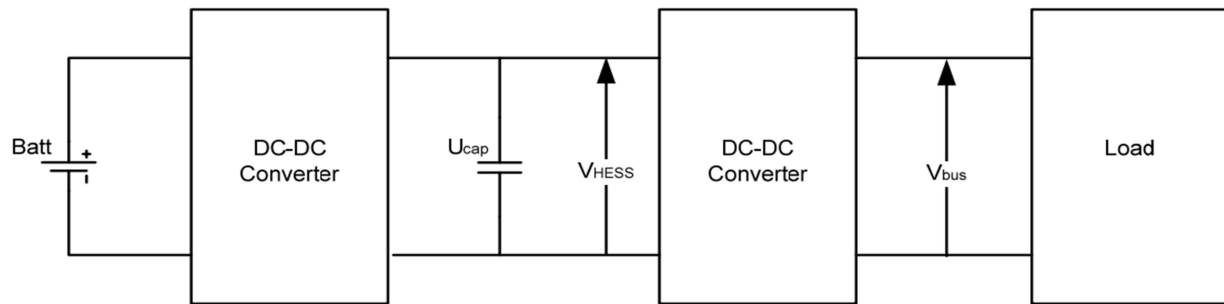


Figure 2.24: HESS with bidirectional converter between the battery and supercapacitor: [19]

A third form of active HESS configuration is shown in Figure 2.25. Both the battery and the supercapacitor are connected to the load through a two input bidirectional converter. The battery dc-dc converter is current controlled with the supercapacitor dc-dc converter voltage controlled. The current supplied by each component is based on the load requirement and the component SOC. This configuration gives the highest efficiency, reliability, and flexibility [9].

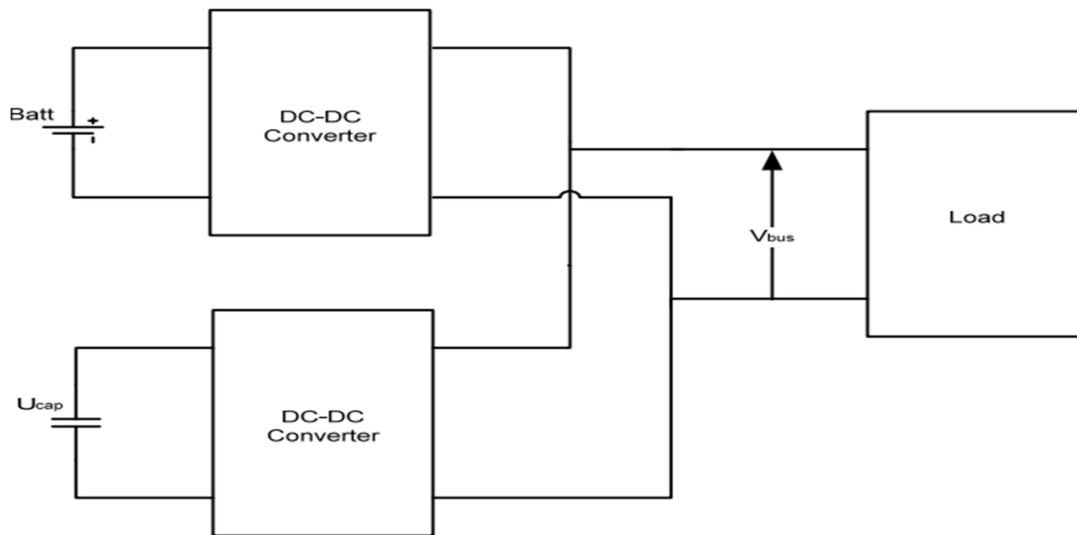


Figure 2.25: HESS with two input bidirectional converter between the battery supercapacitor and load: [19]

2.1.5 Types of DC-DC Converter

DC-DC converter is an electrical circuit whose main application is to transform a dc voltage from one level to another level. It is similar to a transformer in AC source, it can able to step the voltage level up or down. The variable dc voltage level can be regulated by controlling the duty ratio (on-off time of a switch) of the converter. A DC-DC converter is required for the PV system with a battery supercapacitor HESS to provide an active platform to control the flow of power between the supercapacitor, battery, PV panel and load.

There are various types of dc-dc converters that can be used to transform the level of the voltage as per the supply availability and load requirement. Some of them are discussed below.

- ✓ Buck converter
- ✓ Boost converter
- ✓ Buck-Boost converter

Each of them is explained below.

a) **Buck converter:** -The functionality of a buck converter is to reduce the voltage level. The circuit diagram of the buck converter is manifested in Figure 2.26.

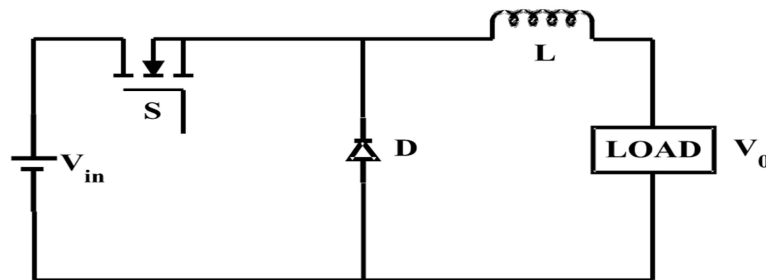


Figure 2.26: Circuit diagram of buck converter: [18]

When the switching element is in state of conduction the voltage appearing across the load is V_{in} and the current is supplied from source to load. When the switch is off the load voltage is zero and the direction of current remains the same. As the power flows from source side to load side, the load side voltage remains less than the source side voltage. The output voltage is determined as a function of source voltage using the duty ratio of the gate pulse given to the switch. It is the product of the duty ratio and the input voltage

b) **Boost converter:** -The functionality of boost converter is to increase the voltage level. The circuit configuration of the boost converter is manifested in Figure 2.27.

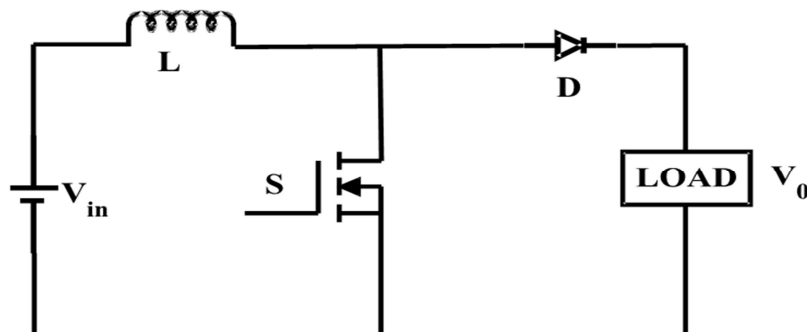


Figure 2.27: Circuit diagram of boost converter: [18]

The current carried by the inductor starts rising and it stores energy during ON time of the switching element. The circuit is said to be in charging state. During OFF condition, the reserve energy of the inductor starts dissipating into the load along with the supply. The output voltage level exceeds that of the input voltage and is dependent on the inductor time constant. The load side voltage is the ratio of source side voltage and the duty ratio of the switching device.

- c) **Buck-Boost converter:** - The functionality of a buck-boost converter is to set the level of load side voltage to either greater than or less than that of the source side voltage. The circuit configuration of the buck-boost converter is manifested in Figure 2.28.

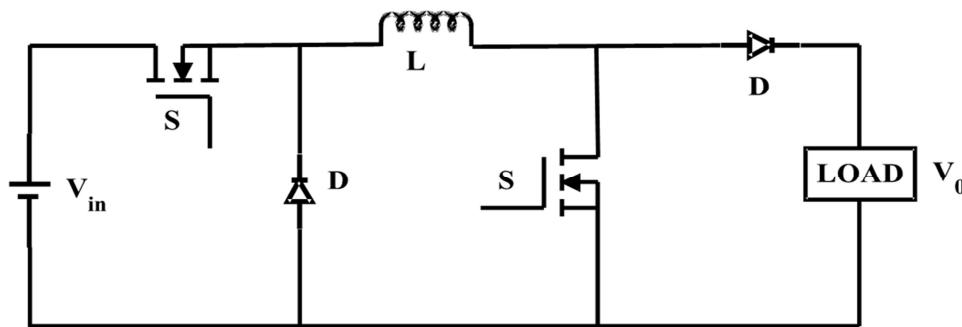


Figure 2.28: Circuit diagram of buck-boost converter: [18]

When the switches are in the state of conduction, the current carried by the inductor starts rising and it stores energy. The circuit is said to be in charging state. While the switches are in the OFF state, this stored energy of the inductor is dissipated to the load through the diodes. The output voltage can be varied based on the On-time of the switches.

The buck-boost converter acts as both buck and boost converters depending on the duty cycle of the switches. For the duty ratio less than 50% it acts as a buck converter and for the duty ratio exceeds than 50% it acts as boost converter.

As the voltage can be stepped both up and down, we use buck-boost converter for our convenience in our work.

2.1.5.1 Boost Converter for Battery Charging

As mentioned earlier, the boost converter has many applications and here in the work, the converter is used for charging and discharging the battery based on the surplus and deficit of the power respectively.

When there is a surplus of energy, i.e. the supply is greater than demand then the battery is charged, allowing the converter to operate in forward direction. When there is a deficit in power i.e. the supply is less than demand then the battery starts discharging supplying the deficit of power to the load. This requires the converter to operate in reverse direction. Charging/discharging of the battery is done by the help of a bidirectional converter [18].

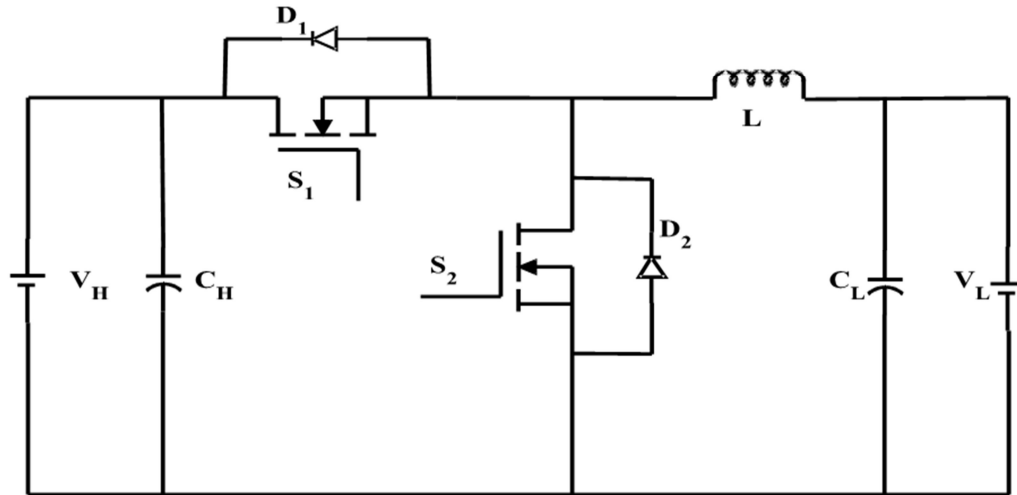


Figure 2.29: Circuit diagram of the bidirectional converter: [18]

2.1.6. PV array sizing

The first step toward sizing the PV array is to determine the daily energy requirement from the array. The required energy obtained is then divided by the average sun-hours per day for Addis Ababa to obtain the peak power. The peak power is then divided by the selected system dc voltage to obtain the total dc current. Finally, the number of series and parallel modules can then be determined to give the array size.

2.1.6.1. PV Cell Model

PV panels convert solar radiation into dc electricity using the photoelectric effect. A number of different semiconductor materials are used for the construction of PV panels with different levels of efficiency. A PV model simulates the output power of a particular panel for a given solar radiation and temperature input using data provided from the PV panel manufacturer. A simplest equivalent circuit of an ideal solar cell is shown in Figure 3.4. The ideal solar cell circuit includes a current source that models the solar irradiance, a diode in anti-parallel models the p-n junction, as observed in figure. The output of the current source is proportional to the incident photon flux this current is called photocurrent. During darkness, the solar cell is not active and behaves as an ordinary p-n junction diode and this gets modeled as a diode in the equivalent circuit. This diode determines the I-V characteristics of the solar cell [10]. It produces neither a current nor a voltage. This comes into action whenever a potential difference exists between the terminals of the solar cell and constitutes a current called Dark current. When the photovoltaic cells are exposed to the sunlight, the direct current produced changes with the solar irradiance. The model is improved with shunt resistance and series resistance to represent the losses. The diode represents the p-n junction of the cell. The series resistor R_s and the parallel resistor R_{sh} represent resistor R represent the losses in the PV cell. R denotes the internal resistance of the cell. The parallel shunt resistor R_{sh} characterizes the leakage current of the p-n junction. R_{sh} is

generally high and therefore can be neglected to simplify the model. The net output current of the PV cell is the difference between the photocurrent I_{ph} the diode current I_d .

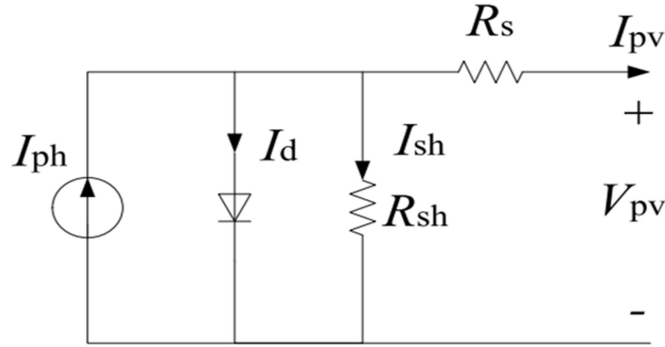


Figure 2.30: Photovoltaic equivalent circuit cell based on single diode model

The PV output current can be obtained from Kirchhoff's law. The equation is given below [10]

$$I_{pv} = I_{ph} - I_d - I_{sh} \quad (2.1)$$

Where I_{pv} is the cell current, I_{ph} is the photocurrent, I_d is the diode current, is the parallel current. The following are the parameters which are needed to be considered for accurate modeling of PV cell: -

- ✓ Temperature dependence of the diode saturation current (reverse) I_s .
- ✓ Temperature dependency of the photo current I_{ph} .
- ✓ Series resistance R_s [10], representing internal losses due to current flow.
- ✓ Shunt resistance R_{sh} [10], in parallel with the diode, this corresponds to the leakage current.

Equations which are used to model the PV cell in MATLAB Simulink

$$V_t = \frac{kT_{op}}{q} \quad (2.2)$$

$$V_{oc} = V_t \ln\left(\frac{I_{ph}}{I_s}\right) \quad (2.3)$$

$$I_d = \left[e^{\frac{(V + IR_s)}{nV_t}} - 1 \right] I_s N_p \quad (2.4)$$

$$I_s = I_{rs} \left(\frac{T_{op}}{T_{ref}} \right)^3 e^{\left[\frac{qE_g}{nk} \left(\frac{1}{T_{op}} - \frac{1}{T_{ref}} \right) \right]} \quad (2.5)$$

$$I_{rs} = \frac{I_{sc}}{\left[e^{\left(\frac{V_{oc}q}{kT_{op}n} \right)} - 1 \right]} \quad (2.6)$$

$$I_{sh} = \frac{V + IR_2}{R_1} \quad (2.7)$$

$$I_{ph} = G_k [I_{sc} + K_1 (T_{op} - T_{ref})] \quad (2.8)$$

$$I = I_{ph} N_p - I_d - I_{sh} \quad (2.9)$$

The stand-alone PV system is sized to generate sufficient electrical power to meet the load demand during the critical design month. In this manner, the battery is always charged, and the system availability is high during the whole year. Firstly, the required PV array current is computed from the load demands and, and the nominal system voltage, and insolation of critical design month [20]. On the other hand, as the battery efficiency is of 0.85, more current must be provided to charge battery bank than is taken back on discharge. The following equation is used to calculate the required array current [18].

$$I_{array} = \frac{E_{crit}}{\eta_{bat} V_{SDC} t_{PSH}} \quad (2.10)$$

Where I_{array} The required array maximum-power current (A),

η_{bat} Battery system charging efficiency, and

t_{PSH} The peak sun hours for the critical month (hr/day)

The maximum current and output voltage generated by PV were already solved by the above equations. The final part of sizing process is to determine the array configuration based on the voltage and current parameters. The numbers of parallel modules are determined by dividing the rated array current output by the module current at maximum-power and rounding up to the next integer. The required numbers of series modules are determined by dividing the rated array voltage by the module voltage at maximum-power and rounding up to the next integer.

$$N_{PVmin} = \frac{\int_1^{8760} P_{Load}}{\int_1^{8760} P_{PVmax}} \quad (2.11)$$

Where P_{Load} – Load power account of system losses and P_{PVmax} – Maximum power output from one PV panel fixed at the optimum tilt angle calculated

The maximum quantity of PV panels is set to the minimum number of PV panels required to supply the maximum daily load for the worst day of the year, the day when the PV panel receives the lowest solar radiation. The minimum and maximum values of PV panels are two opposite extremes which are not optimal and would require a large storage system for the minimum quantity of PV panels and a small storage system if the maximum quantity of PV panels is utilized. While varying the quantity of PV panels the PV power and the load requirement are compared to obtain the charge/discharge profile of the storage system for each step point over the optimization horizon.

2.1.7. Battery Sizing

Batteries are used to store the excess of energy generated by the PV array during sunny and high insolation of periods, and they provide power to the system during nighttime and low insolation of periods [29]. The PV array is the only charging source for the battery bank. In the HESS the main function of the battery bank is energy storage as the supercapacitor provides the power requirements. The battery bank is optimized taking the PV array and the supercapacitor bank capability into account. The HESS charge discharge profile is adjusted using the supercapacitor profile to obtain the charge discharge profile of the battery bank.

The battery type recommended for using in solar PV system is deep cycle battery. Deep cycle battery is specifically designed for to be discharged to low energy level and rapid recharged or cycle charged and discharged day after day for years. The battery should be large enough to store sufficient energy to operate the appliances at night and cloudy days. The required battery capacity for stand-alone PV system depends on load demands and desired autonomy. The autonomy day is the time during which a lonely battery provides power for load requirements, without any solar energy, beginning from a full state of charge [33]. Greater autonomy days are associated with larger and higher cost battery banks. However, it drops the average daily depth of charge (DOD), and it provides longer lifetime for battery in this manner. The required battery capacity is calculated by using following equation;

Battery Capacity (Ah) = Total Watt-hours per day used by appliances x Days of autonomy
(Battery loss x Depth of discharge x nominal battery voltage)

$$E_{est} = E_d \times D_{aut} \quad (2.12)$$

$$E_{safe} = \frac{E_{est}}{D_{disch}} \quad (2.13)$$

$$C_{tb} = \frac{E_{safe}}{V_b} \quad (2.14)$$

$$B_{out} = E_{crit} \frac{t_a}{V_{SDC}} \quad (2.15)$$

$$B_{rated} = \frac{B_{out}}{DOD_a V_{SDC}} \quad (2.16)$$

Where B_{out} is the required battery output (Ah), E_{crit} is the daily energy demand during critical design month (Wh/day), t_a is autonomy days V_{SDC} is the nominal dc system voltage (V) and, DOD_a is the allowable depth of discharge which is assumed to be 80% in this study.

In order to size the battery bank, the estimated energy storage is first determined. The obtained energy value is then divided by the allowable depth of discharge of the battery to give a safe energy storage value of the required battery bank. At this point, the particular battery to be used is selected and using its specifications, the capacity of the entire battery bank in Ampere-hours is computed, and subsequently the total number of batteries in the bank is computed. Finally, the

number of batteries in series and parallel branches of the bank are determined and an estimate of the cost of the battery bank (B_{bcost}) is made from the knowledge of the cost the selected single battery (B_{cost}).

$$N_{tb} = \frac{C_{tb}}{C_b} \quad (2.17)$$

$$N_{sb} = \frac{V_{dc}}{V_b} \quad (2.18)$$

$$N_{pb} = \frac{N_{tb}}{N_{sb}} \quad (2.19)$$

$$B_{bcost} = N_{tb}XB_{cost} \quad (2.20)$$

$$N_{Battser} = V_{Sys}/V_{batt} \quad (2.21)$$

Where V_{Sys} – System operating voltage and V_{batt} – Battery rated voltage

Determining the number of batteries connected in parallel to increase the battery bank capacity is more complicated. The available energy from the batteries and the reduction in capacity due to the discharge current are taken into account. The accessible battery energy in the HESS is dependent on the SOC limit implemented in the system and is determined.

$$E_{Batt} = V_{Batt}Ah_{cap}(1 - SOC_{limit}) \quad (3.22)$$

Where E_{Batt} Available battery energy
 Ah_{cap} Nominal battery capacity
 SOC_{limit} Battery SOC limit

Traditionally in PV systems the size of the battery bank is determined based on the daily load requirement and the number of Days of Autonomy (DOA). The DOA outlines the number of days the PV system can deliver full power to the load from the battery bank without charge from the PV array, utilized to ensure the load can be maintained during rainy and cloudy periods [7]. This work adopts a different approach to calculating the DOA, days of inadequate charge. In this methodology the daily charge and discharge battery energy is compared to calculate the number of consecutive days the battery bank is inadequately charged. Therefore, in this situation the contribution of the PV array and the supercapacitor bank to the load is taken into account which will reduce the initial battery bank size. The initial number of parallel batteries in the battery bank is calculated.

$$N_{BattPar} = \left(\frac{MaxDailyDischarge}{E_{Batt}} \right) * DayInadChar \quad (2.23)$$

Where MaxDailyDischarge- Maximum energy discharged from the battery bank in one day during the optimization horizon and DayInadChar -Number of consecutive days the battery is not recharged

The Max Daily Discharge is chosen, worst case, to ensure the battery bank will be large enough to supply the maximum battery load energy for the required number of days. If the battery bank is fully recharged every day, DayInadChar equals 1, as battery storage is required to supply the night time load. Both the MaxDaily Discharge and the DayInadChar are dependent on the supercapacitor and PV array capacity and vary accordingly.

The initial battery bank capacity calculated uses the worst case values over the optimization horizon. The worst case conditions may only occur for a short period of time, therefore, the battery bank may be oversized. To optimize the battery bank for the given PV array and supercapacitor bank the operation of the battery bank is observed with respect to the LVD limit implemented by the control system over the optimization horizon with the battery capacity adjusted according to Peukert's law. The capacity is reduced until the minimum battery bank capacity which obeys the LVD limit is obtained.

2.1.7.1. Peukert's Law

Peukert's law expresses the capacity of the battery in terms of the discharge rate. Increasing the rate of discharge of the battery decreases the battery available capacity. The battery capacity is modified to take the impact of Peukert's law into account [58].

$$T_B = H * \left(\frac{C_{BatDisRated}}{IH} \right)^{K_p} \quad (2.24)$$

$$Ah_{Peuk} = IT_B$$

Where H-Battery rated discharge time (Hours)

$C_{BatDisRated}$ -Rated capacity at the discharge rate (Ah)

I Actual discharge current (A)

T_B Actual time to discharge the battery (Hours)

K_p Peukers constant

Ah_{Peuk} Adjusted battery capacity

A Peukert's constant of close to one indicates the efficiency of the battery is good with minimal loss of energy due to increased discharge rate. Increasing Peukert's constants indicates less efficient batteries.

2.1.8. Supercapacitor Sizing

Supercapacitor has following two functions in the power circuit:

- It supplies the peak demand when power from solar is not available.
- It clamps the DC bus voltage to a constant value.

In the HESS the supercapacitor bank is utilized to supply the peak power requirements of the load discharged from the storage system with the lower average power supplied by the battery bank. The required capacitance of the supercapacitor bank is calculated from the energy equation

$$C_{CaReq} = \frac{2E_{Cap}}{V_a^2 - V_b^2} \quad (2.25)$$

Where E_{Cap} Energy requirement of supercapacitor (J), V_a - Maximum supercapacitor operating voltage and V_b - Minimum supercapacitor operating voltage

The supercapacitor operating range can vary between its rated voltage and zero volts. In this work the supercapacitor bank is allowed to discharge to half its maximum voltage i.e. $V = 0.5V$, which utilizes approximately 75% of the supercapacitor energy. This gives the best utilization of the supercapacitor energy without increasing the voltage drop [20].

In the optimization methodology the supercapacitor bank is given priority with respect to charging. To endeavor to maintain the supercapacitor bank at an adequate SOC to supply the load peak power requirements, both the PV Array and the battery bank can be utilized for supercapacitor charging. The peak power requirement of the load can be unpredictable and adequate recharge between peaks cannot be guaranteed, for this reason E is varied during the optimization process.

The peak power requirements of the load are assessed when choosing the minimum and maximum E_{cap} values. The minimum value is selected to ensure the largest peak in the load occurring during the optimization horizon can be met. As the load peaks can occur in quick succession the maximum value of E_{cap} is calculated to enable the supercapacitor to supply the largest daily peak power requirement since supercapacitors are not intended for energy storage.

The number of supercapacitor s connected in series and parallel can be obtained using the capacitance calculated based on the minimum and maximum value of E_{cap} .

$$N_{CapSer} \geq \frac{V_a}{V_{Cap}} \quad (2.26)$$

$$N_{CapPar} \geq \frac{C_{CapReq} \times N_{CapSer}}{C_{Cap}} \quad (2.27)$$

$$\frac{2 \times V_{load} \times I_{load} \times T_{Peak}}{V_{SC}^2} \quad (2.28)$$

Where V_{Cap} supercapacitor voltage and C_{Cap} Nominal supercapacitor capacitance

This only decides the lower limit of the supercapacitor rating, for finding the actual storage size a detailed SIMULINK model is developed which is run for several hours and batteries charge/discharge cycles are plotted as the function of the capacity of the supercapacitor.

2.1.9. Bidirectional DC-DC Converter Sizing

Following are the parameters that are needed to be evaluated for all the converters introduced.

- Inductor
- Input capacitor
- Output capacitor

For Buck Converter

Inductor selection

$$L = \frac{V_{out} \times (V_{in} - V_{OUT})}{\Delta I_L \times f_s \times V_{IN}} \quad (2.29)$$

$$\Delta I_L = (0.2 \text{ to } 0.4) \times I_{OUT(max)} \quad (2.30)$$

$$C_{OUT(min)} = \frac{\Delta I_L}{8 \times f_s \times V_{OUT}} \quad (2.31)$$

$$V_{OUT(ESR)} = ESR \times \Delta I_L \quad (2.32)$$

Where V_{OUT} =desired output voltage

V_{IN} =typical input voltage

ΔI_L =estimated inductor ripple current

f_s =minimum switching frequency

A good estimation for inductor ripple is 20% to 40% of out put current

$I_{OUT(max)}$ =maximum output current

Therefore, it is advised to use a low-ESR capacitor to minimize the ripple of the ripple on the output voltage. Ceramic capacitors are a good choice.

For Boost Converter

Inductor Selection

$$L = \frac{V_{in} \times (V_{OUT} - V_{in})}{\Delta I_L \times f_s \times V_{OUT}} \quad (2.33)$$

$$\Delta I_L = (0.2 \text{ to } 0.4) \times I_{OUT(max)} \quad (2.34)$$

$$C_{OUT(min)} = \frac{I_{OUT(max)} \times D}{f_s \times \Delta V_{OUT}} \quad (2.35)$$

$$D = \frac{I_L \times V \times L}{V_{IN(min)}} \quad (2.36)$$

Based on the equations the value of parameters used for power circuit are determined.

2.1.10. Charge Controller

Sizing a suitable charge controller starts by computing the required total current that the controller should withstand. From the results of the required current, the total number of charge controllers can then be computed and once the cost of a single charge controller is known, the total cost of the controllers can then be determined.

2.1.10.1 The solar charge controller

The charge controller is used to manage the energy flow to PV system, batteries, supercapacitor and loads by collecting information on the battery and supercapacitor voltage and knowing the maximum and minimum values acceptable for the bus voltage. The use of HESS as a storage form implies thus the presence of a charge controller.

The solar charge controller is typically rated against Amperage and Voltage capacities. Select the solar charge controller to match the voltage of PV array and batteries and then identify which type of solar charge controller is right for your application. Make sure that solar charge controller has enough capacity to handle the current from PV array.

For the series charge controller type, the sizing of controller depends on the total PV input current which is delivered to the controller and also depends on PV panel configuration (series or parallel configuration).

2.1.10.2. Battery Charge-Discharge Controller

For avoiding capacity degradation constant voltage charging mode is not used so the charge controller has to control the charge current only, a variable duty cycle generator based on hysteresis control is used as the charge controller. There are two main operating modes for the controller:

- 1) Normal operating condition, when the battery voltage fluctuates between maximum and minimum voltages.
- 2) Overcharge or over-discharge condition, which occur when the battery voltage reaches some critical values.

To protect the battery against an excessive charge, the PV arrays are disconnected from the system, when the terminal voltage increases above a certain threshold $V_{max-off}$ and when the

current required by the load is less than the current delivered by the PV arrays. PV arrays are connected again when the terminal voltage decreases below a certain value V_{max-on} . This can be done by using a switch with a hysteresis cycle, as illustrated in Figure 3.9.

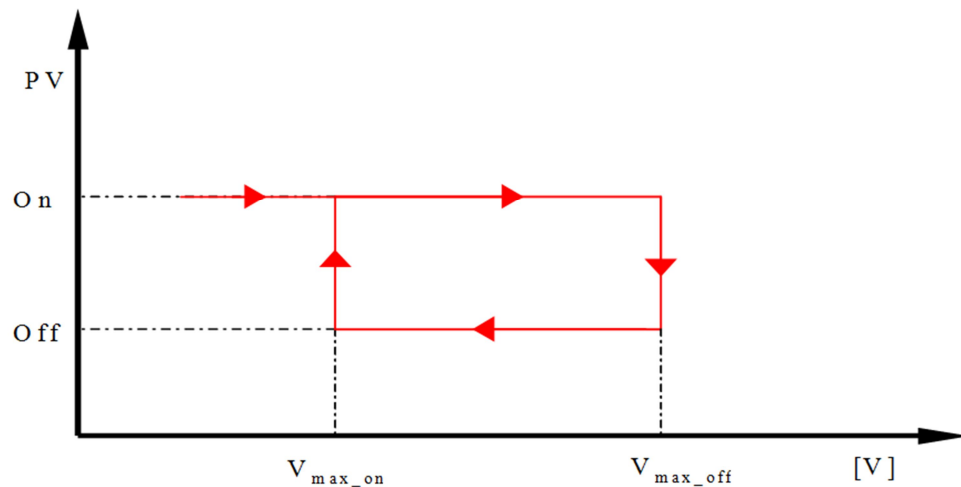


Figure 2.31: Operating principle of an overcharge protector.

To protect the battery against excessive discharge, the load is disconnected when the terminal voltage falls below a certain threshold V_{min_off} and when the current required by the load is bigger than the current delivered by the PV arrays. The load is reconnected to the system when the terminal voltage is above a certain value V_{min_on} , using a switch with a hysteresis cycle, as shown in Figure 3.10.

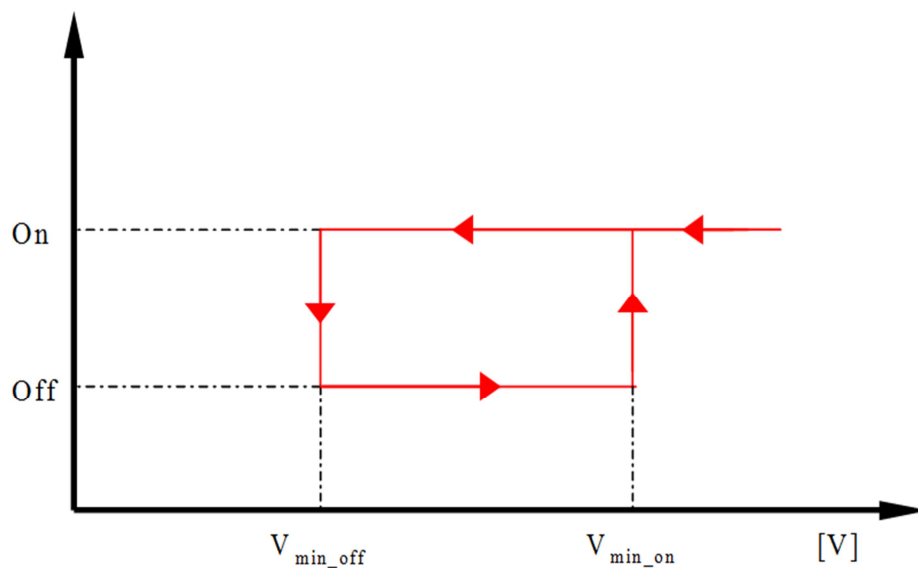


Figure 2.32: Operating principle of a discharge protector.

The switches may either be electromechanical (relay, contactors, etc.) or solid state (bipolar transistors, MOSFET's etc) – see (Lorenzo, 1994).

The steps in the modeling of the controller process are summarized in Table 2.5.

Table 2.5: Summary of the controller process

S/N	Constraint	Command
1	If $V > V_{\max_off}$ and $I_{load} < I_{pv}$	Disconnect PV arrays from the system
2	If command (1) is done and $V < V_{\min_on}$	Reconnect PV arrays to the system
3	If $V < V_{\max_off}$ and $I_{load} > I_{pv}$	Disconnect the load from the system
4	If command (3) is done and $V > V_{\min_on}$	Reconnect the load to the system

2.1.10.3 Discharge Controller

Two types of discharge controllers are used one for providing the load current to the system and second (Battery charge Scap Controller) for charging supercapacitor when PSOLAR is not available. The need for this controller arrives due to very small impedances of battery and supercapacitor, direct charging will result in a very high current (about 500 Ampere's) which will destroy the battery.

$$V = (1/S) / \left[\frac{1}{C} - \frac{V}{RC} \right] \quad (2.37)$$

2.1.10.4 SOC and OCV Calculation

The state of charge (SOC) of the battery is as the ratio of its current capacity to nominal capacity. The nominal capacity is the maximum amount of charge that can be stored in the batter. The relationship between SOC and OCV should be established to include it as part of the battery equivalent circuit [3]. A typical representation of this relationship between SOC and OCV for Li-ion battery is given in Figure 3.11. This relationship is detected from implementing a pulse load in battery at each SOC level, and after allowing the battery to reach equilibrium in open circuit.

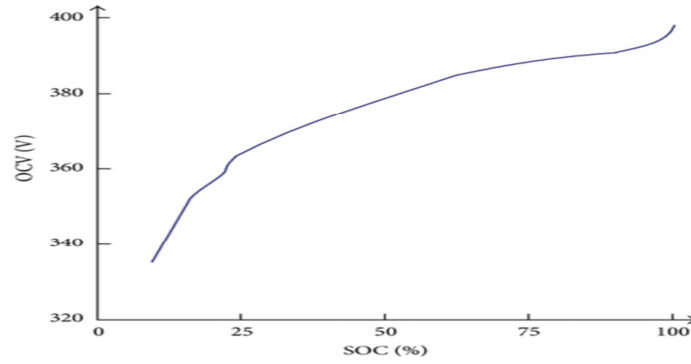


Figure 2.33: Typical relationship between OCV and SOC

$$OCV(SoC) = K_0 + K_1 e^{-\alpha SoC} + K_2 SoC + K_3 SoC^2 + K_4 SoC^3 \quad (2.38)$$

Where, α , K_0 , K_1 , K_2 , K_3 , K_4 are the constant values, SOC is the state of charge. The SOC equation is also given below.

$$SOC_{(t)} = SOC_{(t-1)} + \frac{I_c(t)}{Q_n} \Delta t \quad (2.39)$$

2.1.10.5 Battery Health Cost

To demonstrate the effectiveness of HESS in mitigating battery's stress, a battery-only ESS will be simulated for comparison purpose. As suggested in battery lifetime characteristic studies, these are two of the many factors that accelerate the battery aging and performance deterioration. Thus, minimizing these factors can potentially improve the service life of the battery. To quantify the improvement in battery's health, a battery health cost function $C(T)$ is formulated based on common life-limiting factors of chemical battery is shown in the following equation [41].

$$C(T) = \sum_{t=0}^T n_1 [i_b(t)]^2 + n_2 \left| \frac{di_b(t)}{dt} \right| + n_3 [\max(b(t)) - \min(b(t))] + n_4 \begin{cases} 1; \text{if } [i_b(t) \times i_b(t-1) < 0] \\ 0; \text{if } [i_b(t) \times i_b(t-1) \geq 0] \end{cases} + n_5 \quad (2.40)$$

Where T is the total operating time,

$i_b(t)$ is the battery current,

$b(t)$ is the battery's SoC,

While n_1, n_2, n_3, n_4 and n_5 are weight ages of each life-limiting factor.

Five life-limiting factors are considered in this cost function: (I) charge/discharge rate, (II) dynamicity of battery current, (III) DoD, (IV) charge/discharge transition, (V) Calendar life. In general, the lower the value of $C(T)$, the slower the battery ages.

HOMER is software that only help to model consider important factors, and evaluate and compare options for battery health cost and life cycle cost of the system. The economic factors of

the project such as Annual Interest Rate, Project life time, System Fixed Capital Cost, System Fixed O&M Cost and Capacity Shortage Penalty can all be defined by clicking on the Economics icon in HOMER.

The value that HOMER suggests for this lifetime throughput is the average of the points from the lifetime curve above the minimum state of charge, but the user can modify this value to be more or less conservative. The assumption that lifetime throughput is independent of cycle depth means that HOMER can estimate the life of the battery bank simply by monitoring the amount of energy cycling through it, without having to consider the depth of the various charge - discharge cycles. HOMER calculates the life of the battery bank in years as

2.1.10.6. Supercapacitor Charge-Discharge Controller

A single double loop PI controller is used for implementing charge discharge controller, the outer loop is slow acting and act as master and decides the reference for inner loop which is fast in action and acts as slave to the outer loop.

2.1.11. System wiring sizing

The design of a PV power system is incomplete until the correct size and type of cable is selected for wiring the components together. The following cables links in the PV system must be appropriately selected. The dc cable are from the PV array to the battery bank through the charge controller to the distribution board (DB) required for dc residence load.

2.1.12. Constraints on Component Size

The optimization function is to minimize the system lifetime cost. A range of constraints can be implemented in the optimization methodology. The components in the system can be large requiring a large area to be made available, which is not always possible. The program has been developed to incorporate constraints on the size of components utilized to produce a viable solution for the area available to accommodate the system. The area constraint can be placed on the PV array and the HESS. For the HESS the supercapacitor bank is not limited, but its area is taken into account and the battery bank is reduced as required. To implement the constraints on the area of the PV array and the HESS the maximum allowable number of the components is reduced depending on the available space.

2.2 Review of Related Works

The choice of storage in the PV model is limited to batteries. A suggestion is made to the value of the PV array and battery size, and the generator size for a hybrid system. The suggestion is basic with the generator size based on the max AC demand, the battery size is based on the DOA selected by the user as in and the PV array size is selected to ensure the output is greater than 1.2 times the load for all months of the year. Continuous and reliable electric PV system is important for power systems. Sometimes, unwilling outages or using an energy source with low reliability can be harmful for electrical systems. But these renewable energies require efficient and reliable energy storage.

Although renewable energy is free and environment friendly source of electricity, a storage element is required as an energy buffer in wind and photovoltaic systems to bridge the gap between available and required energy. The lead acid battery is generally the most popular energy storage device, because of its low cost and wide availability. However photovoltaic panels or wind are not an ideal source for battery charging as the output is unreliable and heavily dependent on weather conditions. The batteries cannot immediately response to the load requirement when sudden clouds or no wind occur. The batteries are often deep discharged, which damages the battery and shortens its useful life. It is not possible to ensure an optimum charge/discharge cycle. Undercharging of the battery leads to sulfation and stratification; both of which shorten the lifetime of the battery. Another cause of reduced battery life is gassing, which results from battery overcharging.

One of the latest energy storage introduced to the market today is the supercapacitor. Supercapacitors are components for energy storage, dedicated for applications where both energy and power density are needed.

R.A. Dougal et al [13] analytically explored the power and life extension of a battery in a supercapacitor passive hybrid system, with a pulse load of 5A, 1Hz, and a duty cycle of 10%. It was shown that the peak power of the system was increased, the internal losses were reduced and the battery discharge life was extended. The benefits of the hybrid system are increased as the duty cycle is decreased, the pulse frequency is increased and the supercapacitor equivalent series resistance (ESR) is decreased. Adding supercapacitor in parallel to increase capacitance reduces the ESR, while adding supercapacitors in series to increase voltage increases the ESR.

A. Kuperman et al [15] performed a review of battery supercapacitor hybrids for pulsed current loads. It was found that passive, semi active and fully active hybrids provides enhanced performance compared to battery only storage for pulsed loads.

L. Gao et al [19] investigated the power enhancement of an actively controlled Li-ion battery supercapacitor hybrid system, with a DC-DC converter placed between the battery and supercapacitor/ load. Greater specific power and efficiency is achieved by the hybrid system. The current draw from the battery is reduced resulting in lower internal losses and lower temperature operation, benefiting battery life. Investigations were performed for a 30A pulse current load of 0.2Hz with a duty ratio of 10%. Compared to a passive hybrid configuration, the active system was found to have a threefold increase in power capability and an increase of seven times the battery only power capability. Other advantages of the active system include smaller battery current ripple and better output voltage regulation. The passive system had an increased cycle time compared to the active system due to converter losses and supercapacitor losses as a result of high current discharge.

M. Uzunoglu et al [22] describes the control procedure implemented for a PV system with a fuel cell supercapacitor HESS. The PV panel is given priority for supplying power to the load. Excess

power is supplied to charge the supercapacitor until it reaches full SOC at which point the excess power is used to generate hydrogen. Once the limits of the hydrogen storage tank have been attained the excess energy is dumped. A deficit in PV power is supplied by the fuel cell to a predefined limit with the remainder supplied by the supercapacitor. The supercapacitor also compensates for the slow response time of the fuel cell.

G. Sikha and B.N. Popov [28] examined the effect of operating parameters on a Li-ion battery compared to a hybrid of the battery and supercapacitor under a pulse power load. It was found that the duty cycle had an impact on the increase in discharge capacity for the hybrid system. The discharge capacity of the hybrid system was higher compared to the battery at lower duty ratios, less than 0.4. The hybrid system has a lower effective resistance compared to the battery storage.

This results in a decreased ohmic drop leading to better utilization of the battery. The polarization drop was also found to reduce in the hybrid system, since lower currents are passed through the battery in the hybrid configuration. These lead to increased run time of the battery bank in the system.

Wang et al [31] proposed an energy management strategy to control a buck boost dc-dc converter for a battery supercapacitor HESS in a PV system. The PV panel is always operated with MPPT. The buck boost converter is operated in constant voltage mode or current limit mode for the battery, when the current is greater than the maximum battery current. The supercapacitor operated in constant voltage mode is utilized to minimize small charging/discharging cycles and to filter the output of the PV panel. The buck boost converter employs dual loop control. The outer loop is voltage controlled and stabilizes the dc bus voltage. The inner loop is current limit controlled to ensure the battery current is within its operating limits.

Holland et al [32] performed experimental characterization of the power and energy density for a Li-ion battery, supercapacitor and a parallel Li-ion battery supercapacitor hybrid under pulse current loads. Ragone plots were used to analyze the system performance. From the system analysis it was found that on a per mass basis the energy and power density of the hybrid system was lower than the battery system. For the battery system at high currents the available energy increases with decreasing duty, while at low currents the available energy was independent of the duty. The hybrid system achieved higher power at a lower cost.

D. Cericola et al [36] analyzed a supercapacitor Li-ion hybrid storage system. Two hybrid systems were considered, an internal and external hybrid system. The internal hybrid system utilizes a battery electrode and a capacitor electrode in a single cell. According to Cericola the internal hybrid energy is limited by the capacitor electrode, with the power limited by the battery electrode. Therefore, an external hybrid configuration was found to be a better option.

A. Jossen [38] investigated the operating conditions of batteries in PV applications. The failure modes of the batteries were highlighted as stratification, sulphation, corrosion, erosion, short circuits, reverse charging and low/high temperature operation.

The battery discharge current has an impact on its SOC and operating time. From the literature a number of EMS's have been implemented to control the flow of power throughout the system. Improvements are seen in the battery SOC and lifetime by implementing load management were possible. For a HESS an EMS is required to control the power between the different storage elements. An EMS to limit the battery current in a HESS to best utilize a supercapacitor should be investigated in greater detail to determine the impact of different current limits.

S. Y. Kan et al [39] studied the utilization of a supercapacitor to buffer the energy from the PV panel to the battery and from the battery to the load. When charged from a PV panel the battery can experience fluctuating charging currents and charge interruption. The supercapacitor buffer is charged quickly from the PV panel, the supercapacitor then charges the Li-ion battery at a slower rate. The reduced charge current results in a lower battery temperature, reducing capacity fading from high temperature cycling and increase battery lifetime.

There was an increase in the capability of the system to supply large currents and a small increase in the available energy. The analysis was performed with a passive system, using an active configuration allowing better utilization of the supercapacitor energy should further improve the results.

G.P. Corey [40] examined battery utilization and premature battery failure. It was found that overcharging can result in warping and possibly shorting of the battery grids. Excessive gassing can result in dry-out, active material shedding and there is a risk of thermal runaway. High discharge rates result in increased temperature. Expansion of the grids due to the increased temperature can lead to active material shedding. Battery capacity is also reduced when operated at low temperatures. Corey also highlighted the importance of choosing the correct battery for the required application either power or energy.

The internal resistance is increase with poor contact between the plates and the separator, due to separator shrinkage. Separator shrinkage is caused by consumption of the electrolyte.

From the literature it can be seen that a hybrid system of supercapacitors and batteries have improved performance over a battery only system for loads that have a high peak to average power requirement. The battery terminal voltage drop is reduced, increasing the runtime of the system and reducing the battery bank size. The hybrid system performance was analyzed but a method to correctly size the combination of the battery and supercapacitor to prevent excess system cost has not been described.

CHAPTER THREE

Modeling and Simulation

3.1. Materials

Materials have been used in this work are articles, theses and dissertations, reference and text books, recognized and regulated documents, media, POWER home page, software (MATLAB, Excel, Homer), internet, stationeries and personal computer.

3.2. Proposed Methodology

Data collection, modeling, analyzing and simulation are the methods used. The following sections present each of these in detail. The performance of the proposed and developed system is evaluated and conducted with Computer simulation using MATLAB/SIMULINK and homer for Economic analysis.

3.3 Photovoltaic System

Standalone PV systems are comprised of various elements, PV panels, controller, converters energy storage and connecting wires. A range of energy storage components exist to buffer the PV energy, these include flywheels, hydrogen, batteries and supercapacitor. Each technology has its advantages and disadvantages. A hybrid system combines two or more of these technologies to improve the overall systems operating performance. Figure 3.1 shows an example of a standalone PV system containing a battery and supercapacitor HESS. A number of different hybrid configurations can be employed.

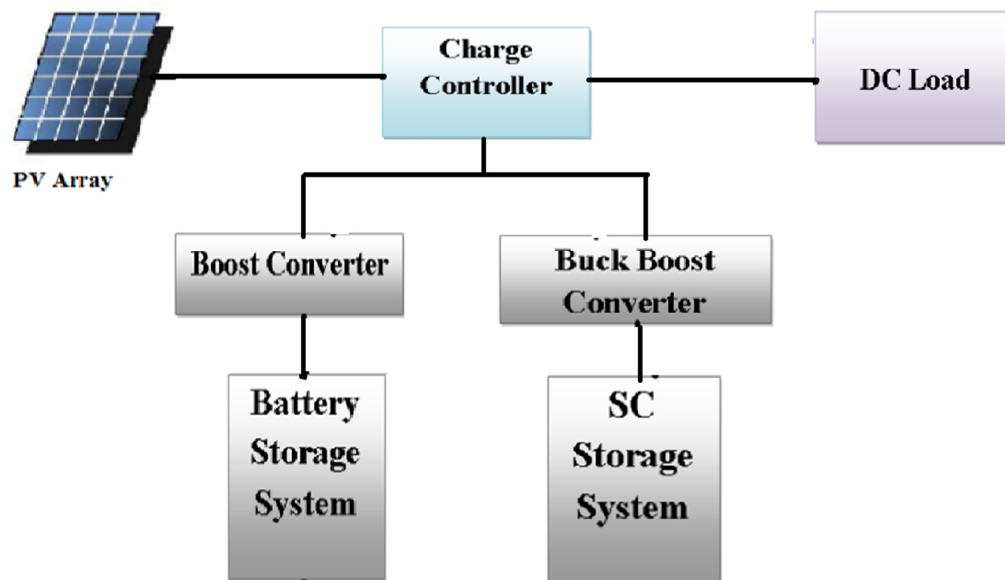


Figure 3.1 Stand-alone PV systems with HESS

This chapter describes modeling and simulation of the PV system components shown in Figure 3.1 and illustrates the individual models compiled to simulate the system. Both mathematical and electrical component models are utilized in the system design.

3.4 System Sizing

When sizing the photovoltaic system, the logical first step is to consider the energy demand. Thus, a primarily standalone PV system sizing begins at the load side and proceeds backward to the PV arrays.

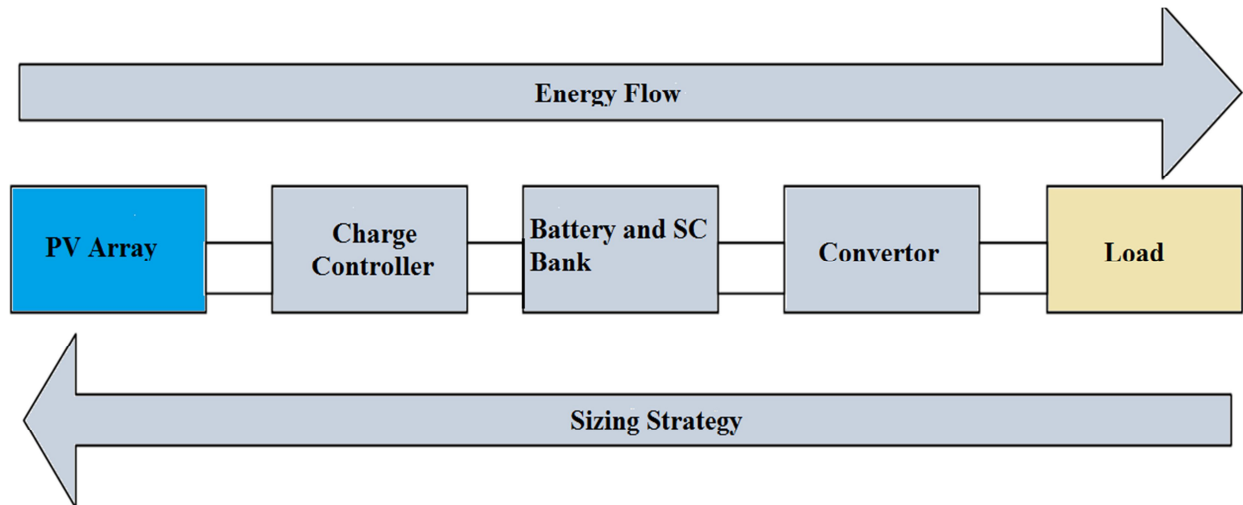


Figure 3.2: Sizing strategy for standalone system

The purpose is first to decide the system loads needed and then to decide the size of the PV module, converter, and battery that are required to meet the energy demand from load side.

3.4.1. Sizing Calculation

The sizing stand-alone PV system is based on four fundamental calculations. First, a load analysis decides the energy demand requirements on the load side. Second, monthly load requirements are compared to the isolation of the availability load data to determine the critical design month. Then, the battery bank or storage system should be sized appropriately to produce enough energy for loads to a certain length of time such as if PV arrays reduce outputs during cloudy days. Finally, the PV arrays should be sized to generate enough power for both load requirements and storage system.

3.4.2. Load Analysis

The load analysis is the most significant part in stand-alone PV sizing. The energy utilized necessitates the amount of electricity that must be generated. A number of load profiles were developed to analysis varying conditions. The load profiles utilized were developed to represent a peak, pulse and domestic load profile. The peak load profile was developed to represent the starting of a dc load. The current required to initially start the dc load is significantly greater than

the current necessary to keep the load running in steady state. Typically, the starting current of the dc load could be six times the steady state current [37]. In this study, for perfect storage system design and economical issue with a sample residential DC load were used for Addis Ababa where the meteorological data's obtained from the NASA Surface meteorology and Solar Energy center.

Load's State

In an electric system, loads are required to have either high power, or low power. As it is shown in Fig. 3.3, when load needs low power, the source with high energy density is on top of priorities. When load needs high power, both sources supply the load together. In some special applications energy first stores in the storage device with high power density and then it is delivered to storage devices with high energy density [13].

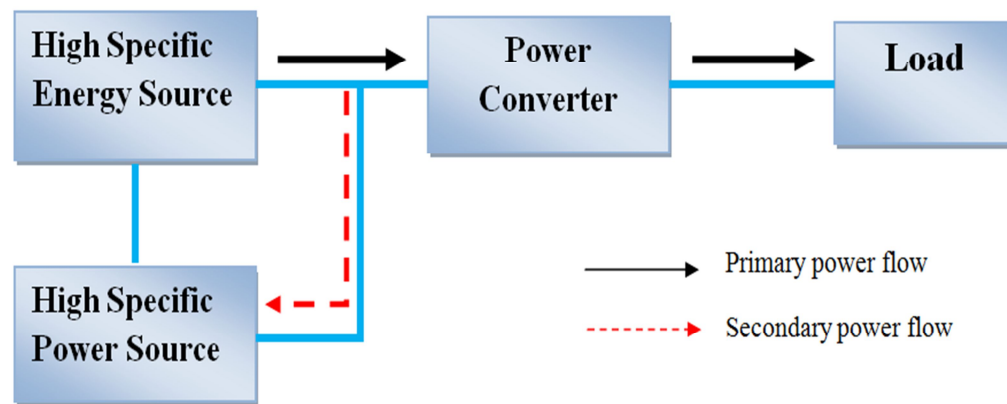


Figure 3.3: Storage system supply to the load: [13]

3.4.3 Residence Load Profile

The residence load profile is determined by itemizing all the residence appliances with their corresponding power ratings and hours of operation to obtain the total average energy demand in watt-hours (residence load profile) per day as indicated in Table 3.1

Table 3.1: Residence Appliances and Daily Load Profile

S/N	APPLIANCE	Quantity	Power Rating (Watt)	Hours Of Use Per Day	Energy Per Day (watt-hour)
1	55" Plasma TV	1	125	12	1500
2	Satellite Receiver	1	25	12	300
3	Refrigerator	1	150	14	2100
4	Computer	1	65	3	195
5	Pressing Iron	1	1000	0.5	500
6	Washing Machine	1	250	1	250
7	Compact Florescent Lamp	8	15	5	600
8	Cell phone	4	2.5	3	30
9	Chargeable Lamp	2	12	4	96
10	Electric Fan	1	70	6	420
11	Shaver	1	15	1	15
Total Load Profile			1729.5		6006

3.4.4. Critical Design Month

Stand-alone PV systems must generate sufficient electricity in order to meet load demand during each month. Thus, the PV system must be sized according to a worst case scenario of the lowest insolation rate and highest load. This worst-case scenario is used to determine the critical design month that has a critical design ratio. The critical design ratio is calculated by dividing the average daily consumption by the insolation. This ratio is calculated for each month separately and the critical month is detected. After the critical design month is identified, the lowest ratio selects the optimal orientation [5].

Figure 3.4 to Figure 3.8 demonstrate the impact PV cell temperature and solar radiation have on the PV panel output power. Figure 3.5 and Figure 3.6 give the I-V and P-V characteristic curves for the Kyocera KD 185 GX panel with a constant solar radiation of 1000W/m² under varying cell temperature. The impact solar radiation has on the PV panel is highlighted in Figure 3.7 and Figure 3.8, the I-V and P-V characteristic curves under varying solar radiation with a constant cell temperature of 25°C is shown.

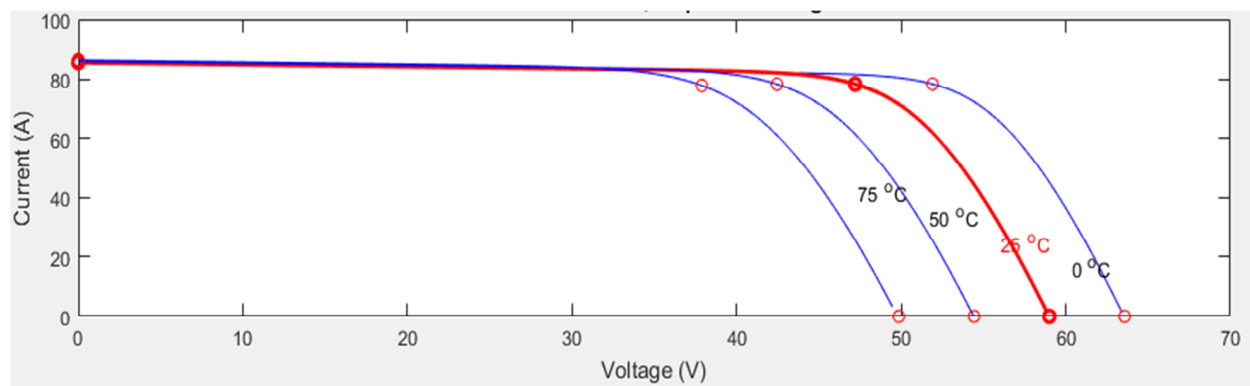


Figure 3.4: KD 185 GX I-V characteristic curve for varying levels of temperature

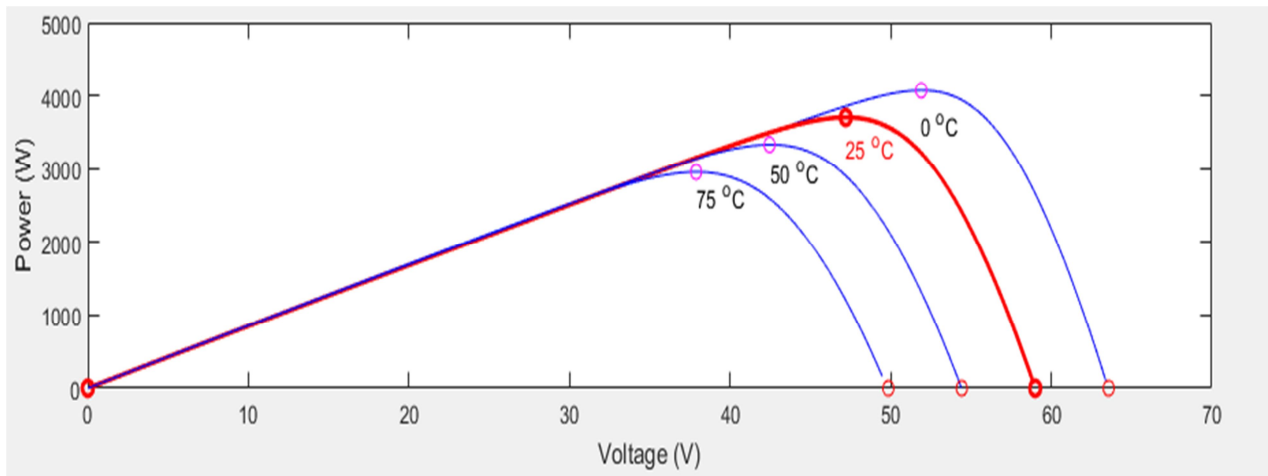


Figure 3.5: KD 185 GX P-V characteristic curve for varying levels of temperature

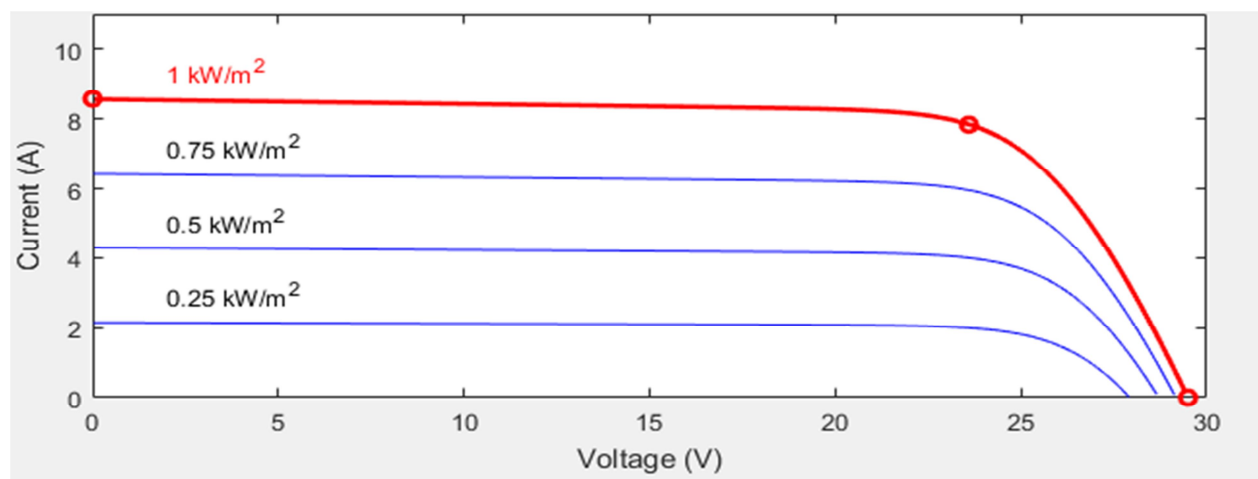


Figure 3.6: KD 185 GX I-V characteristic curve for varying levels of solar radiation

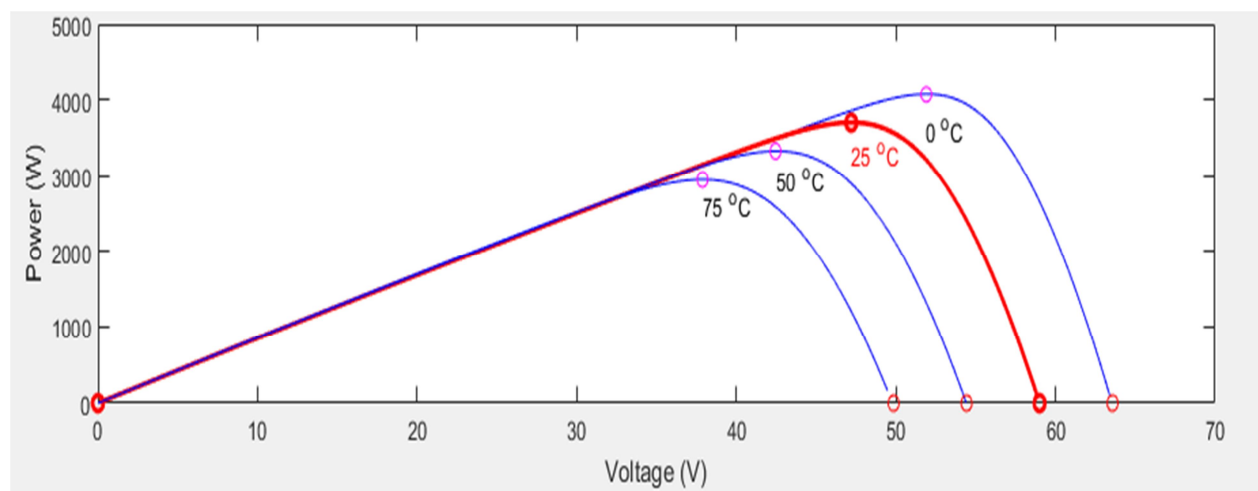


Figure 3.7: KD 185 GX P-V characteristic curve for varying levels of solar radiation

3.5. PV array sizing

Thus, the load profile of the residence is 6006 watt-hours per day and will be used to determine the stand- alone PV power system component sizes as detailed here under.

Solar radiation for the site location Addis Ababa is:

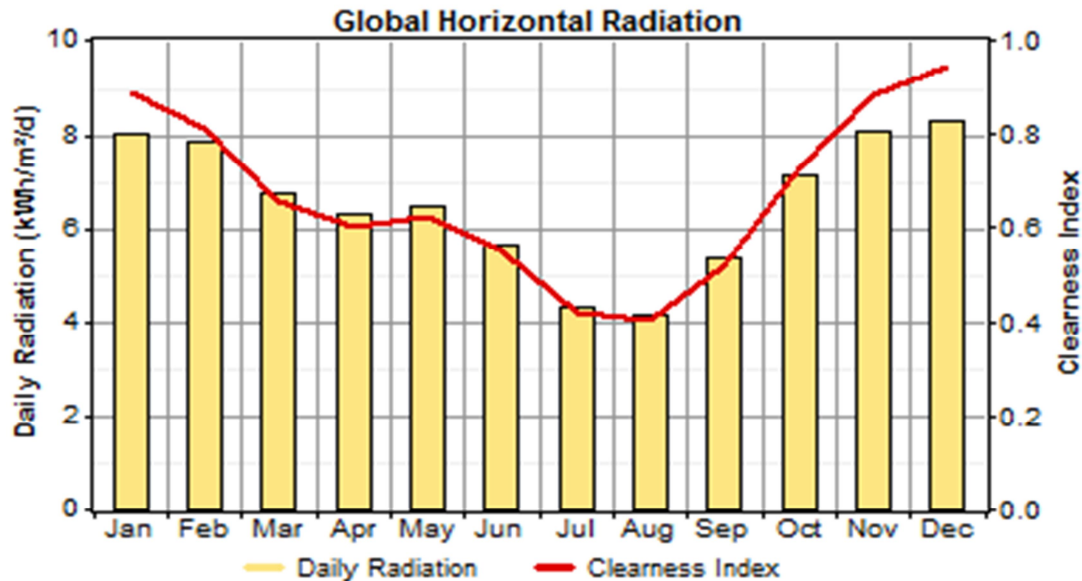


Figure 3.8: Homer program global horizontal radiation

Table 3.2: Monthly Averaged Insolation Incident on A Horizontal Surface (kWh/m²/day)

Lat 9.02°N Lon 38.75°E	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
22-year Average	6.18	6.59	6.52	6.48	6.42	5.86	5.15	5.18	5.84	6.40	6.31	6.11	6.08

Take into account the design for the month when there is the least sun and the most demand is July=5.15KWh/m²/day.

If more PV modules are installed, the system will perform better and battery life will be improved and if fewer PV modules are used, the system may not work at all during cloudy periods and battery life will be shortened so the result of the calculation should have to be the maximum number of PV panels.

Required Information

Solar module: Selected PV module Kyocera KD185GX, 185W, Vmax=23.6V, Imax =7.84A, Voc=29.5, Isc=8.58 A. Ccost=\$92.4

System Voltage (Vdc): nominal voltage of the module is 24V

Average Sun-hour for Addis Ababa (T_{sh}): 7 hour

Daily average demand (E_d) from Table 4.1=6.006Kwh

Battery efficiency (η_b): 0.85

Converter efficiency (η_i): 0.9

Charge controller efficiency (η_c): 0.9

Table 3.3: Summary of PV Array Sizing and Cost Estimate

Parameter Being Determined	Working Formula	Computed Parameter Value
Required Daily Energy Demand(E_{rd})	$E_{rd} = \frac{E_d}{\eta_b \eta_i \eta_c}$	8.7233 KWh/Day
Average Peak Value(P_{ave,peak})	$P_{ave,peak} = \frac{E_{rd}}{T_{sh}}$	1246.187 W
Total DC Current(I_{dc})	$I_{dc} = \frac{P_{ave,peak}}{V_{dc}}$	51.9245A
Number of Series Modules(N_{sm})	$N_{sm} = \frac{V_{dc}}{V_{rm}}$	2
Number of Parallel Modules(N_{pm})	$N_{pm} = \frac{I_{dc}}{I_{rm}}$	10
Total Number of Module(N_{tm})	$N_{tm} = N_{sm} \times N_{pm}$	20
Total Cost of Array in Birr(A_{cost})	$A_{cost} = N_{tm} \times M_{cost}$	\$1848

3.6 Battery Bank Sizing

Battery Capacity (Ah) = Total Watt-hours per day used by appliances x Days of autonomy
(Battery loss x Depth of discharge x nominal battery voltage)

Days of autonomy (the number of days that you need the system to operate when there is no power produced by PV panels) =3,

Required Information

Number of Days of Autonomy (D_{aut}) =3 Days

Battery: battery of deep cycle Lead-Acid battery of type Surette 12CS11PS of 12V, $D_{disch}=0.8$, Nominal Voltage =26.4 and $C_b= 357$ Ah. $B_{cost}=\$34.55$

Table 3.4: Summary of Battery Bank Sizing and Cost Estimate

Parameter being Determined	Working Formula	Computed Parameter Value
Estimated Energy Storage(E_{est})	$E_{est} = E_d \times D_{aut}$	18.018 KWh
Safe Energy Storage(E_{safe})	$E_{safe} = \frac{E_{est}}{D_{disch}}$	22.5225 KWh
Total Capacity of Battery Bank(C_{tb})	$C_{tb} = \frac{E_{safe}}{V_b}$	1876.875 Ah
Total Number of Batteries Bank(N_{tb})	$N_{tb} = \frac{C_{tb}}{C_b}$	6
Number of Batteries in Series(N_{sb})	$N_{sb} = \frac{V_{dc}}{V_b}$	2
Number of Batteries in Parallel(N_{pb})	$N_{pb} = \frac{N_{tb}}{N_{sb}}$	3
Cost of Battery Bank in Birr(B_{bcost})	$B_{bcost} = N_{tb} \times B_{cost}$	\$207.3

3.7 Supercapacitor Bank Sizing

Required Information

Maxwell Technologies BMOD0165-24V Supercapacitor Capacitance =1500F, $V_{cell}=2.7V$, $ESRDCESR_{DC}=8.1$ m Ohm, Leakage Current =120mA, $E_{max}= 3.1$ Whr /kg, $P_{max}=10KW/kg$, $SC_{cost}=\$49.95$, V_a Maximum supercapacitor operating voltage=26V, V_b Minimum supercapacitor operating voltage=20V

Table 3.5: Summary of Supercapacitor Bank Sizing and Cost Estimate

Parameter being Determined	Working Formula	Computed Parameter Value
Estimated Energy Storage($E_{est,cap}$)	$E_{est,cap} = E_d \times D_{aut}$	6.006KWh
Required capacitance of the Supercapacitor bank($C_{cap,req}$)	$C_{cap,req} = \frac{2E_{est,cap}}{V_a^2 - V_b^2}$	43.522F
Supercapacitor in series($N_{cap,ser}$)	$N_{cap,ser} \geq \frac{V_a}{V_{cap}}$	10
Supercapacitor in parallel ($N_{cap,par}$)	$N_{cap,par} \geq \frac{C_{cap,req} \times N_{cap,ser}}{C_{cap}}$	1
Total Number of Supercapacitor Bank ($N_{cap,tot}$)	$N_{cap,tot} = N_{cap,ser} \times N_{cap,par}$	10
Cost of Supercapacitor Bank in Birr(SC_{tcost})	$SC_{tcost} = N_{cap,tot} \times SC_{cost}$	\$499.5

3.8 Charge Controller Sizing

3.8.1 Solar Charge Controller Sizing

According to standard practice, the sizing of solar charge controller is to take the short circuit current (I_{sc}) of the PV array, and multiply it by 1.25. So the solar charge controller should be rated 100 A at 24 V. Table 4.6 presents the summary of the Charge Controller sizing procedure and its cost estimate

Required Information

Charge controller: Xantrex XW-MPPT60-150, $V_{cc}=24$, $I_{cc}=60A(dc)$, $C_{cost}=\$478.20$

Safety Factor: $F_{safe}=1.25$

Table 3.6: Summary of Charge Controller Sizing and Cost Estimate

Parameter Being Determined	Working Formula	Computed Parameter Value
Required charge Controller Current(I_{rcc})	$I_{rcc} = I_{sc} \times N_{pm} \times F_{safe}$	94.75A
Number of Charge Controllers (N_{cc})	$N_{cc} = \frac{I_{rcc}}{I_{cc}}$	2
Cost of Charge Controllers in Birr(C_{tcost})	$C_{tcost} = N_{cc} \times C_{cost}$	\$956.4

3.8.2. Convertors Sizing

For Buck Converter

The equivalent series resistance (ESR) of the capacitor adds some more ripples, given by: Therefore, it is advised to use a low-ESR capacitor to minimize the ripple of the ripple on the output voltage. Ceramic capacitors are a good choice.

Table 3.7: Value of Inductor Selection Parameters for buck boost convertor

Parameter Being Determined	Working Formula	Computed Parameter Value
Inductor selection (L)	$L = \frac{V_{out} \times (V_{in} - V_{OUT})}{\Delta I_L \times f_s \times V_{IN}}$	100mH
Inductor ripple current (ΔI_L)	$\Delta I_L = (0.2 \text{ to } 0.4) \times I_{OUT(max)}$	
Output capacitor selection($C_{OUT(min)}$)	$C_{OUT(min)} = \frac{\Delta I_L}{8 \times f_s \times V_{OUT}}$	26 μ F
Cost of Buck Boost in Birr(C_{tcost})	$C_{tcost} = N_{cc} \times C_{cost}$	\$200.59

For Boost Converter

Table 3.8: Value of Inductor Selection Parameters for buck convertor

Parameter Being Determined	Working Formula	Computed Parameter Value
Inductor selection Boost Converter (L)	$L = \frac{V_{out} \times (V_{in} - V_{OUT})}{\Delta I_L \times f_s \times V_{IN}}$	15mH
Inductor ripple current (ΔI_L)	$\Delta I_L = (0.2 \text{ to } 0.4) \times I_{OUT(max)}$	
Output capacitor selection($C_{OUT(min)}$)	$C_{OUT(min)} = \frac{I_{OUT(max)} \times D}{f_s \times \Delta V_{OUT}}$	50 μ F
Cost of Boost Converter in Birr(C_{tcost})	$C_{tcost} = N_{cc} \times C_{cost}$	\$224.25

3.9 System Wiring Size

Table 4.8 presents the summary of the procedure for selecting the correct cable sizes for these two important connections.

Table 3.9: Summary of Procedure for Selecting Cable Sizes

PV System Cable Link	Current Rating of Cable(I_{cab})	Selected Cable Size and Type
PV Array to Battery Bank through Charge Controller	$I_{cab} = I_{rcc} = I_{sc}^M \times N_{pm} \times F_{safe}$ $8.58 \times 10 \times 1.25 = 107.25A$	2x16mm ² Insulated Flexible Copper Cable
Inverter to DB of Residence	Current Produced By Converter Output $I_{oi} = \frac{P_i}{V_{io} \times pf_i} = \frac{1200}{24 \times 0.8} = 62.5A$	2x4 mm ² Insulated Flexible Copper Cable

Where,

I_{cab} = Cable Current between Array and Battery Bank;

I_{oi} = Current at Inverter Output;

P_i = Power rating of Inverter;

V_{oi} = Inverter Output Voltage;

pf = Power Factor

3.10 System Simulation

In the system simulation all components (which are PV, dc-dc converter, supercapacitor, battery and battery controller) are put together, and the stand-alone PV/Battery MATLAB®/Simulink simulation is created. Simulink models constructed according to the component models described in previous section with the addition of a controller are combined to develop the system model. Three system models are developed to compare the battery only, supercapacitor alone and the supercapacitor battery HESS. The simulation results are obtained by simulating for 24 hours in one critical month.

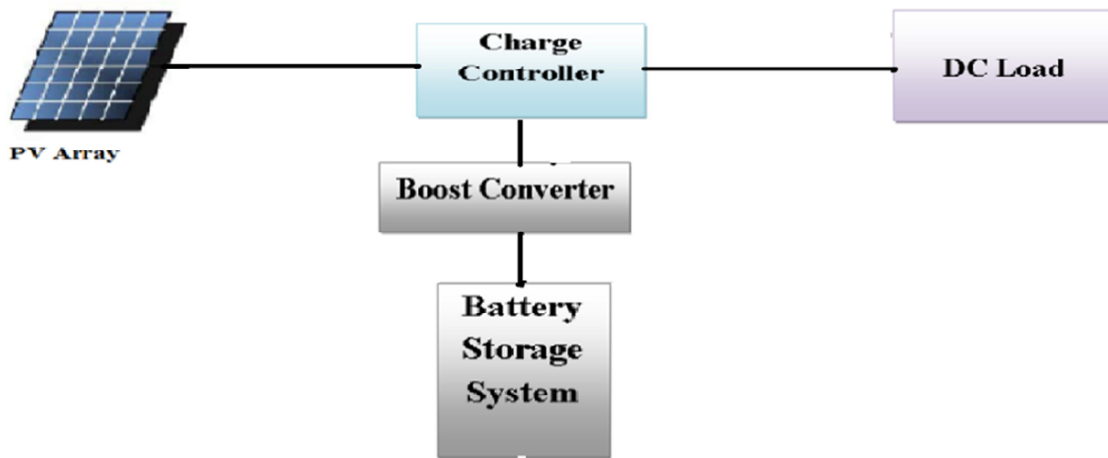


Figure 3.9: PV System with Battery storage alone

Figure 3.9 shows the photo voltaic model with battery only storage system which is widely used in current scenario that this thesis proposed to modify.

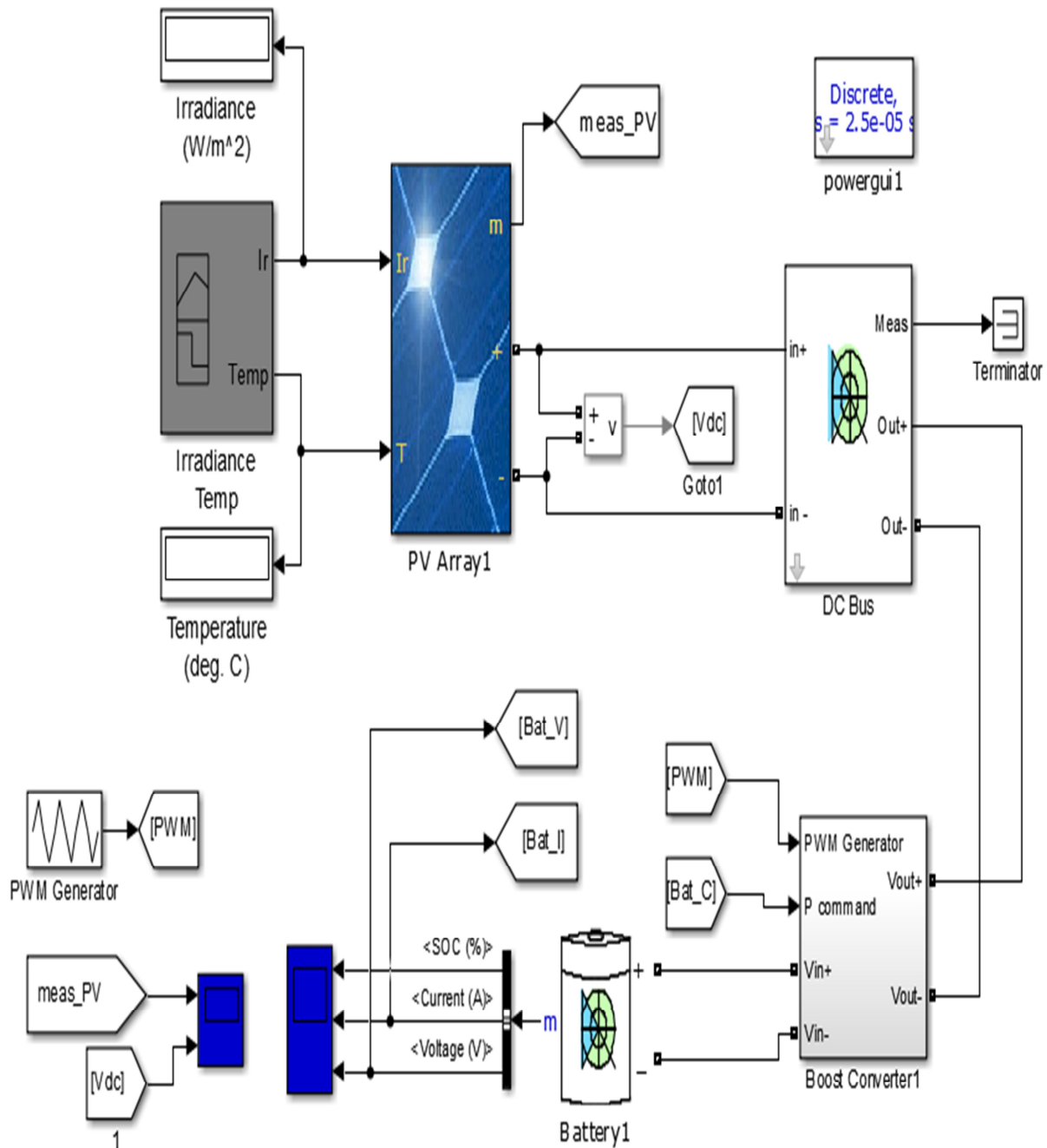


Figure 3.10: PV system Battery storage Simulink model

The above figure 3.10 shows the Mat lab Simulink model with battery storage. This Mat lab Simulink model includes PV array, boost convertor, storage battery and irradiance.

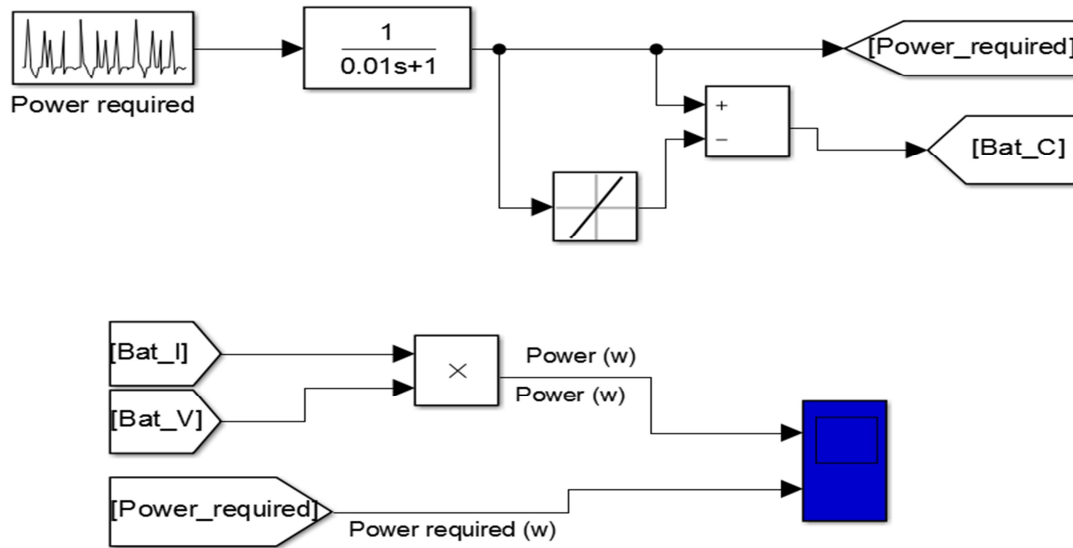


Figure 3.11: Power required Simulink model

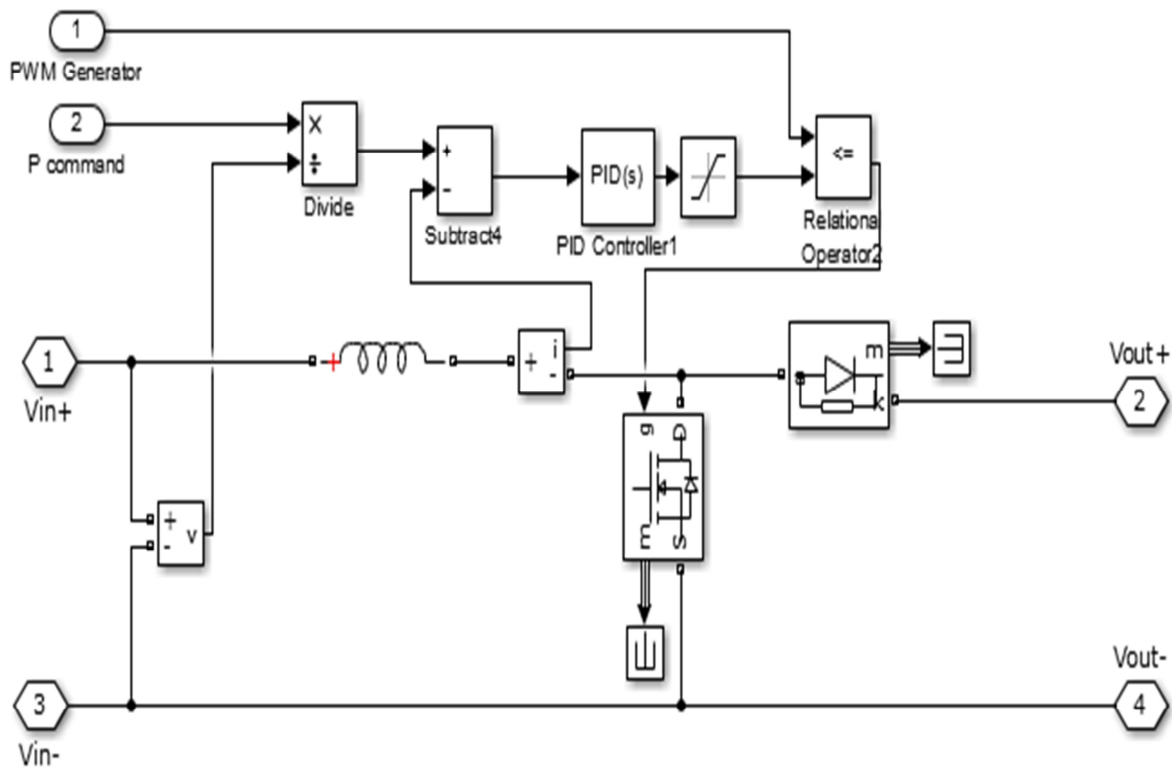


Figure 3.12: Boost Converter Simulink model

Figure 3.11 shows the Simulink model for the Load Power required and battery power calculation. The boost converter Simulink model for the PV system with battery storage model is shown in figure3.12.

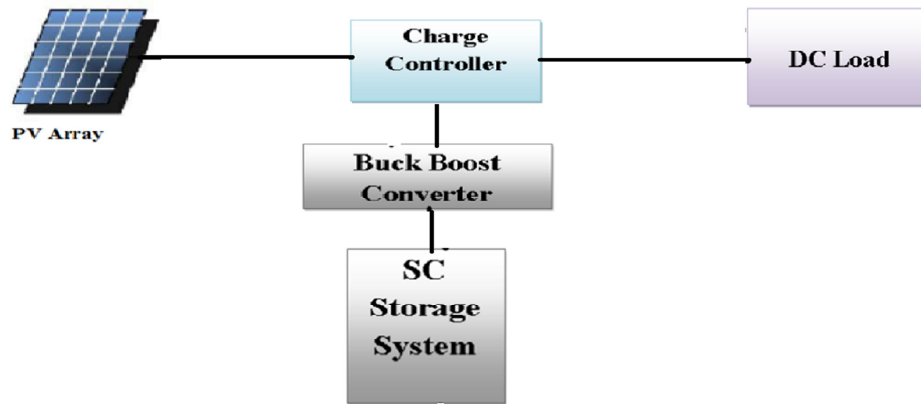


Figure 3.13: PV System with Super capacitor storage alone

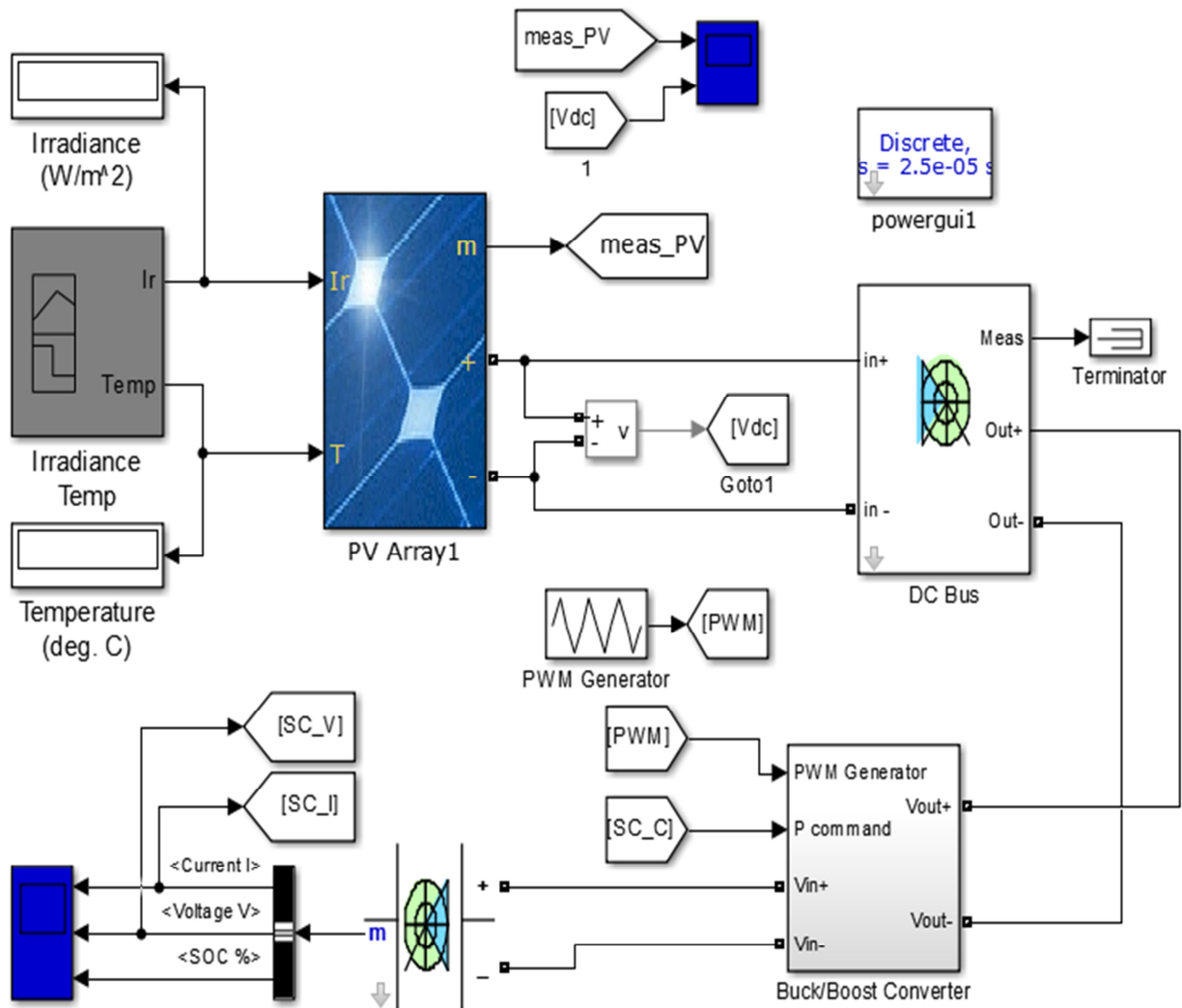


Figure 3.14: PV system with SC storage Simulink model

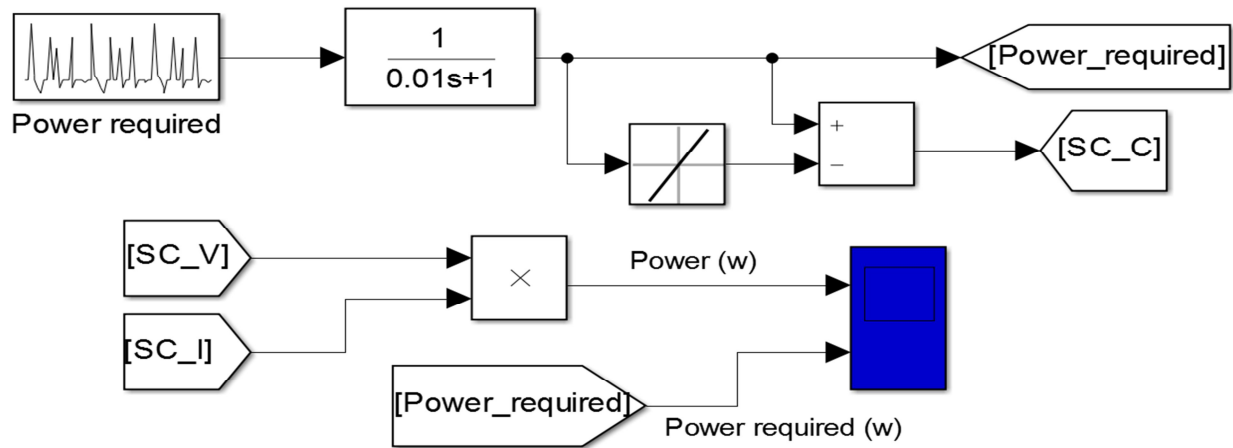


Figure 3.15: Power required Simulink model

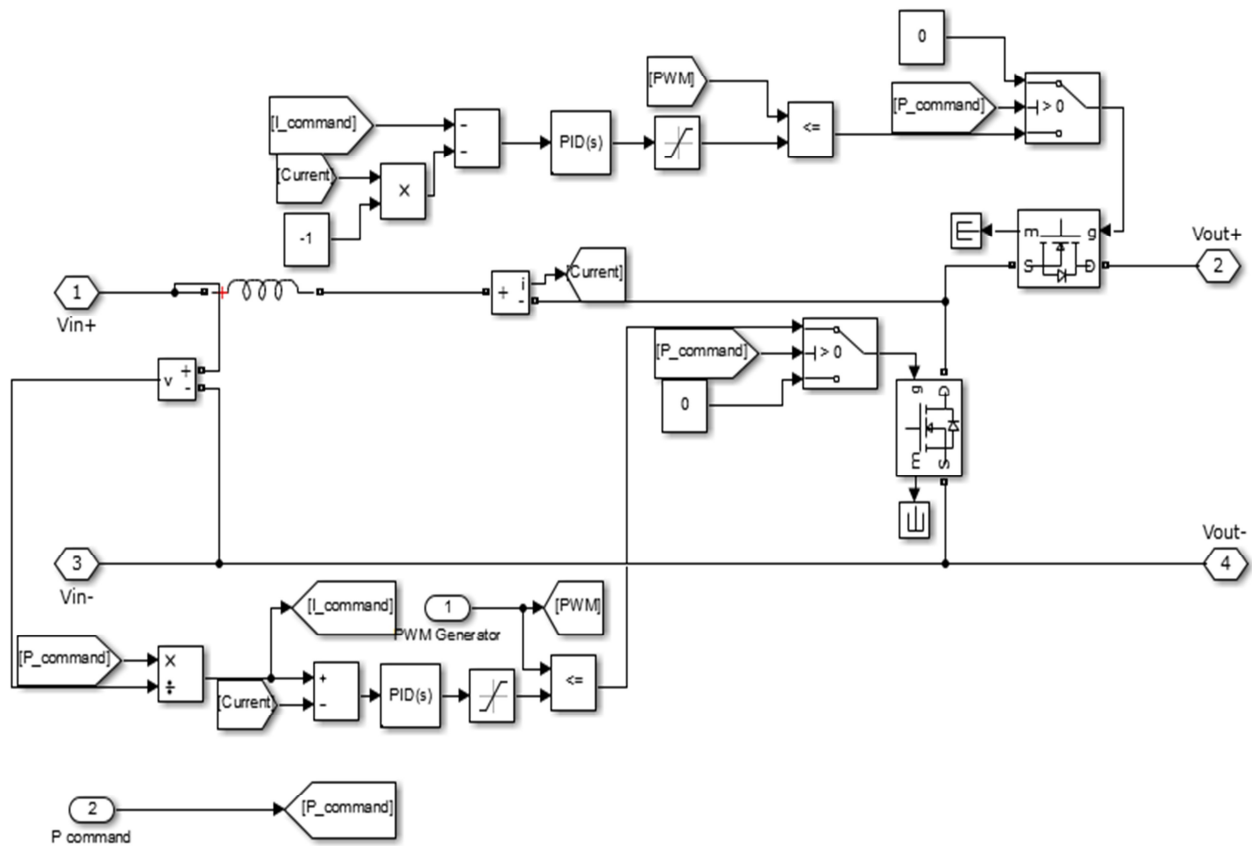


Figure 3.16: Buck Boost convertor_Simulink model

The above figures show the photo voltaic model using mat lab Simulink with supercapacitor storage only. In this model we use a buck boost converter model with a mat lab Simulink as shown in figure 3.16.

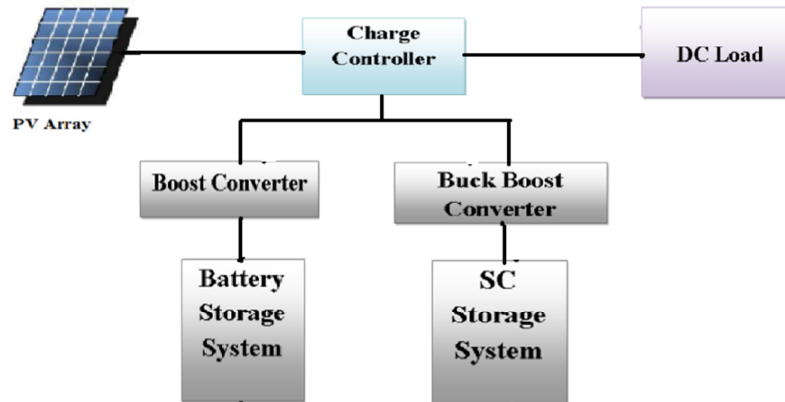


Figure 3.17: PV System with Hybrid battery-supercapacitor storage

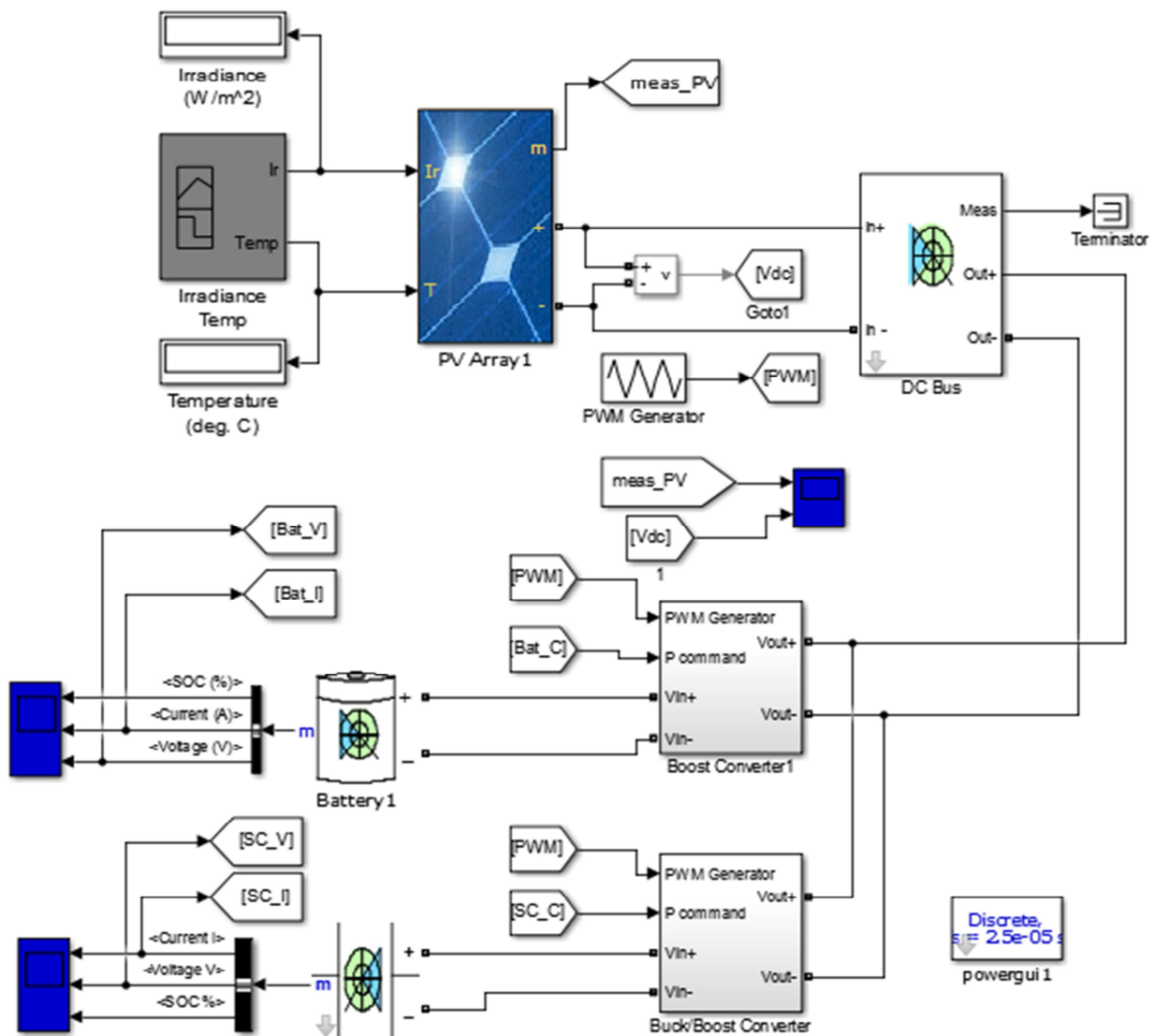


Figure 3.18: PV system Battery-SC hybrid storage Simulink model

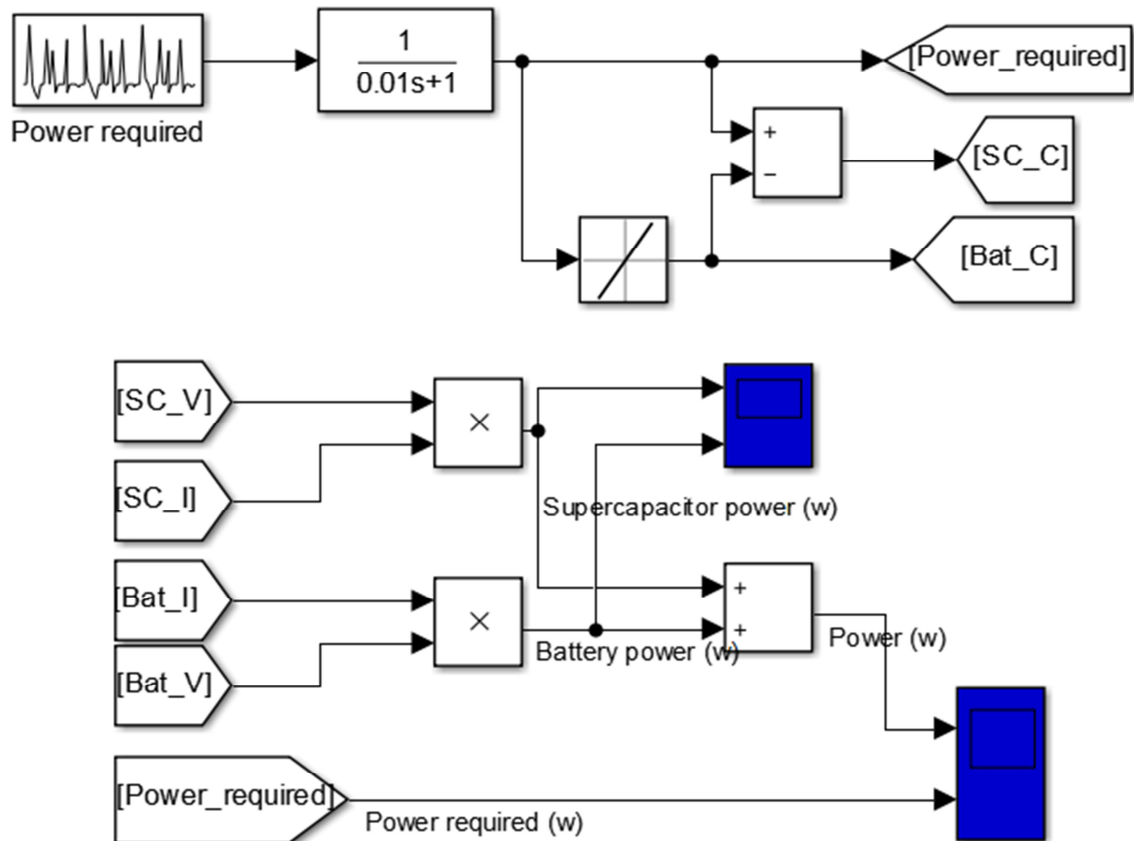


Figure 3.19: PV system Power required Simulink model

Figure 3.17 shows the PV System with Hybrid battery-supercapacitor storage model for which this thesis mainly concern with. The figure 3.18 clearly shows the full mat lab photovoltaic system Battery-SC hybrid storage Simulink model. As shown in the figure the battery storage with boost convertor and supercapacitor with buck-boost convertor are connected in parallel. For which the storage system is efficient and good performance. In Figure 3.19 the comparison of demand and photo voltaic system generated power compared on the scope.

CHAPTER FOUR

Result and Discussion

In this chapter, the simulations outcome carried out on MATLAB®/Simulink to test the ability of battery-supercapacitor hybrid storage system for photovoltaic system will be shown and a brief discussion will be elaborated.

All the simulations have a simulation time of 2.4 minutes. Otherwise, a higher simulation time would take too long to finish it. The load considered is a DC single phase standalone of 24V and 50 Hz. Therefore the load profile is given in Table 3.1. These data values used for the purpose of searching storage system responses with respect to variable load profile. As given in modeling the load with a small local residential DC load consuming a total of 6.006kWhr and the chosen number for the PV arrays connected in series are due to the common DC bus voltage operates around 24V.

Figure 4.1 shows the power required by the load and the power obtained from PV system with Battery only storage. As shown in Figure 4.1 the power obtained from the PV system battery storage serve up to 900watt where the additional power faded from PV cell directly to the DC bus this is due to less battery respond capacity so the required power where 1200 watt is supplied. During demand load is falling, the battery power decreases instantly. This is due to charge controller that regulates the battery power.

On Figure 4.2 the current, voltage and state of charge of battery statues for Battery only storage system is shown. Due to random change of the load power the battery state of charge decreases accordingly. To regulate the system voltage battery voltage increase with increasing load. As seen on the graph, when the battery voltage increases the battery state of charge decreases instantly and the battery current will decreases, this accelerate the rate of charging and discharging of the battery accordingly.

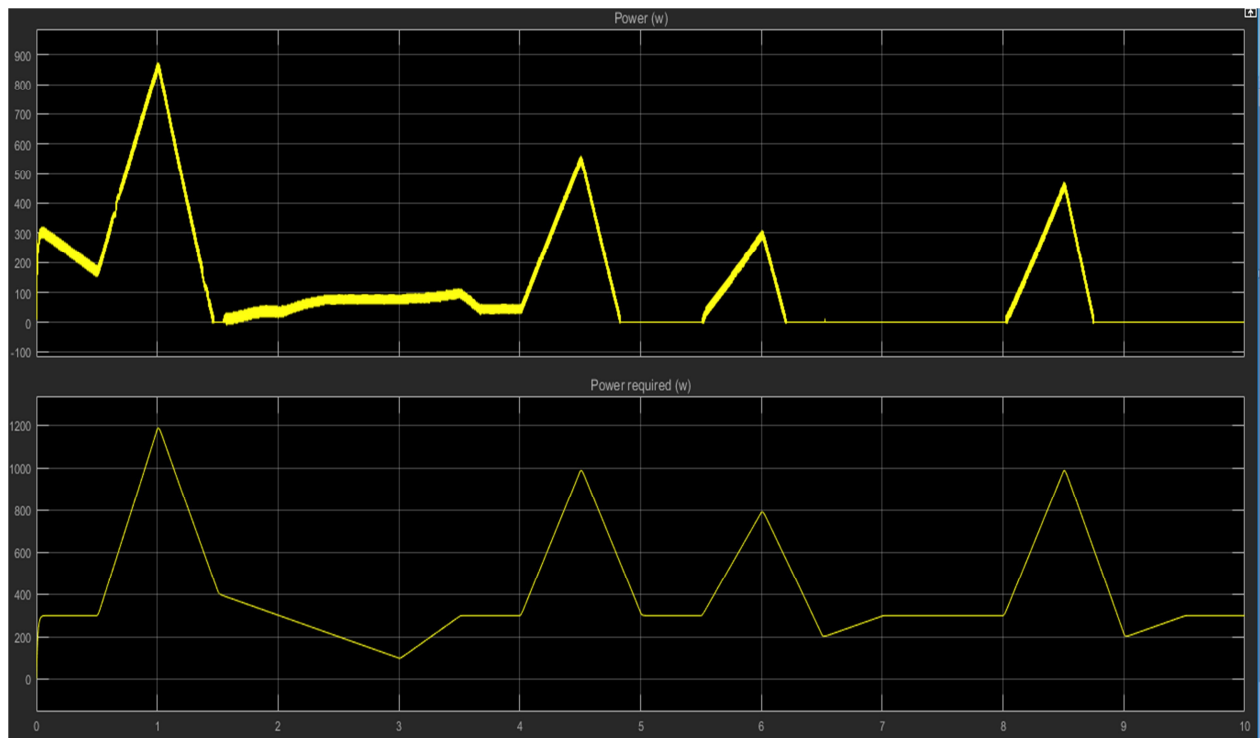


Figure 4.1: Power required and Power obtained from PV system Battery storage alone

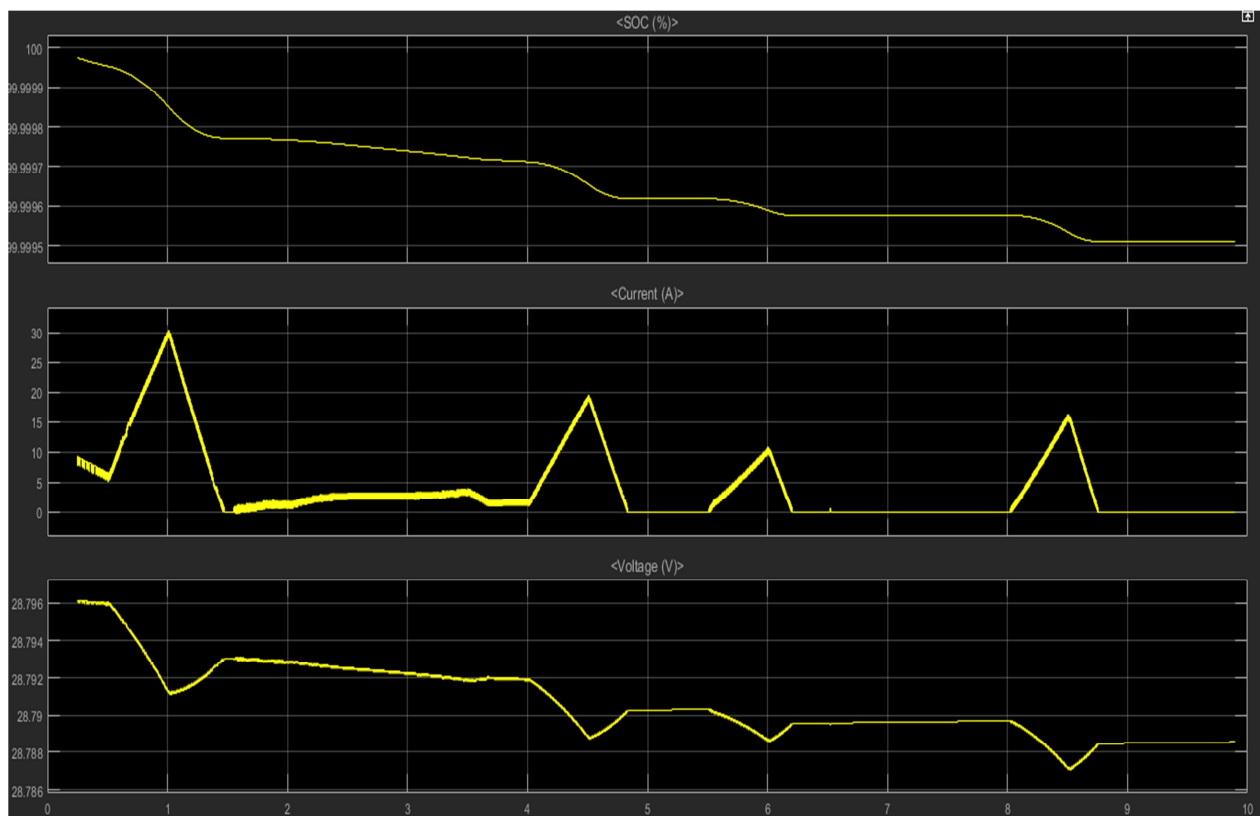


Figure 4.2: Current, Voltage and SoC for battery storage Simulink model

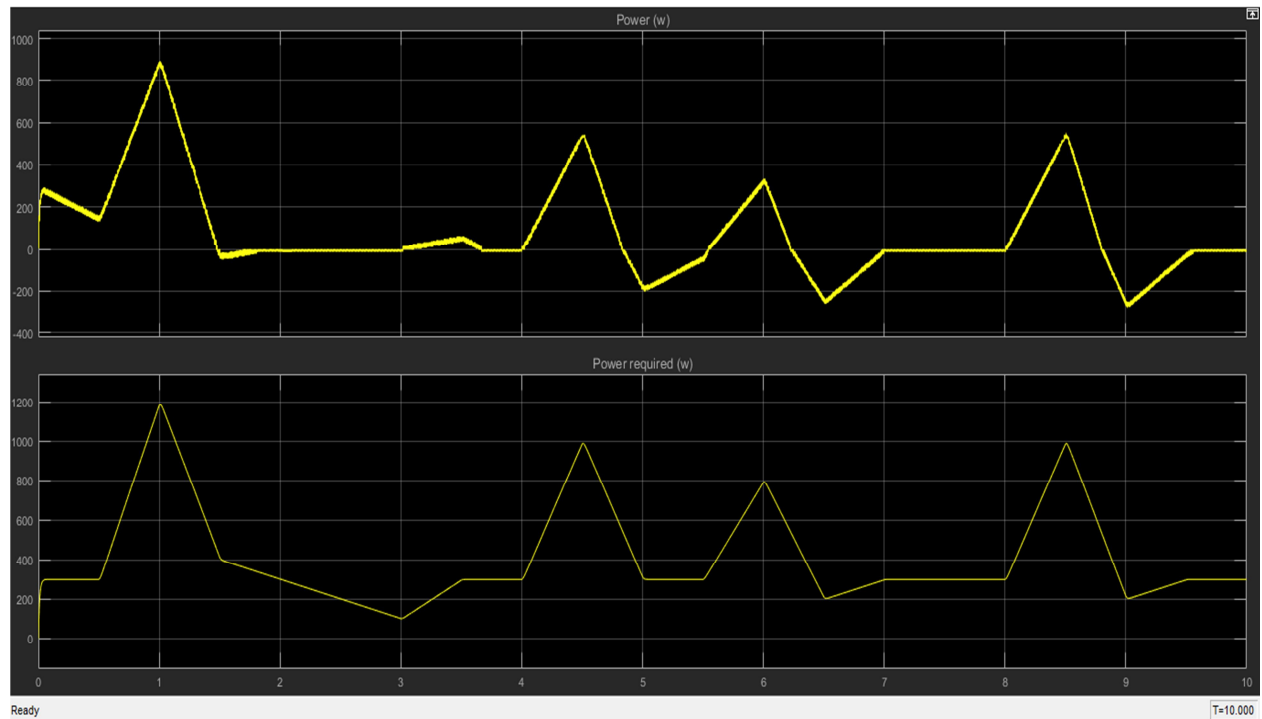


Figure 4.3: Power output obtained from PV system for SC storage Simulink model

Figure 4.3 shows the power required by the load and the power obtained from PV system with Supercapacitor storage alone. The power obtained from the supercapacitor does not supply all demand power rather it only supplies on peak load and start to recharge based on available power on the PV system.

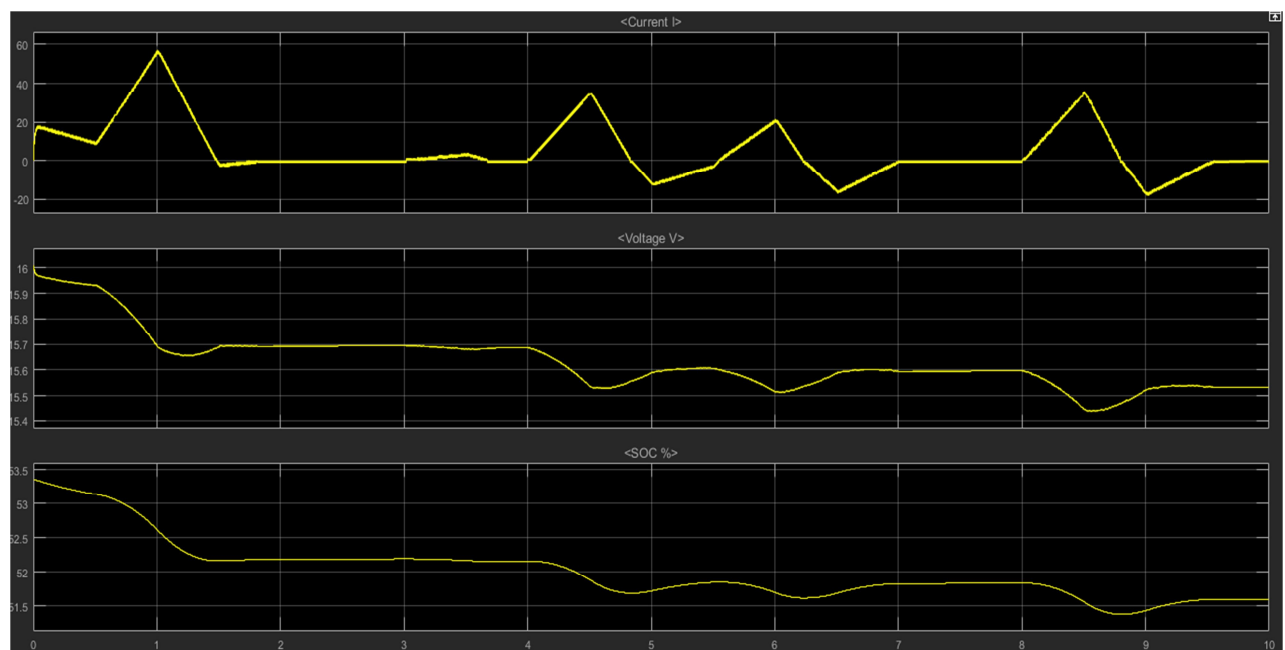


Figure 4.4: Current, Voltage and SoC for SC storage Simulink model

Figure 4.4 shows the current the voltage and state of charge of supercapacitor. From this figure it is shown that the instantly varying current sense the load property and the charging and discharging property of supercapacitor due to buck-boost converter is shown. The supercapacitor voltage and the state of charge decrease through the simulation and the power obtained from the supercapacitor is serving only for the rising load power.

Figure 4.5 sows the power required by the load and the power obtained from PV system with Battery-Supercapacitor HESS. As shown in Simulink scope the graphs are nearly the same. This shows that the PV stem with hybrid battery-Supercapacitor storage system supplies the power that required by the load efficiently.

Figure 4.6 sows the power obtained from the battery and the supercapacitor where battery supplies base load and the supercapacitor supplies power with peak load moment.

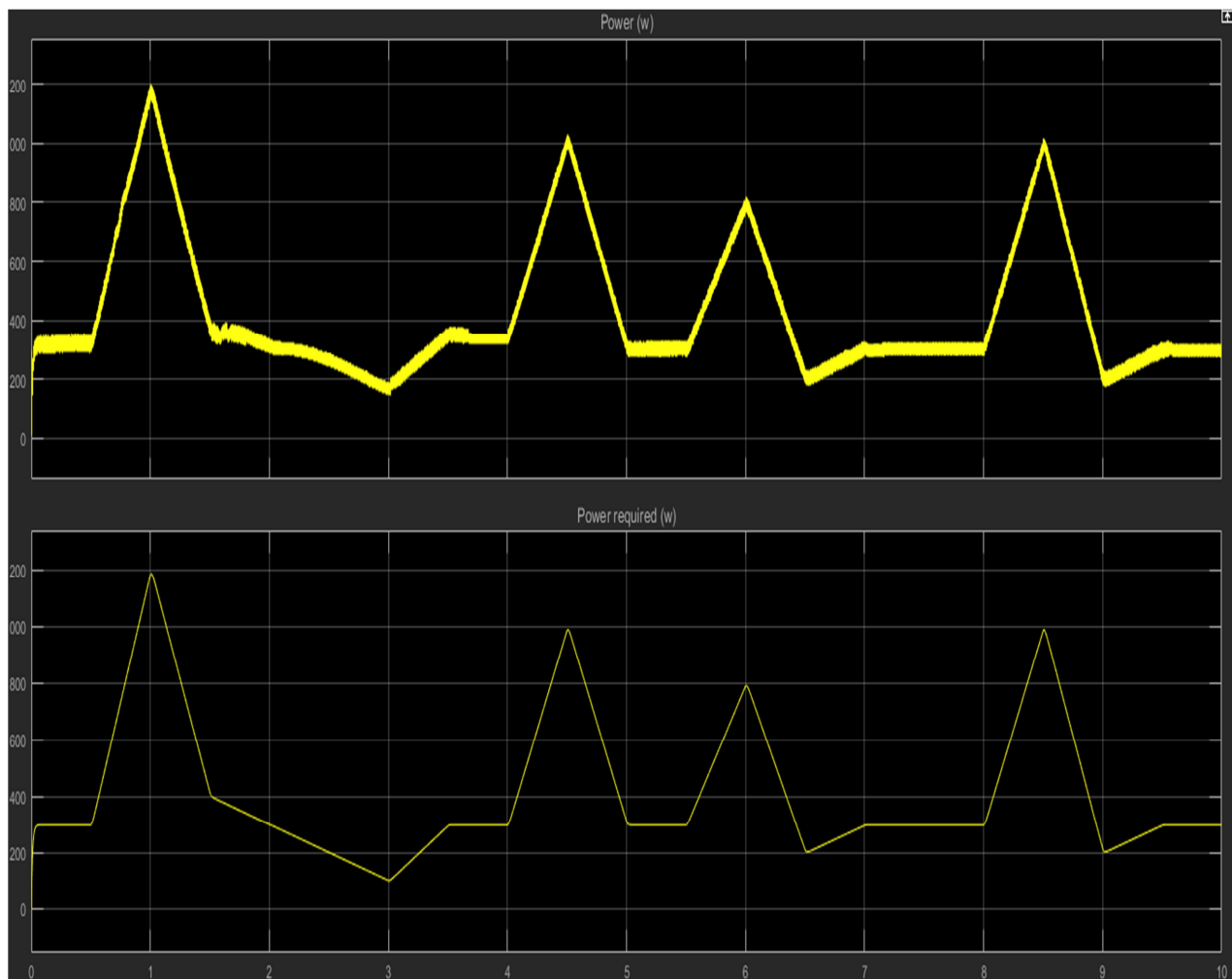


Figure 4.5: PV system Power required and Power obtained from HESS

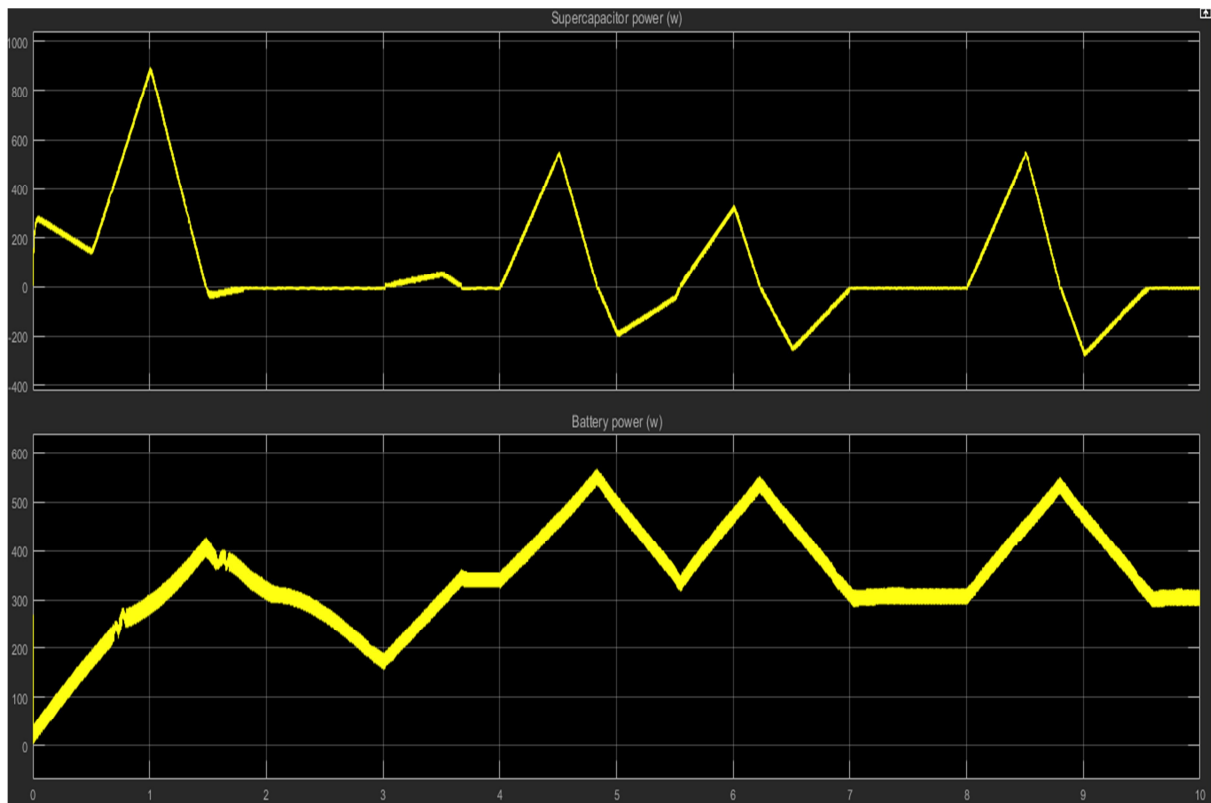


Figure 4.6: Battery and SC Power

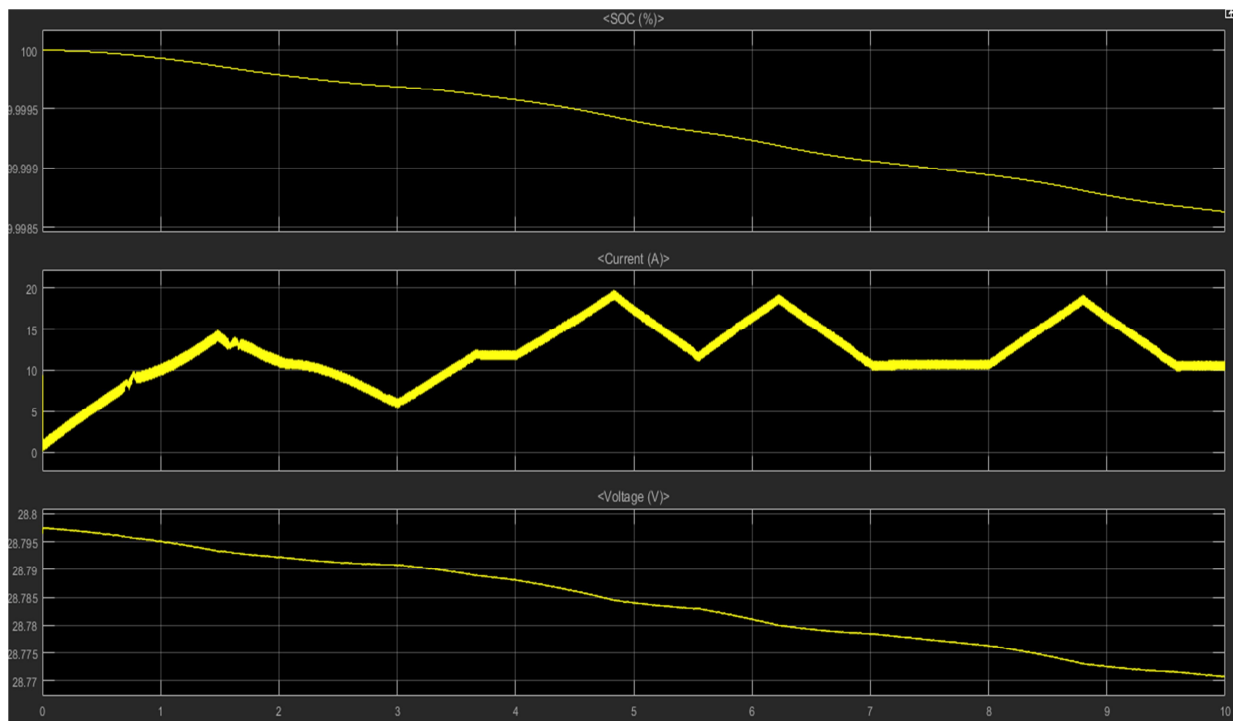


Figure 4.7: Battery Current, Voltage and SoC for HESS

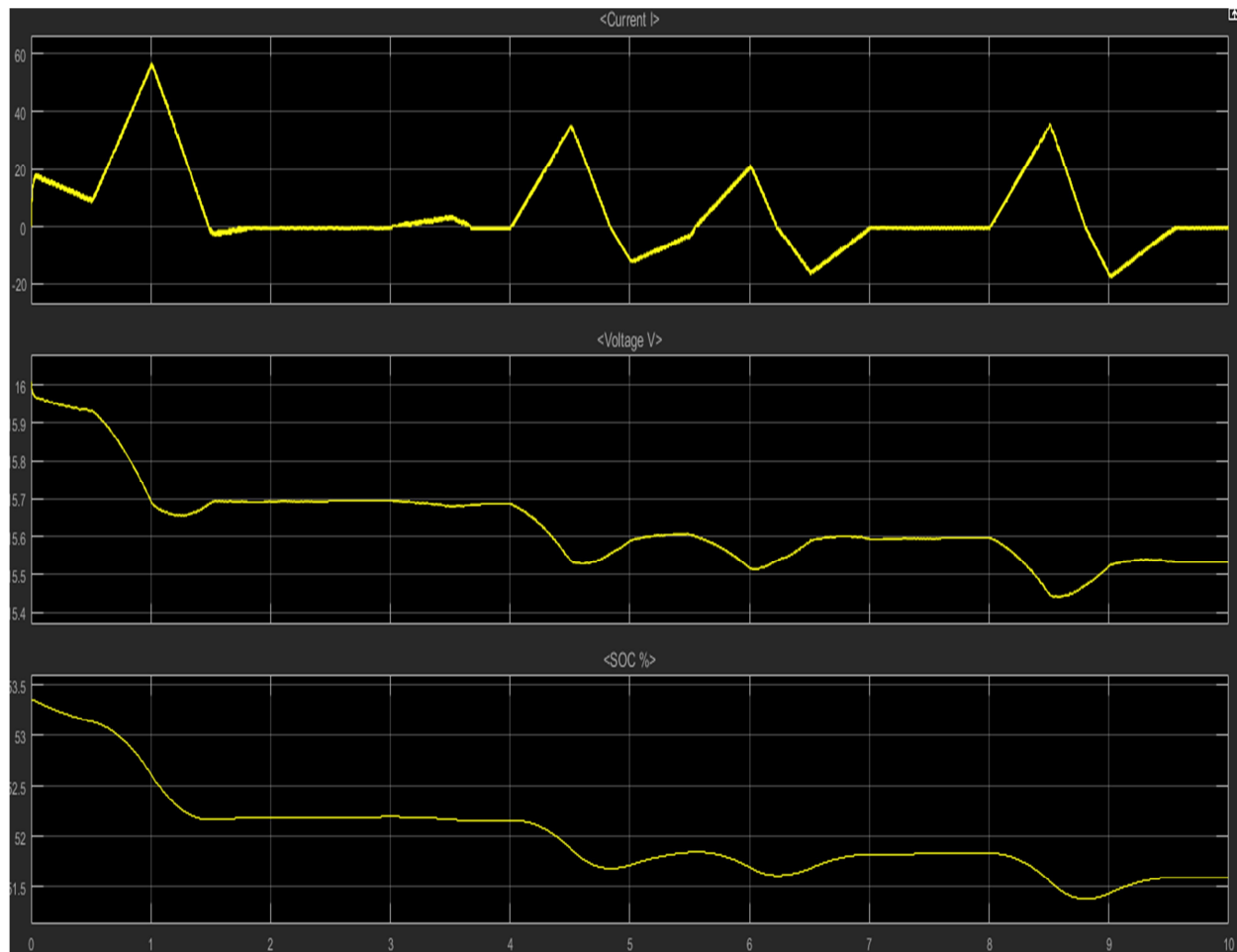


Figure 4.8: SC Voltage, Current and SoC for HESS

Figure 4.7 shows the battery current, voltage and state of charge for battery supercapacitor hybrid storage system. Figure 4.8 shows the supercapacitor current, voltage and state of charge for battery supercapacitor hybrid storage system. From the figures the state of Battery charge decreases with 8%, current varies with respect to the load variation and voltage decrease 12%.

Figure 4.9 shows the battery current for PV system with battery only storage and HESS. The initial state has a load power=200W, the SC supplied the load in transient state, whereas the Battery power satisfies the load power demanded in steady state. At $t = 1\text{s}$, the load power steps to a constant value of 1200W, synchronously, the final battery power is in its limited maximum power (900W). Thus, the SC supplies most of the transient power that is required during stepped load, it remains in a discharge state after the stepped load because the steady-state load power (1200W) is higher than the Battery limited maximum power (900W). Subsequently, at $t = 5\text{s}$, the load power steps from 900W to 200W. As a result, the SC changes its state from discharging to charging. Here from battery only storage system it is clear that the battery charging and discharging status decreased and this enhances the battery life and reduces life cost of the PV system and the battery storage.

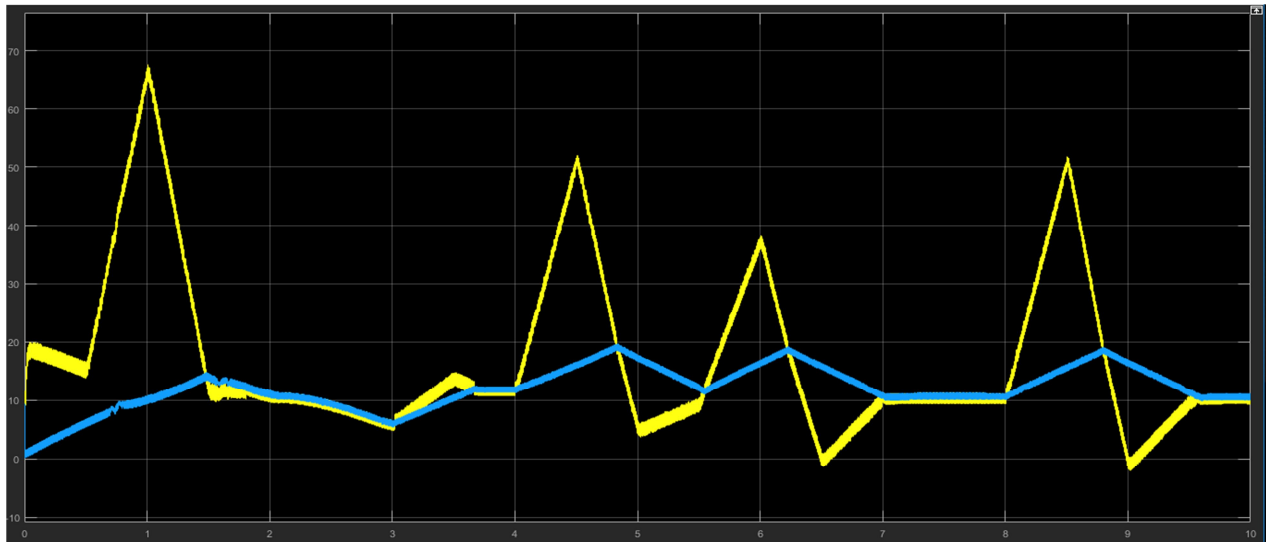


Figure 4.9: Simulated battery current HESS systems

The simulation results showing the battery current exchange in battery for HESS systems illustrated above. The yellow graph shows the HESS over all battery and supercapacitor contribution and the blue graph shows the battery current independent contribution to the model. As we see from the graph the battery only contribution of HESS to the battery only storage system, the battery currents were reduced by 50.5% for the sample solar load cycle and reduced by 60.9% for the sample load cycle. When more delivery of current is required for high peak load, battery can be used in HESS for better power sharing performance. In contrast, the percentage improvement of current per installed supercapacitor capacity was found to be higher for the solar load cycle. The reduction in currents is directly proportional to the supercapacitor contribution to the load and the developed model can be used to quantify the reduction for various levels of supercapacitor contribution. The reported percentage reduction in battery currents should serve as a foundation for battery life time extension which in turn should provide for a full life cycle saving.

Some integration issues for battery-supercapacitor systems directly impact the reduction of battery currents. It was observed that the depth of discharge (DoD) of the supercapacitor was fast for a battery-supercapacitor in simple parallel circuit. This is due to the rapid drop in current of the supercapacitor as it gets discharged. The DC-DC buck boost converter then regulates the system current, thus the supercapacitor's depth of discharge (DoD) improved significantly to the aforementioned values of 50.5%.

Modeling PV with hybrid battery-supercapacitor storage system rather than a single battery only storage system has two effects. First, the battery cannot be fully discharged all at once; Second, the battery's ability to charge and discharge depends not only on its current state of charge, but also on its recent charge and discharge history.

As seen from the Figure 4.9, the battery current for system with HESS experienced less period for attaining peak load current compared with the battery only system. But the supercapacitor

compensates this problem. In addition, at the peak current for system with HESS the state of discharge is also improved compared with system without HESS.

4.1 System Costs

Summary of PV system components and cost estimate

The PV power system components that have been sized and needed to setup a complete stand-alone power system for the suggested residence are summarized in Table 4.9. The cost of equipment (Modules, Batteries, Charge Controller, and Converter) for battery only storage system is \$3,212.29 and The cost of equipment for HESS is (Modules, Batteries, Super Capacitor, Charge Controller and Converter) is \$3,936 while the costs of Cables, Design, Labor, Metering and Control Devices are lumped together as 20% of equipment cost and add up to \$150. Thus, taking the data on component costs, preliminary estimates of total system cost of the stand-alone PV power system with battery only is \$3,362.29 and with HESS is \$4,086. The battery lifetimes characteristic basically are the battery aging and performance deterioration. Thus, minimizing these factors can potentially improve the service life of the battery. a battery health cost function $C(T)$ is formulated based on common life-limiting factors of chemical battery for which the battery life increment reduce the HESS system cost by increasing battery replacement. Battery health cost function $C(T)$ with proper Simulink graph will be shown on simulation.

Table 4.1: Summary of PV system components and cost estimate

Component	Qty	Model	PV component Rating			Total Cost (\$)
			Power (W/Ah)	Current (A)	Voltage (V)	
Module	20	Kyocera KC158G	158W	7.58A	23.2V	\$1848
Battery	6	Surette 12CS11PS	357 Ah	–	12V	\$207.3
Supercapacitor	10	Maxwell Technologies BMOD0165-48.6V	10KW/kg			\$499.5
Controller	2	Xantrex XW-MPPT 60-150	–	60A	24V	\$956.4
Buck Converter	1	UNIV 5000PI	3300W	–		\$200.59
Buck-Boost Converter	1	UNIV 5000P	3300W	–	24V	\$224.25
Cable	Lot	Array to-battery	3x35mm ² Insulated Flexible Copper Cable			\$150
		Converter to DB	3x4 mm ² Insulated Flexible Copper Cable			
			Design, Labor, Metering and Control Device			
Total Standalone PV Cost						\$4,086

Table 4.2: Energy Storage System Costs

Parameter	W/o supercapacitor	With Supercapacitor
System Voltage (V)	24	24
Battery Size (Ah)	2344.22Ah	2344.22Ah
Battery Capacity (Wh)	28.130 KWh	28.130 KWh
Battery Cost (Birr)	\$207.3	\$207.3
Supercapacitor Size (F)	-	117.97F
Supercapacitor Capacity (Wh)	-	3.1 Wh /kg
Supercapacitor Cost(Birr)	-	\$499.5
Total System Cost(Birr)	\$207.3	\$706.80

4.2 Economics Analysis and Constraints

Project economic analysis and financial evaluation both involve identifying project benefits and costs during the years in which they occur and converting all future cash flows into their present value by means of discounting. The perspectives and objectives of financial evaluation assess the ability of the project to generate adequate incremental cash flows for the recovery of financial costs (capital and recurrent costs) without external support and assesses whether a project is economically viable for the customer.

Both analyses generate net present value (NPV) and internal rate of return (IRR) indicators. As suggested in battery lifetime characteristic studies, these are two of the many factors that accelerate the battery aging and performance deterioration. The end of battery service life is when the battery capacity has reached 80% of its initial capacity or when it fails to function. The dynamic performance of a battery in charge and discharge is the speed at which current can be put into and taken from storage. In battery only storage PV systems the normal life limiting factor is the deep cycling, even for batteries with low cycle life. The terminal voltage rises and falls during charging and discharging. The charge and discharge dynamics of batteries can be characterized by measurements of charge and discharge current inputs to the system voltage under constant. Adding supercapacitor on storage system minimizes those factors and can potentially improve the service life of the battery.

The battery lifetime curve, supplied by the manufacturer, outlines the number of charge discharge cycles the battery can undergo at a particular SOC. The number of charge discharge cycle's decreases as the SOC limit is decreased.

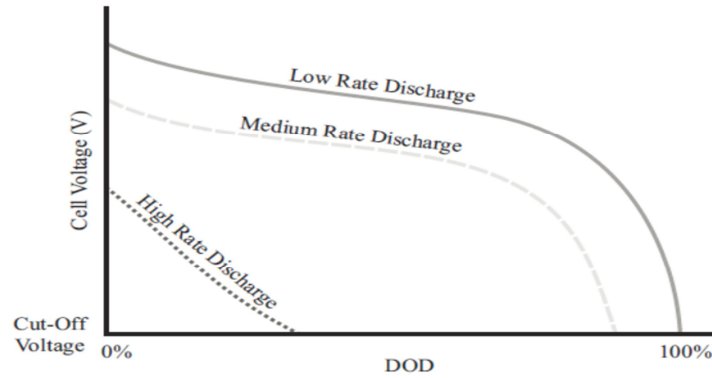


Figure 4.10: Voltage curves for different discharge rates

To determine the lifetime throughput from the curve the average annual SOC of the battery is calculated by the optimization program on the company and the number of charge discharge cycles is determined.

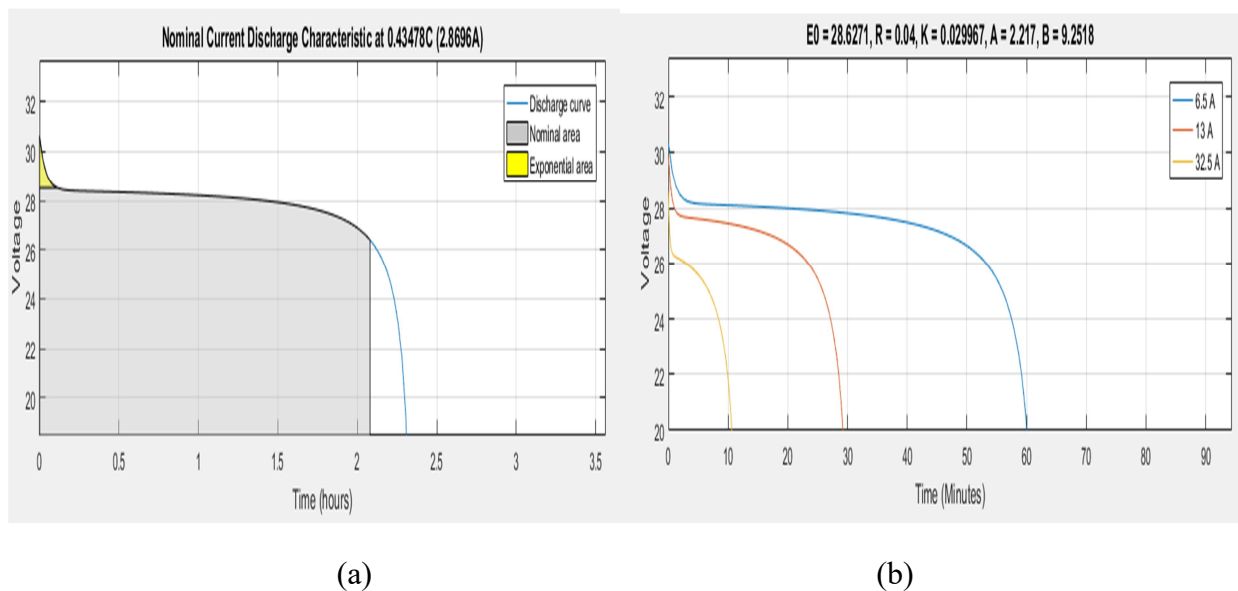


Figure 4.11: Mat lab battery discharge characteristics

The lifetime of each of the components in the system needs to be determined in calculating the cost. One of the advantages of hybrid battery supercapacitor storage system is to decrease the system lifetime cost. According to the manufacturers datasheet the PV panels have a lifetime of 25 years, which is taken as the system lifetime. Supercapacitors are not replaced during this time as they have a cycle life of greater than 500,000 cycles. The cost of batteries is usually stated in units of \$/Watt-hrs (or \$/KWatt-hrs). The cost will largely depend on the capacity of the battery and depth of charge discharge characteristics. The cost should be weighed with the deep-cycle selection criteria to make a final decision.

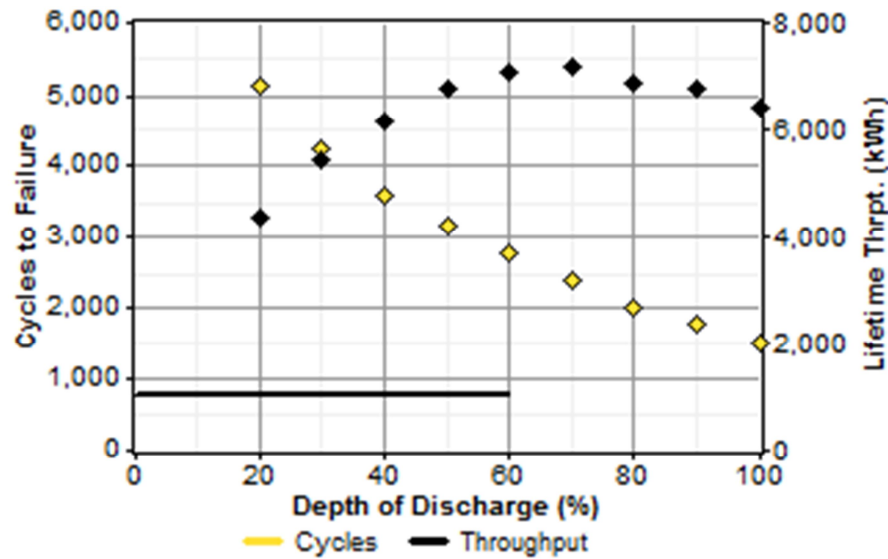


Figure 4.12: Homer Simulink for Number of cycles to failure as function of SOC

Figure 4.12 shows a lifetime curve typical of a deep-cycle lead acid battery. The number of cycles to failure drops sharply with increasing depth of discharge. For each point on this curve the amount of energy that cycled through the battery before failure can be calculated by finding the product of the number of cycles, the depth of discharge, the nominal voltage of the battery, and the aforementioned maximum capacity of the battery.

To determine the number of battery replacements required throughout the system lifetime a battery life model was incorporated into the optimization process. The battery model is an energy throughput model based on the model utilized in the Homer optimization program.

Figure 4.13 shows the PV stand alone scheme as implemented in the Homer simulation tool. Monthly average data of global solar radiation in the Addis Ababa are used as the solar energy resource.

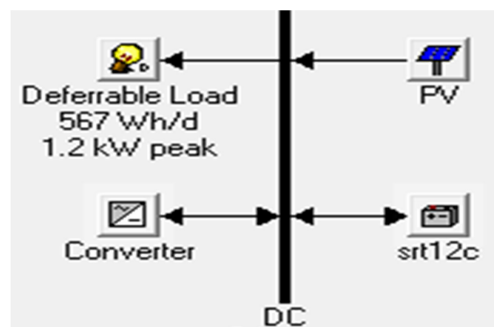


Fig4.13: Homer implementation of the stand-alone PV system

The installation, replacement and maintenance cost of all components of photovoltaic system are shown in Table 4.3. For the battery commercially available models such as surette Engineering's

surette12CS11PS model is considered in the model. The cost results of the system are shown in Figure 3.17 with initial capital cost is 4,086\$ where the replacement cost is 728 \$ and the maintenance cost is 837\$. The total net present value of the system is 5,651\$.

Table 4.3: Cost of different components of Stand-alone PV system

Component	Capital cost (\$)	Replacement cost (\$)	Operation and maintenance cost (\$)	Total cost (\$)
PV	1,848	0	432	2280
Battery	207.3	195	186	588.3
Controller	956.6	200	254	1410.6
Convertor	424	163	84	671
System	3,436	558	956	4,950

(a) The total net present value of the system with Battery storage system

Component	Capital cost (\$)	Replacement cost (\$)	Operation and maintenance cost (\$)	Total cost (\$)
PV	1,848	0	432	2280
Battery	207.3	145	167	519.3
Supercapacitor	499.5	220	0	719.5
Controller	956.6	200	254	1410.6
Convertor	424	163	84	671
System	4086	728	837	5,651

(b)The total net present value of the system with HESS

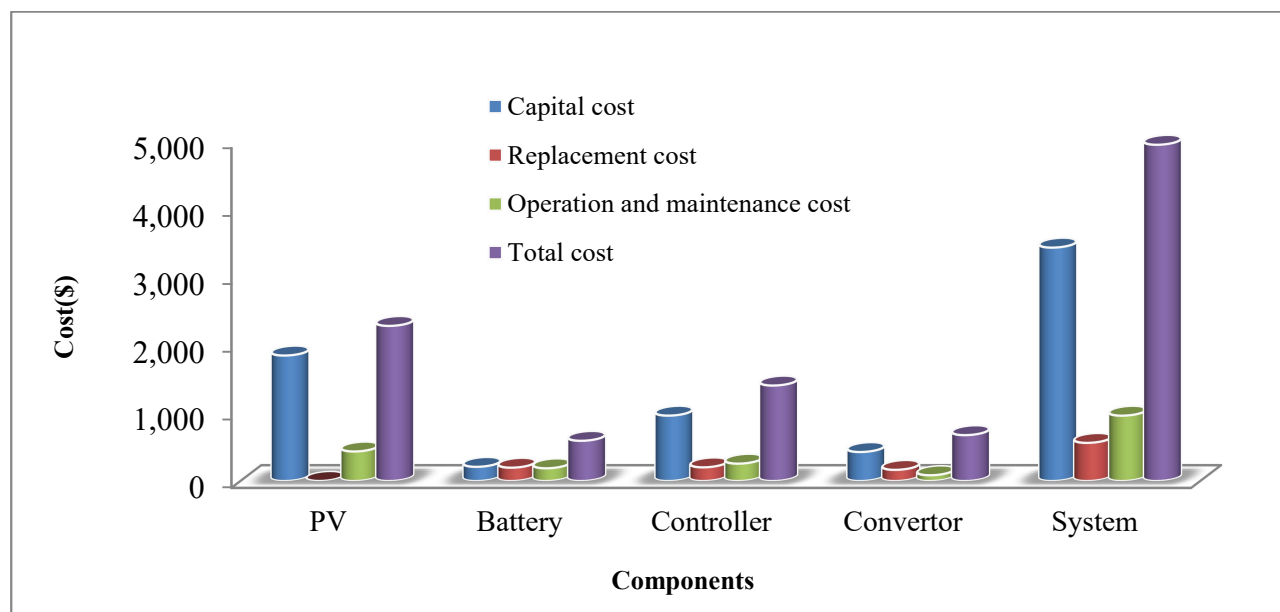


Figure4.14: Cost type life time expense of PV system for battery only storage system

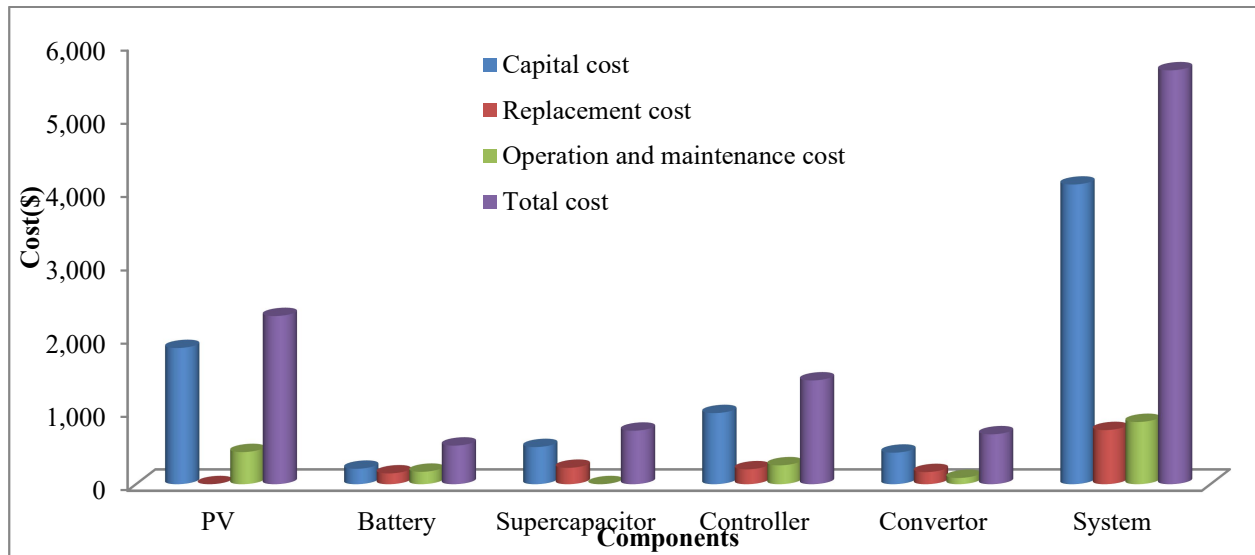


Figure 4.15: Cost type life time expense of PV system for battery SC hybrid storage system

As for Figure 4.14 and Figure 4.15 are the cash flow summary by component and by cost type for battery only and HESS respectively. As can be seen in Figure 4.145cost for hybrid ranked the highest value. In accordance to by cost type on Figure 4.14 and 4.15, PV panels ranked the highest which capital cost is at \$ 2,280. Operating cost for this system is at 837\$/yr. the above result consists of cost for each component that is broken down into capital cost, replacement cost, operation and maintenance cost.

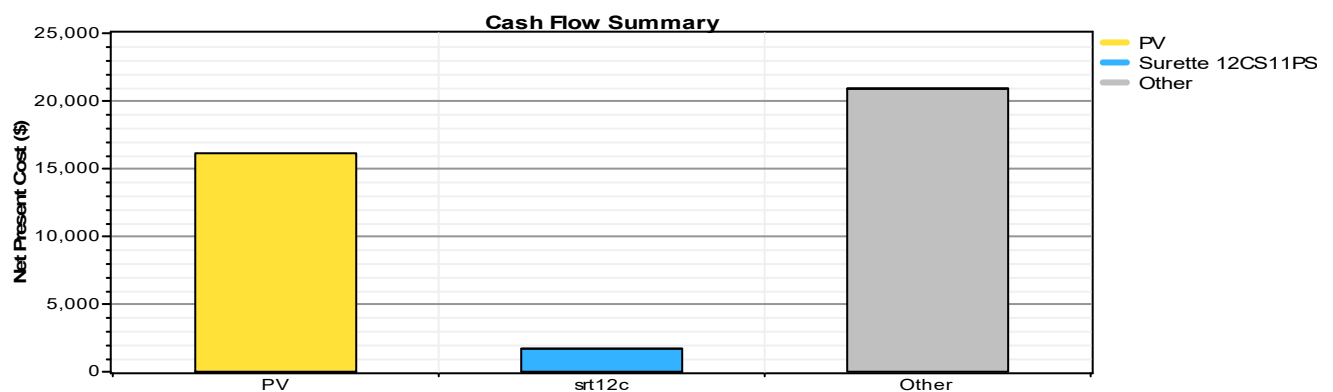


Figure 4.16: Net present Cost summary

Table 4.4: Net present cost comparison

Component	Capital (\$)	Replacement (\$)	O&M (\$)	Fuel (\$)	Salvage (\$)	Total (\$)
PV	1,848	468	14,062	0	-262	16,115
Surette 12CS11PS	207	126	1,406	0	-17	1,722
Other	3,000	0	17,897	0	0	20,897
System	5,055	594	33,365	0	-279	38,734

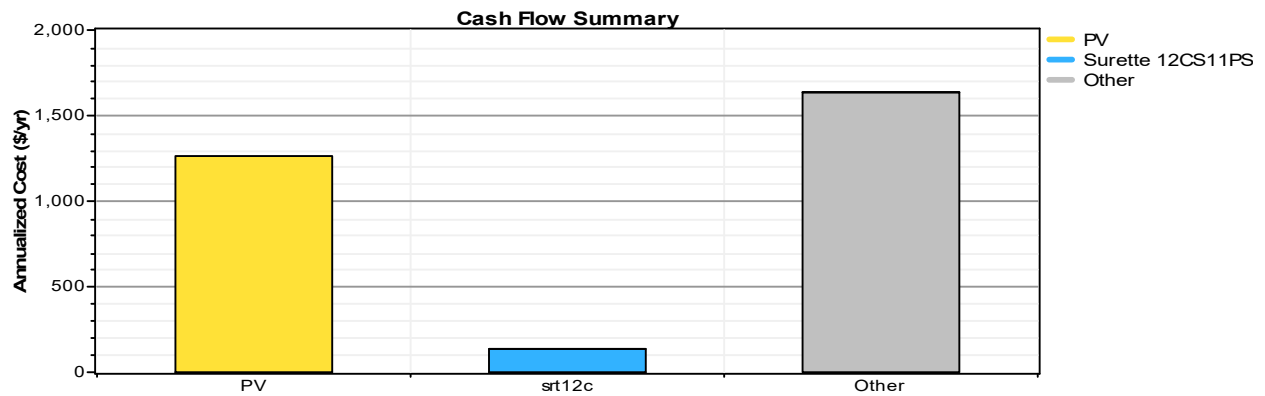


Figure 4.17: Cash flow summary by cost type

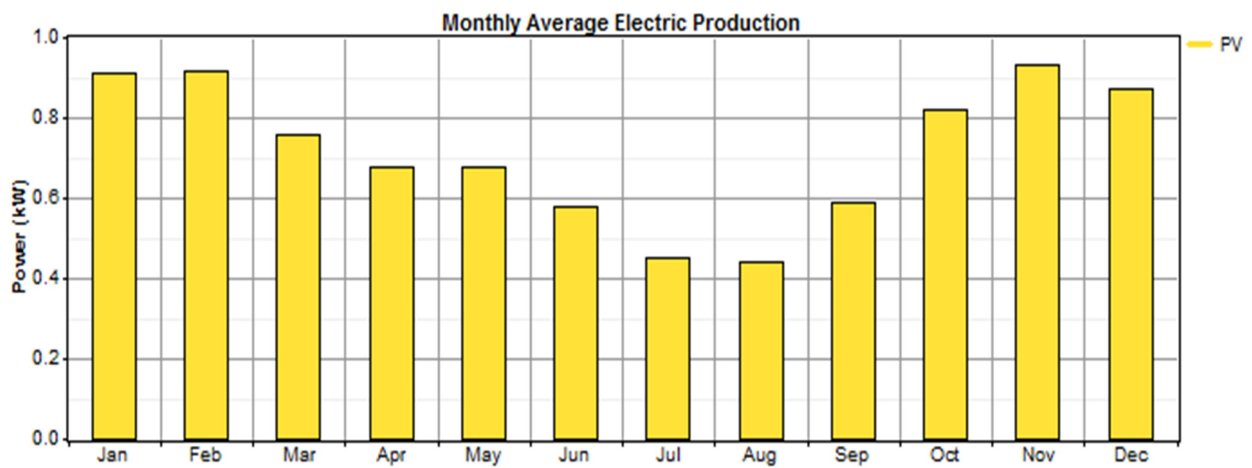


Figure 4.18: Annual load profile

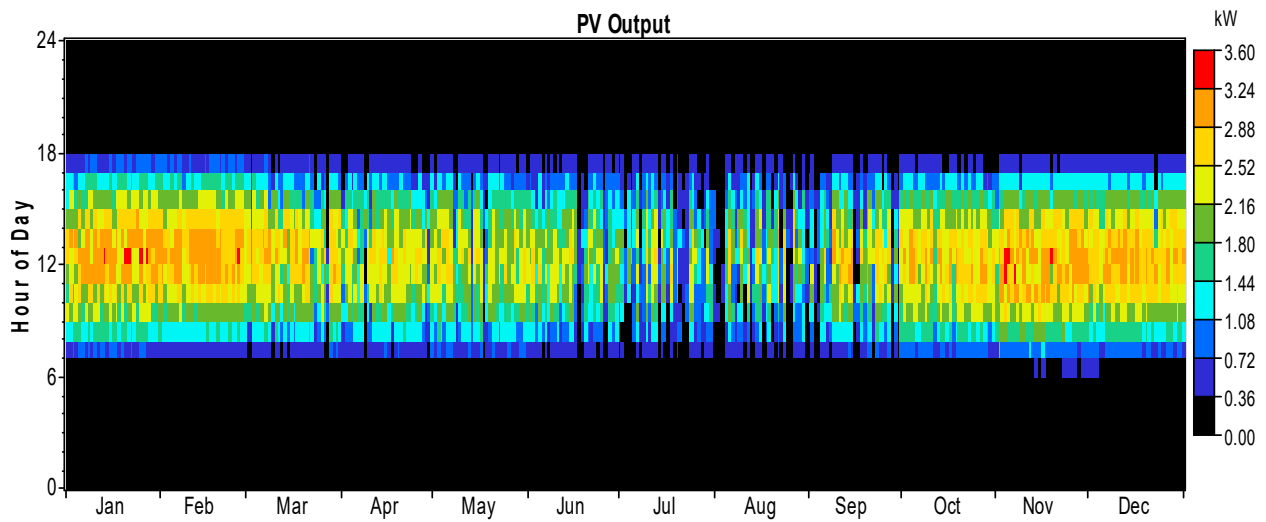


Figure 4.19: PV output with hour of the day

Table 4.5: Overall optimization result

				PV (kW)	srt12c	Conv. (kW)	Initial Capital	Operating Cost (\$/yr)	Total NPC	COE (\$/kWh)	Ren. Frac.
				3.16	6		\$ 5,055	2,635	\$ 38,734	14.651	1.00

Table 4.6.: Sensitivity result

Def. Load Storage (kWh)	Def. Load Peak (kW)					PV (kW)	srt12c	Conv. (kW)	Initial Capital	Operating Cost (\$/yr)	Total NPC	COE (\$/kWh)	Ren. Frac.
0.800	1.200					3.16	12	3.3	\$ 5,487	3,012	\$ 43,997	16.641	1.00
0.800	1.300					3.16	12	3.3	\$ 5,487	3,012	\$ 43,997	16.641	1.00
0.800	1.200					3.16	12	3.3	\$ 5,487	3,012	\$ 43,997	16.641	1.00
0.800	0.900					3.16	12	3.3	\$ 5,487	3,012	\$ 43,997	16.641	1.00
4.000	1.200					3.16	12	3.3	\$ 5,487	3,012	\$ 43,997	16.641	1.00
4.000	1.300					3.16	12	3.3	\$ 5,487	3,012	\$ 43,997	16.641	1.00
4.000	1.200					3.16	12	3.3	\$ 5,487	3,012	\$ 43,997	16.641	1.00
4.000	0.900					3.16	12	3.3	\$ 5,487	3,012	\$ 43,997	16.641	1.00
3.800	1.200					3.16	12	3.3	\$ 5,487	3,012	\$ 43,997	16.641	1.00
3.800	1.300					3.16	12	3.3	\$ 5,487	3,012	\$ 43,997	16.641	1.00
3.800	1.200					3.16	12	3.3	\$ 5,487	3,012	\$ 43,997	16.641	1.00
3.800	0.900					3.16	12	3.3	\$ 5,487	3,012	\$ 43,997	16.641	1.00

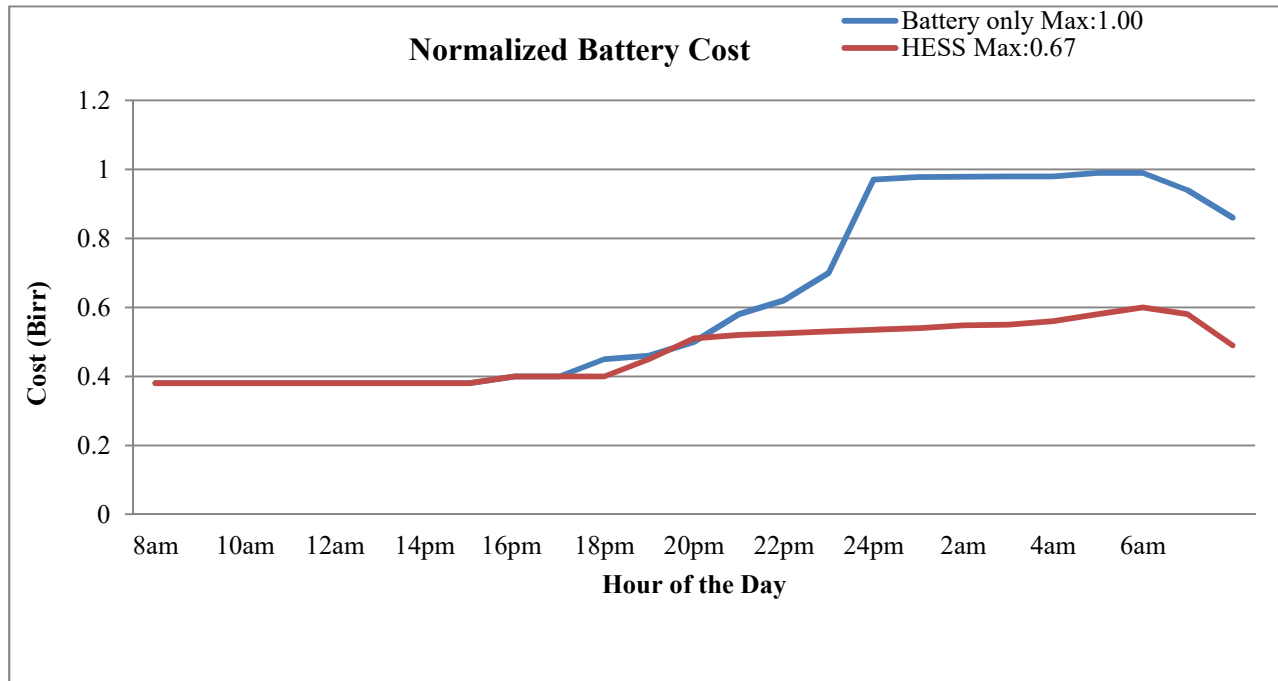


Figure 4.20: Normalized battery health cost $C(T)$ for battery-only and HESS systems in 24 h

Figure 4.20 show the normalized $C(T)$ for battery only and HESS systems in 24 h. The system with HESS shows a 33% reduction in battery health cost, which suggests substantial slowdown in battery aging and performance deterioration. Though the battery aging process is a complex phenomenon which cannot be quantified accurately with the simplified cost function, the proposed cost function does suggest a significant improvement in battery life when HESS is used instead of just using the battery only.

CHAPTER FIVE

Conclusions, Recommendations and Future Work

Based on the results obtained from the study and the simulations conducted with MATLAB/SIMULINK model, the following conclusions and recommendation have been made and the possible future works are proposed.

5.1 Conclusion

As studied in this thesis the supercapacitor possesses unique properties that can complement other energy storage technologies, such as batteries. Due to its fast charge and discharge capability, highly reversible process functionality, high power density, high recyclability and relatively small internal resistance it is an attractive alternative in hybrid electric energy storage systems. A battery-supercapacitor hybrid storage technique is tested for PV system to balanced power supply and enhances the lifetime of the storage system to given load.

The purpose of this study was to quantify the improvement in the stand alone PV system performance via a reduction in battery charging discharging rates and battery over discharging with the addition of a supercapacitor as an auxiliary energy storage device.

In order to quantify the improvement in battery performance, a battery-supercapacitor model was developed, capable of accurately predicting the system performance in solar power system. From this thesis the following conclusion is done.

- ✓ The simulation results show that the battery rate of discharge current is reduced up to 50.5% and the Normalized battery health cost reduced up to 33% which suggests substantial slowdown in battery aging and performance deterioration. The supercapacitor is discharged from its state just before the arrival of peak current which ensures that the discharge rate of the battery is low resulting in increased lifetime of the battery.
- ✓ In addition to power quality improvement on power supplying to the load the results of the thesis also indicate that the developed battery-supercapacitor model improves battery lifetime by the reduction in battery RMS currents with the addition of supercapacitors for the given load cycles. Hence, this plays an active role in the battery aging process.
- ✓ Problem of the battery draining when solar power is not available will be reduced by adding of the supercapacitor. The consumption of Supercapacitor with the addition of Buck-Boost converter improves the efficiency of the overall circuit.
- ✓ As the simulation result shows the battery charging current is maintained at a value under both excess and deficit power conditions on DC bus by supplying only the base constant current and supercapacitors supplying the shortage and excess load current profile. This will further increase the cycle life of the battery.
- ✓ The possibility of performing additional functions of supercapacitor model to capture the non linear rise and fall of the DC voltage is controlled at any time.

- ✓ Generally in this storage system, in addition to the role of supercapacitor as storage device its energy buffering capacity when solar power is available is also tested and the reason being the dependence of cycle life of the battery is on the discharge rate.
- ✓ From the cost comparison it is revealed that the battery-supercapacitor system cost is higher than that of battery system alone. But battery cycle life costs on hybrid storage will further decrease than that of battery only storage.
- ✓ Using a hybrid battery-supercapacitor storage system increase the reliability of the PV system and supply regulated supply to the load. The system can also lower the costs of consumed energy.

In general using hybrid electric energy storage in the PV systems has advantages like Power saving and higher system efficiency, voltage regulation, power enhancement and run time increase compared to a battery-alone system, especially at high peak power demand.

5.2 Recommendation

The following recommendations are suggested for extension of this work:

- Supercapacitors have high power density that makes them suitable for applications where high power is required for short durations of time. Thus in the passive hybrid system the capacitance of the supercapacitor must be sufficiently large, since the system time constant is an important performance parameter.
- Also, due to their fast charge and discharge rates and their low internal resistance, they are the ideal devices for storing high current transient electrical surges to boost energy efficiency of a system. So the protection scheme is necessary as the components used in the circuit are randomly distributed transient peak power demand in time intervals longer time constants, the supercapacitor is fully recharged between each power transient and is able to cover a significant larger share of the demand than it can manage under a constant pulse train load in steady state. Overall, the higher the frequency of the pulse load and the smaller the pulse width, the more the supercapacitors utilized, relieving the battery of large voltage fluctuations and reducing the maximum battery current.
- The possible reason for the drawback of the passive hybrid topology is the limited control possibilities, since the load current is shared between the battery and the supercapacitor in a nearly uncontrolled manner, determined predominantly by the internal impedances of the system.
- The final stage for recommendation is the self-discharge of supercapacitor. There are a number of different mechanisms for self-discharge, but the commonly result from uncontrollable Faradic reactions, such as the reduction and oxidation of impurities in the electrode material. In addition to this the supercapacitor is actually over-dimensioned in order to achieve the wanted system performance. Thus, improving material purity has been identified as one way to decrease the rate of self-discharge in supercapacitors.

5.3 Future Works

This work could further advanced by including additional components for possible line work by modeling the energy storage system to be more realistic, i.e. the battery system with all its characteristics such as the capacity, state of charge, depth of discharge among others. This would also mean to adjust the simulation time to the reality or to adjust the parameters of the system to the simulation time.

A set load and solar radiation profile will be applied to the load modeling or even better, a complete study of the energy management system to distribute the power each element of the system generates or consumes in order to make the stand alone system perform at its highest efficiency.

Third suggestion would be in remote locations the alternative option to a standalone system is to add other renewable generation sources to make a complete study of the economic and technical viability in case of implementing the hybrid storage system in a specific location, taking into account the laws, costs, licenses and other requirements of the chosen load type. A more accurate battery lifetime model could also be investigated to increase the accuracy of the calculated battery life.

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Appendix

Appendix A: NASA Surface meteorology and Solar Energy Available Tables

A new POWER home page with enhanced responsive GIS-enabled web data services and mapping capabilities will soon replace the current SSE home page with a target date of June 13, 2018. This current set of SSE web applications and website will no longer be accessible after that date. The new POWER will include improved solar and meteorological data with all parameters available on a 0.5-degree global grid. The beta version of the new home page, featuring the updated parameters, schedule updates and FAQ can be accessed at [POWER](#). Please direct any questions to [POWER Project Team](#)



NASA Surface meteorology and Solar Energy - Available Tables



Latitude 9.02 / Longitude 38.75 was chosen.

Geometry Information

Elevation: 2071 meters
taken from the
NASA GEOS-4
model elevation

Northern boundary
10
Center
Latitude 9.5
Longitude 38.5
Western boundary
38
Eastern boundary
39
Southern boundary
9

The meteorological data used from NASA for calculations and simulations over the solar energy potential and temperatures affecting PV modules in Addis Ababa 9.02° N, 38.75° E.

Parameters for Solar Cooking:

Monthly Averaged Clear Sky Days (days)

Lat 9.02 Lon 38.75	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
22-year Average	7	5	2	1	1	0	0	0	0	5	7	10

Parameter Definition

Parameters for Sizing and Pointing of Solar Panels and for Solar Thermal Applications:

Monthly Averaged Insolation Incident On A Horizontal Surface (kWh/m²/day)

Lat 9.02 Lon 38.75	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
22-year Average	6.18	6.59	6.52	6.48	6.42	5.86	5.15	5.18	5.84	6.40	6.31	6.11	6.08

Minimum And Maximum Difference From Monthly Averaged Insolation (%)

Lat 9.02 Lon 38.75	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Minimum	-10	-13	-10	-8	-9	-15	-19	-15	-13	-18	-12	-12
Maximum	11	12	11	9	7	10	20	22	15	11	6	8

Parameter Definition

Monthly Averaged Direct Normal Radiation (kWh/m²/day)

Lat 9.02 Lon 38.75	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
22-year Average	8.02	7.83	6.76	6.32	6.48	5.64	4.31	4.16	5.35	7.13	8.05	8.26	6.52

Minimum And Maximum Difference From Monthly Averaged Direct Normal Radiation (%)												
Lat 9.02 Lon 38.75	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Minimum	-5	-8	-7	-6	-8	-16	-24	-17	-11	-16	-11	-9
Maximum	7	9	10	9	6	11	32	37	19	6	0	3

NOTE: Diffuse radiation, direct normal radiation and tilted surface radiation are not calculated when the clearness index (K) is below 0.3 or above 0.8.

Parameter Definition

Monthly Averaged Insolation Normalized Clearness Index (0 to 1.0)

Lat 9.02 Lon 38.75	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
22-year Average	0.62	0.62	0.57	0.56	0.56	0.52	0.45	0.45	0.51	0.59	0.63	0.64

Parameter Definition

Monthly Averaged Clear Sky Insolation Incident On A Horizontal Surface (kWh/m²/day)

Lat 9.02 Lon 38.75	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
22-year Average	6.66	7.16	7.48	7.60	7.42	6.88	6.80	7.06	7.07	7.07	6.74	6.49	7.03

Parameter Definition

Monthly Averaged Clear Sky Insolation Clearness Index (0 to 1.0)

Lat 9.02 Lon 38.75	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
22-year Average	0.74	0.73	0.72	0.72	0.71	0.67	0.66	0.68	0.68	0.72	0.73	0.74

Parameter Definition

Monthly Averaged Clear Sky Insolation Normalized Clearness Index (0 to 1.0)

Lat 9.02 Lon 38.75	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
22-year Average	0.67	0.67	0.66	0.65	0.65	0.61	0.60	0.62	0.62	0.65	0.67	0.68

Parameter Definition

Solar Geometry:

Monthly Averaged Daylight Hours (hours)

Lat 9.02 Lon 38.75	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average	11.6	11.8	12.0	12.3	12.5	12.6	12.5	12.4	12.1	11.9	11.7	11.6

Parameter Definition

Monthly Averaged Maximum Solar Angle Relative To The Horizon (degrees)

Lat 9.02 Lon 38.75	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average	60.2	68.5	79.1	89.3	80.1	75.9	77.7	85.2	84.0	72.5	62.8	58.0

Parameter Definition

Parameters for Tilted Solar Panels:

Monthly Averaged Radiation Incident On An Equator-Pointed Tilted Surface (kWh/m²/day)

Lat 9.02 Lon 38.75	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
SSE HRZ	6.18	6.59	6.52	6.48	6.42	5.86	5.15	5.18	5.84	6.40	6.31	6.11	6.08
K	0.68	0.68	0.63	0.61	0.61	0.57	0.50	0.49	0.56	0.65	0.69	0.70	0.61
Diffuse	1.23	1.43	1.82	2.01	1.91	2.00	2.18	2.25	2.08	1.61	1.25	1.12	1.74
Direct	8.02	7.83	6.76	6.32	6.48	5.64	4.31	4.16	5.35	7.13	8.05	8.26	6.52
Tilt 0	6.12	6.52	6.44	6.38	6.31	5.75	5.06	5.10	5.76	6.33	6.25	6.06	6.00
Tilt 9	6.63	6.85	6.54	6.37	6.41	5.88	5.14	5.11	5.77	6.57	6.72	6.62	6.21
Tilt 24	7.18	7.11	6.43	6.08	6.32	5.87	5.08	4.95	5.56	6.68	7.19	7.27	6.31
Tilt 90	4.86	3.90	2.56	1.91	2.61	2.74	2.37	2.00	2.00	3.34	4.63	5.19	3.17
OPT	7.32	7.11	6.54	6.39	6.42	5.91	5.14	5.12	5.78	6.69	7.29	7.50	6.43
OPT ANG	37.0	26.0	12.0	3.00	12.0	16.0	13.0	6.00	5.00	21.0	34.0	39.0	18.6

NOTE: Diffuse radiation, direct normal radiation and tilted surface radiation are not calculated when the clearness index (K) is below 0.3 or above 0.8.

[Parameter Definition](#)

Parameters for Sizing Battery or other Energy-storage Systems:

Equivalent Number Of NO-SUN Or BLACK Days (days)

Lat 9.02 Lon 38.75	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1 day	0.62	0.59	0.66	0.61	0.54	0.54	0.60	0.72	0.52	0.47	0.45	0.48
3 day	0.95	1.14	1.46	0.94	1.21	1.25	1.17	1.70	0.97	1.28	1.15	1.07
7 day	1.95	1.89	1.93	1.51	1.89	2.71	2.51	1.87	1.70	2.39	2.26	1.51
14 day	3.33	2.63	2.38	2.61	2.68	3.53	4.14	2.76	2.83	4.08	3.19	2.71
21 day	3.03	3.17	3.26	2.81	3.35	3.48	5.67	3.32	3.33	5.56	4.09	3.48
Month	3.16	3.69	3.13	2.26	2.80	4.35	5.95	4.72	3.85	5.47	3.70	3.75

[Parameter Definition](#)

Parameters for Sizing Surplus-product Storage Systems:

Available Surplus Insolation Over A Consecutive-day Period (%)

Lat 9.02 Lon 38.75	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Max/1 day	122	121	130	128	126	130	144	140	133	128	121	118
Max/3 day	121	119	126	127	123	128	134	134	130	124	117	116
Max/7 day	119	117	119	125	119	119	127	127	123	119	115	113
Max/14 day	114	115	115	116	117	114	124	123	116	116	112	113
Max/21 day	112	114	114	110	112	111	122	123	116	114	109	109
Max/Month	111	112	111	109	107	110	120	122	115	111	106	108

[Parameter Definition](#)

Cloud Information:

Monthly Averaged Daylight Cloud Amount (%)

Lat 9.02 Lon 38.75	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
22-year Average	33.6	38.9	54.6	60.3	58.1	60.6	72.2	72.0	56.0	38.4	28.4	28.2	50.2

[Parameter Definition](#)

Meteorology (Temperature):

Monthly Averaged Air Temperature At 10 m Above The Surface Of The Earth (°C)

Lat 9.02 Lon 38.75	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
22-year Average	17.6	19.2	20.4	20.0	19.5	17.4	16.1	16.3	16.5	16.5	16.8	16.8	17.8
Minimum	12.5	14.1	16.0	16.1	15.6	14.4	13.5	13.4	12.7	11.0	11.3	11.6	13.5
Maximum	22.3	23.7	24.4	23.7	23.3	21.0	19.5	20.0	21.3	22.0	22.1	21.7	22.1

[Parameter Definition](#)

Meteorology (Other):

Monthly Averaged Specific Humidity At 10 m Above The Surface Of The Earth (kg/kg)

Lat 9.02 Lon 38.75	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
22-year Average	0.007102	0.006925	0.008027	0.009747	0.010549	0.012239	0.012059	0.012021	0.011235	0.008706	0.007167	0.007196

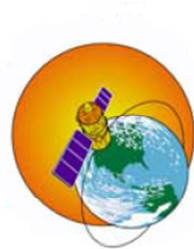
[Parameter Definition](#)

Supporting Information:

Monthly Averaged Top-of-atmosphere Insolation (kWh/m²/day)

Lat 9.02 Lon 38.75	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
22-year Average	8.98	9.68	10.3	10.5	10.4	10.2	10.2	10.3	10.2	9.81	9.11	8.72	9.89

[Parameter Definition](#)



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[Page](#)

Responsible > Data: Paul W. Stackhouse, Jr., Ph.D.
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Site Administration/Help: NASA Langley [ASDC](#) User
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Appendix B: Homer optimization program result System Report and excel data

Sensitivity case

Deferrable Load Storage Capacity:	3.8	kWh
Deferrable Load Peak:	0.9	kW

System architecture

PV Array	3.16 kW
Battery	12 Surette 12CS11PS
Inverter	3.3 kW
Rectifier	3.3 kW

Cost summary

Total net present cost	\$ 44,558
Levelized cost of energy	\$ 16.853/kWh
Operating cost	\$ 3,056/yr

Net Present Costs

Component	Capital (\$)	Replacement (\$)	O&M (\$)	Fuel (\$)	Salvage (\$)	Total (\$)
PV	1,848	468	14,062	0	-262	16,115
Surette 12CS11PS	414	339	4,755	0	-45	5,463
Converter	225	83	1,790	0	-16	2,083
Other	3,000	0	17,897	0	0	20,897
System	5,487	891	38,503	0	-323	44,558

Annualized Costs

Component	Capital (\$/yr)	Replacement (\$/yr)	O&M (\$/yr)	Fuel (\$/yr)	Salvage (\$/yr)	Total (\$/yr)
PV	145	37	1,100	0	-21	1,261
Surette 12CS11PS	32	27	372	0	-4	427
Converter	18	7	140	0	-1	163
Other	235	0	1,400	0	0	1,635
System	429	70	3,012	0	-25	3,486

Electrical

Component	Production (kWh/yr)	Fraction
PV array	6,289	100%
Total	6,289	100%

Load	Consumption (kWh/yr)	Fraction
Deferrable load	207	100%
Total	207	100%
Quantity	Value	Units
Excess electricity	6,082	kWh/yr
Unmet load	0.00	kWh/yr
Capacity shortage	0.00	kWh/yr
Renewable fraction	1.000	

PV

Quantity	Value	Units
Rated capacity	3.16	kW
Mean output	0.718	kW
Mean output	17.2	kWh/d
Capacity factor	22.7	%
Total production	6,289	kWh/yr

Quantity	Value	Units
Minimum output	0.00	kW
Maximum output	3.34	kW
PV penetration	0.00	%
Hours of operation	4,465	hr/yr
Levelized cost	0.200	\$/kWh

Battery

Quantity	Value
String size	2
Strings in parallel	6
Batteries	12
Bus voltage (V)	24

Quantity	Value	Units
Nominal capacity	51.4	kWh
Usable nominal capacity	30.8	kWh
Autonomy	1,306	hr
Lifetime throughput	12,000	kWh
Battery wear cost	0.036	\$/kWh
Average energy cost	0.000	\$/kWh

Normalized battery health cost C (T) for battery-only and HESS systems in 24 h

	Battery only Max:1.00	HESS Max:0.67
8am	0.38	0.38
	0.38	0.38
10am	0.38	0.38
	0.38	0.38
12am	0.38	0.38
	0.38	0.38
14pm	0.38	0.38
	0.38	0.38
16pm	0.4	0.4
	0.4	0.4
18pm	0.45	0.4
	0.46	0.45
20pm	0.5	0.51
	0.58	0.52
22pm	0.62	0.525

	0.7	0.53
24pm	0.97	0.535
	0.978	0.54
2am	0.9788	0.548
	0.98	0.55
4am	0.98	0.56
	0.99	0.58
6am	0.99	0.6
	0.94	0.58
	0.86	0.49

Appendix C: Supercapacitor Product Specification, Characteristics and Datasheet

PRODUCT SPECIFICATIONS & CHARACTERISTICS

BMOD0009 P024 B02
EMHSR-0009C0-024R0

ELECTRICAL		TEMPERATURE	
Rated Voltage, V_R	24 VDC	Operating Temperature Range	-40°C to +65°C
Surge Voltage ¹	31 VDC	Storage Temperature Range (Stored without charge)	-40°C to +70°C
Rated Capacitance, C^3	9 F	LIFE*	
Min. / Max. Capacitance, Initial	9 F / 10.8 F	Projected DC Life at Room Temperature (At rated voltage and 25°C, EOL ⁴)	10 years
Typical Capacitance, Initial ^{2,3}	9.4 F	DC Life at High Temperature (At rated voltage and 65°C, EOL ⁴)	1,500 hours
Rated (Max.) ESR_{DC} , Initial ³	139 mΩ	Projected Cycle Life at Room Temperature ⁷ (Constant current charge-discharge from V_R to $1/2V_R$ at 25°C, EOL ⁴)	500,000 cycles
Typical ESR_{DC} , Initial ^{2,3}	93 mΩ	Shelf Life (Stored uncharged at 25°C)	4 years
Typical Leakage Current ⁴	5 mA	UMU / MONITORING	
Maximum Peak Current, Non-repetitive ⁵	45 A	Cell Balancing	Passive single cell balancing
PHYSICAL		Over-Voltage Monitoring	Voltage check pin
Nominal Mass	410 g	SAFETY	
Output Terminals	2 × AWG16 wires (positive / negative)	Certifications	RoHS REACH, UL 810A (Cell Level)
Insulation Coordination	IEC 60664-1 (Category: OV II)		
Protection Degree	IEC 60529 – IP 20		
Vibration	IEC 60068-2-6 Table B-1		
Shock	IEC 60068-2-27		
POWER & ENERGY			
Maximum Stored Energy, $E_{max}^{6,8}$	0.72 Wh		
Gravimetric Specific Energy ⁶	1.7 Wh/kg		
Usable Specific Power ⁶	1.2 kW/kg		
Impedance Match Specific Power ⁶	2.5 kW/kg		

*Results may vary. Additional terms and conditions, including the limited warranty, apply at the time of purchase. See the warranty details for applicable operating and use requirements.

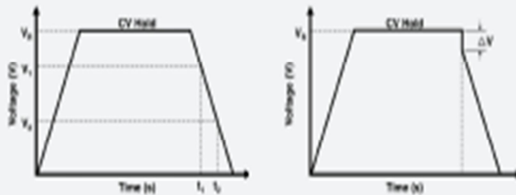
Datasheet: 24V 9F ULTRACAPACITOR MODULE

1. Surge Voltage
Absolute maximum voltage, non-repetitive. Duration not to exceed 1 second.

2. *Typical* values represent mean values of production sample.

3. Rated Capacitance & ESR_{DC} (measure method)

- Capacitance: Constant current charge with 1A to V_R, 5 min hold at V_R, constant current discharge with 1A to 2.2V.
- ESR_{DC}: Constant current charge with 1A to V_R, 5 min hold at V_R, constant current discharge with (40 ° C * V_R [mA]) to 2.2V.
e.g. in case of 24V 9F module, discharge with 40 ° 9 * 24 = 8,640 mA.



$$C = \frac{I \times (t_2 - t_1)}{V_1 - V_2}$$

$$ESR_{DC} = \frac{\Delta V}{I}$$

where C is the capacitance (F);
I is the absolute value of the discharge current (A);
V_R is the rated voltage (V);
V₁ is the measurement start voltage, 0.8xV_R (V);
V₂ is the measurement end voltage, 0.4xV_R (V);
t₁ is the time from start of discharge to reach V₁ (s);
t₂ is the time from start of discharge to reach V₂ (s);
ESR_{DC} is the DC-ESR (Ω);
ΔV is the voltage drop during first 10ms of discharge (V).

4. Typical Leakage Current

- Current measured after 72 hrs at rated voltage and 25°C. Initial leakage current can be higher.
- If applicable, module leakage current is the sum of cell and balancing circuit leakage currents.

5. Maximum Peak Current

- Current needed to discharge cell/module from rated voltage to half-rated voltage in 1 second.

$$I = \frac{1/2 V_R}{\Delta t / C + ESR_{DC}}$$

where Δt is the discharge time (sec); Δt = 1 sec in this case.

- The stated maximum peak current should not be used in normal operation and is only provided as a reference value.

6. Energy & Power (Based on IEC 62391-2)

- Maximum Stored Energy, E_{max} (Wh) = $\frac{1/2 CV_R^2}{3600}$
- Gravimetric Specific Energy (Wh/kg) = $\frac{E_{max}}{mass}$
- Usable Specific Power (W/kg) = $\frac{0.12 V_R^2}{ESR_{DC} \times mass}$
- Impedance Match Specific Power (W/kg) = $\frac{0.25 V_R^2}{ESR_{DC} \times mass}$

- Presented Power and Energy values are calculated based on Rated Capacitance & Rated (Max.) ESR_{DC}, initial values.

7. Cycle Life Test Profile

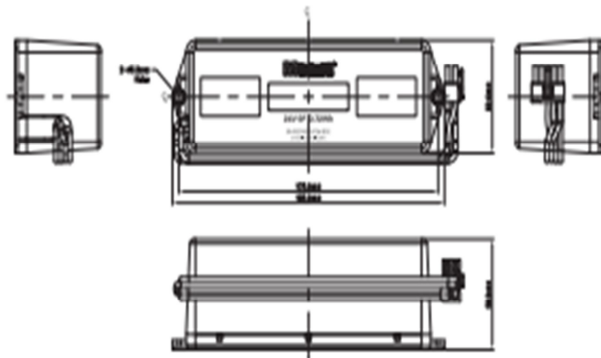
- Cycle life varies depending upon application-specific characteristics. Actual results will vary.

8. Per United Nations material classification UN3499, all Maxwell ultracapacitors have less than 10 Wh capacity to meet the requirements of Special Provisions 361. Both individual ultracapacitors and modules composed of those ultracapacitors shipped by Maxwell can be transported without being treated as dangerous goods (hazardous materials) under transportation regulations.

9. BOL: Beginning of Life, rated initial product performance

- EOL: End of Life criteria.
- Capacitance: 80% of min. BOL rating
- ESR_{DC}: 2x max. BOL rating

BMOD0009 P024 B02



When ordering, please reference the Maxwell Model Number below.

Maxwell Model Number: Maxwell Part Number: Alternate Model Number:

BMOD0009 P024 B02 133735 EMHSR-0009C0-024R0

Part Description	Dimensions (mm)		
	Length (±2.0)	Width (±2.0)	Height (±2.0)
BMOD0009 P024 B02	185.0	59.4	58.0

Conext MPPT 60 150 solar charge controller



Device short name	MPPT 60 150
Electrical specifications	
Nominal battery voltage	12, 24, 36, 48, 60 V
Battery voltage operating range	0 Vdc to 60 Vdc
Max. PV array voltage (operating)	140 V
Max. PV array open circuit voltage	150 V including temperature correction factor
Max. array short-circuit current	60 A (48 A @ STC)
Max. charge current	60 A (for all battery voltages except 60 V)
Max. and min. wire size in conduit	#8 AWG to #14 AWG (10 to 2.5 mm ²)
Max. output power	3500 W
Charger regulation method	Three-stage (bulk, absorption, float) plus manual equalization Two-stage (bulk, absorption) plus manual equalization
Supported battery types	Flooded, GEL, AGM, Custom
Efficiency	
Max. power conversion efficiency	93% (nominal 12 V), 96% (nominal 24 V), 97% (nominal 36 V), 98% (nominal 48 V), 99% (nominal 60 V)
General specifications	
Power consumption, night time	2.5 W
Battery temperature sensor	Included
Auxiliary output	5 • 13 V, up to 200 mA
Enclosure material	Indoor, ventilated, sheet metal chassis with 2.2 cm and 2.8 cm (7/8 in and 1 in) knockouts and aluminium heat-sink
IP degree of protection	IP20
Product weight	4.8 kg (10.8 lb)
Shipping weight	8.0 kg (17.6 lb)
Product dimensions (H x W x D)	36.8 x 14.6 x 13.8 cm (14.5 x 5.8 x 5.5 in)
Shipping dimensions (H x W x D)	48.3 x 22.9 x 35 cm (19.0 x 9.0 x 9.8 in)
Device mounting	Vertical wall mount
Ambient air temperature for operation	-20°C to 45°C (-4°F to 113°F)
Storage temperature range	-40°C to 85°C (-40°F to 185°F) full power, power derating above 45°C

