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Department of Mechanical and Manufacturing Engineering

Development of Battery/Supercapacitor Hybrid Energy Storage Scheme for Grid Connected Solar PV Source

by

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Registration Number: F56/37306/2020

A Project Report Submitted for Examination in Partial Fulfillment of the Requirements for Award of the Degree of Master of Science in Energy Management in the Department of Mechanical and Manufacturing Engineering at the University of Nairobi

May 2022

DECLARATION

I declare that the Project Report is my research work and has not been presented before for any Academic Credit.

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DEDICATION

I commend my family, classmates, workmates and the entire fraternity in Science, Engineering and Technology.

ACKNOWLEDGEMENT

I give thanks to the Lord Almighty for the grace and mercy throughout the entire period of my masters studies in college. I do not take it for granted having commenced my studies during the Covid-19 pandemic but God is great, that, He sustained my colleagues and I through the studies. I further wish to thank my entire supervision team led by Dr. Peter Musau and Dr. Cosmas Kiruki for their professional guidance during the entire period of conducting and writing this research report. I also extend my gratitude to my employer Kenya Airports Authority for allowing me academic leave days whenever I needed time for my sitting for examinations as well as using data acquired in the line of duty as part of my research work. I also salute my fellow classmates (Masters Class 2020) for the encouragement we have accorded each other. Finally, I give gratitude to my family especially my mother Mrs Joyce Kagichu, my wife Mrs Gladys Ng’ang’a, children Chris and Cathy for being my pillar and motivational support in my life. May the good Lord protect them and shower them with multiple blessings.

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LIST OF ABBREVIATIONS

AC – Alternating Current

Batt –Battery

BESS – Battery Energy Storage System

CAES - Compressed Air Energy Storage

DC – Direct Current

EC – Electro-capacitor

ESR – Equivalent Series Resistance

ESS – Energy Storage System

HESS – Hybrid Energy Storage System

kW - Kilowatts

kWh – Kilowatts Hour

LCOE – Levelized Cost of Electricity

LCOS – Levelized Cost of Storage

MWh – Megawatt Hours

PbA – Lead Acid Battery

PHS - Pumped Hydro Storage
PI – Proportional Integral

RE – Renewable Energy

RES – Renewable Energy Source

SC – Supercapacitor

SESS - Supercapacitor Energy Storage System

SMES - Super-conducting Magnetic Energy Storage

SoC – State of Charge

Solar PV – Solar Photovoltaic

VRB – Vanadium Redox-flow

Wh – watt-hours

Zr Br – Zinc Bromine Battery

ABSTRACT

Though attempts for solving the problem of variability of renewable energy (RE) sources have been mitigated through the single energy storages, a gap still exists on the reliability and quality of power produced. The research has expressly developed a hybridized energy scheme for a solar PV source that is integrated to the grid. The prime objective of the study was to achieve a continuous power flow from the solar PV generated with the backup storage from lead acid battery (PbA) and the supercapacitor (SC). The battery would deliver high energy at longer duration while the supercapacitor would deliver high power at shorter period. This research objective was met by obtaining the design parameters and modelling the three power sources namely; solar PV, battery and supercapacitor. The results for this work were obtained through analysing data from the solar PV, battery and supercapacitor using MATLAB Simulink. By observation of the power profiles, comparison was made between the single energy storage systems (ESS) against the hybrid energy storage systems (HESS) components. The outcome from the simulation and presented in graphs format portrayed that the performance of HESS was better than when ESSs were used singularly as means of energy storage backup. The HESS delivered 3.607 kWh against single ESSs at 3.23 kWh for battery and 2.496 kWh for SC respectively. The research report concludes that though the main objectives of harvesting continuous power from a RES with HESS backup was achieved, further studies are recommended.

Keywords: **Hybrid Energy Storage Systems (HESS), Lead acid battery (PbA), Renewable Energy (RE), Supercapacitor (SC).**

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background

Over the years, the world has been dependent on fossil fuels as the source of energy. This has been found not sustainable owing to the former's depletion of the reserves and their effect on pollution to the environment. Safer and reliable sources of energy have been sought where renewable energy sources come into the limelight. Some of these renewable sources are hydro, wind, solar and geothermal. The most common of the renewable sources that are found and have been utilized are hydro, solar and wind. However, due to the vulnerability of the weather conditions hydro is gradually being replaced by solar and wind. The problem with solar and wind is their intermittent nature that causes problem to the generation of power due to their inconsistency. To mitigate this intermittency nature of RES, energy storage systems are being analysed as a feasible answer to this problem [1].

ESS are methods of technologies used to store energy. This stored energy can be drawn at the desirable time of use to perform the operations needed. Since majority of RES provide variable power, ESS can be useful in levelling the 'playing field' of the imbalances caused by the supply and demand. Energy storage sources act as fast response generators and are employed to mitigate by load levelling and peak shaving of the demand curve. Among the various applications of ESS is the integration of renewable energy sources. Depending on these applications, an appropriate ESS need to be sized that can be integrated with renewable energy sources. These ESS are grouped according to their technological characteristics such as Mechanical, Electro-chemical, Electrical and Thermal. Despite the deployment of these forms of ESS, Scientist and Engineers have reckoned that single sources of ESS have weaknesses as each individual of storages have different technological traits [1-5].

Presently, focus has now shifted to hybrid energy storage system (HESS). HESS are paired ESS of different kind and technological characteristics that are coupled in a microgrid system. The HESS paired devices are found to be necessary for their complementary role in long-term and short-term energy storages respectively [1], [2].

However, it has been consistently been a challenge on how to achieve energy storage cost effectively and reliably. The development of these energy storage regimes has lead the research faculty to realise single sources of storage are not enough in terms of quality, reliability and performance, therefore, prompting to hybridizing these energy storage schemes. A combination of two storage devices for inexhaustible sources of energy is one way of achieving quality and reliable power. The benefits of hybridizing storage of energy is twofold [3]:

(i) ESS with a greater power density to dispense more power over a short time span.
(ii) ESS with a higher energy density to dispense lower power for a longer time span.

This project advocates having a hybrid energy storage to enhance the quality of power, reliability and availability for renewable energy sources ready for integration to the grid power network that can provide low and high power frequency respectively.

1.2 Problem Statement

The generation of Solar PV is sometimes done in excess of the demand or curtailed due to vagaries of weather during the day. This has prompted the deployment of energy storages schemes to store energy during excess generation to be dispensed during periods when power is demanded optimally. Studying other concepts that have been investigated for energy storage systems; a gap still exists as most are single sources of energy storage schemes. Where an attempt has been made for a combination of more than one energy storage source, the characteristics of the different sources have not been optimally matched. This study will help solve the problem of pairing two energy storage sources coupled to a solar PV supply. This mode of storage addresses the variability nature of solar PV in various fronts such as: (i) responding as a spinning reserve bank for quick restoration of power, (ii) ensuring constant supply of power form the RES network and (iii) that there is continuous delivery of power to the grid thus, assurance in power resilience.

1.3 Study Objectives

1.3.1 Main Objective

The research work broadly focusses in the development of a battery/supercapacitor hybrid energy storage scheme that can continuously supply power efficiently and stabilize fluctuations of power sources from the renewable generation (microgrid).

1.3.2 Specific Objectives

From the broad objective of the study and the research questions formulated, the following are the specific objectives to be achieved:

(i) To size and model RE source and HESS components,

(ii) To simulate and carry out analysis on multiple scenarios of coupling energy storage components,

(iii) To compare capacities for HESS over that of single ESSs and,

(iv) To validate the use of HESS over that of single ESSs.

1.4 Research Study Questions

In the study of the entire value chain created by the hybrid energy storage systems (HESS) development on a grid connected solar PV; the following key questions were explored:

(i) Can RE source and hybrid energy storage components be sized?

(ii) Can simulations characterize hybrid energy storage systems?

(iii) What value on power system network does hybridized energy storages have over single ESS?

(iv) Can the use of HESS deliver continuous power over the ESSs?

1.5 Justification of the Study

An overview on the market technological trends hypothetically shows that the use of hybrid energy storage schemes integration in recyclable power sources has not been exhaustively implemented. Single ESS are still abundant in usage but they possess limited characteristics in terms of price value, durability, power and energy densities. Therefore, hybrid energy storage system has been proposed for use to get better of these limitations by making use of the different energy storage technologies characteristics.

1.6 Scope

The scope of the project begins with research on the energy storages schemes available and the review of scholarly work in energy storages. Computation of data for the energy requirements of the building to be supplied with solar PV with energy storage backup. This data informs the sizing of the RE source, energy storage components and subsequent modelling of these devices for use in MATLAB software simulations. Simulations for power profiles of the solar PV and energy storage devices are then performed for three case scenarios; (i) battery storage alone, (ii) supercapacitor bank storage alone and (iii) the HESS pairing of the battery and supercapacitor.

1.7 Report Structure

This project report comprises of Five chapters with each having a clear purpose. The First Chapter introduces the subject to be studied with an overview regarding to important issues and the grounds for investigation. The description of the research problem and research questions are highlighted. The Second Chapter provides a detailed review of the energy storage systems along with an assessment of the hybrid technology adopted in the market. The chapter also informs on the research gaps of the work done by other researches. Chapter Three presents the methodology to be used in researching this topic of interest. It highlights the methods used to couple the hybrid energy system and the characterization of the same. It also imperatively compares the existing approaches of other work studies, addresses the existing research gaps by outlining and providing a framework that conceptualises on advancing the research methodology on this work study. Chapter Four leads us to the results got from the investigated parameters via the software simulations and discussing those results. Presentations in form of graphs and tables are also illustrated. Chapter Five concludes the project with reflection on the success derived from the research. It also presents avenues for further studies to improve the research faculty.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Importance of Energy Storage Systems in Grid Connected Renewable Energy

The infrastructure of the electrical grid is designed to support the following key operations: generation, transmission and distribution. However, these three operations pose a challenge for the management of renewable energy when connected to the grid. To begin with, the generation of renewable energy is widely distributed. This poses a threat in variability of generation of power. To compensate this variability on the generation side from these distributed RE supply, energy reserve performs a key part in providing instant stability in DG-generated power [3], [4]. Secondly, for power transmission the renewable energy sources due to their non-dispatchable nature may cause instability during the transmission process [4]. Energy reserve schemes incorporated to the transmission apparatus of these sources of renewable power act as spinning reserve assets to improve voltage stability thereby losses reduction in transmission lines [3], [6]. Thirdly, for distribution of energy to end the consumers; renewable energy's frequency alteration and voltage drops may be consequential to the standard of power dispatched [7], [8]. Therefore, ESS may provide ancillary services, that is, to sustain stable and reliable power [9].

In the development of the ESS, it is important to understand that the various sources of energy resources. These sources give an insight on the criteria of the energy storage technologies desired. These technologies are not only utilized for stockpiling electricity for later consumption but also important devices for stabilizing the intermittent RE sources. Each storage technology is weighted to enable a choice to be undertaken on the best possible match of the two different energy technologies [9]. To have an effective seamless implementation of energy storage system, energy management strategies capable to withstand the fluidity nature of renewable energy is equally challenging [3]. Ways must be sought to achieve effective and efficient storage devices for utilization. Energy management strategies for energy storage systems range from complex optimization algorithms intelligent techniques to rudimentary strategies that avoid overcharging / discharging of these devices [3].

2.2 Energy Storage Systems

Amjed Hima Fathima in [3] discussed the energy banks are highly priced and that good maintenance regime is necessary to safeguard their operational lifespan. Thus, the writer in [3] further comments that when ESSs are reliable, full benefits of RES are realised leading to their widespread coverage.

The study by Rajesh Saiju in [10] discussed the role played by batteries in energy storage schemes (BESS) in a power system. The battery technology discussed in [10] is presented as a simple storage device or as a device whose terminal voltage is dependent on the base current (state of charge). Energy management is advocated for in the application of BESS in [10] to control the SoC status.

Cheng Sing Lui et al in [7] opined that the setup of energy storage systems is important in enhancing the hybrid systems' levelized cost of energy (LCOE). This is by providing energy balance because of the mismatch between demand and supply [7].

Zakari et al in [11] resolve that market benefits derived by the use of ESS technologies in RES for grid power is still not predictable. The researchers in [11] presented the formula for net levelized cost of storage (LCOS) as expressed in (2.1);

$$\text{LCOS} = \text{LCOE} - \frac{\text{Charging Power Cost}}{\text{Overall Efficiencies}} \tag{2.1}$$

Mladin Kezenovic study in [6] presented the tried and tested technologies for electrical storage. However, these technologies have had an effect on significant variations in the market value of power where daily alterations of more than \$50/MWh are noticeable.

As discussed in [12], during the conference of Parties in Paris December 2015, many countries ubiquitously acknowledged that for the Intended Nationally Determined Contributions in the power generation sector to take place the following transformations needs to occur:

(i) Extensive distribution of renewable technologies like wind and solar that are low in carbon.
(ii) The energy storage technologies to protect the dependability of the grid as the penetration of wind and solar energies increase.

2.2.1 Trends on Energy Storage

So far this report has discussed the importance of incorporating energy banks regimes in a power system. Some of the beneficial functions of ESSs include support of ancillary services, power balance in the supply and demand side [3], [9], [13-15].

Batteries as means of energy storage has been the known technology for some time. There has been a setback in their utilisation due to the demand of higher power capacity at low cost which the batteries lack [5]. However, the technological revolution in 2005 marked the beginning of the production of batteries with higher capacities, lower space to volume ratio and at a much reduced costs [5]. Recent development has seen the emergence of Sodium Sulphur (NAS) batteries and flywheel energy storage device with the former favoured for trading in the energy market while the latter for frequency control [16]. Energy trade by ESS has evolved as a trade commodity in the energy market bidding [17]. It follows that the optimum electricity arbitrage by ESS is a model for a business case, where the political administration has no control of the electricity price [17].

2.2.2 Forms of Energy Storage Systems

The different energy storage systems can be classified based on the technology used [3], [8] [9], [13], [18]. The summary of these classifications is in Table 2.1;

Table 2. 1: Energy Storage Classification

Storage Classification	Technology
Mechanical	(i) Flywheel storage (ii) Pumped hydro storage (iii) Compressed air energy storage
Electro-chemical	(i) Batteries (lithium, lead-acid, etc.) (ii) Hydrogen storage
Electrical	(i) Supercapacitors (ii) Super-conducting magnetic storages
Thermal	(i) Molten salt (ii) Low and high temperature thermal storage

2.2.2 Mechanical Systems

2.2.2.1 Flywheel Energy Device

The flywheel stores energy in the form of kinetic energy. The flywheel operates such that during off-peak the system moves the flywheel thus storing the kinetic energy. During peak times, the saved kinetic energy is converted into electricity rendering the electrical device to act like a generator [12]. Thus, charging takes place when the flywheel accelerates and stores energy. During de-energization, the kinetic energy is ejected with the flywheel device decelerating to extract the saved energy [3], [9]. Merits: (i) Highly efficient in operations, (ii) Better power capacity, (iii) Good cycle longevity and (iv) Manageable in maintenance. Demerits: (i) Susceptible to high discharge due to retardation and resistance losses at bearings, (ii) Not suitable for long-term energy storage, (iii)Low energy density and (iv)Cooling system for superconductor bearings required

2.2.2.2 Pumped Hydro Storage (PHS)

Pumped hydro storage are facilities that store large amounts of energy and use the force of gravity to generate electricity by converting the passive energy of water into electrical energy. The basic operation is that at off peak period the water runs from a downstream pool to an upstream pool that rotates the turbine for the electricity to be produced [9]. Merits: (i) The speeds are adjustable to respond to the requirements of the grid and operate in a feedback-controlled mechanism; (ii) The feedback-controlled mechanism of pumped storage hydro can be operated where there is no continuum water floor unlike the conventional pumped-storage hydro this making the former versatile. Demerits: (i)Long-term investment and thus takes longer for development and (ii)The long periods of investment not good for short-term investors who need quick return on investments.

2.2.2.3 Compressed Air Energy Storage (CAES)

Air is pumped into an underground tavern when electricity is in low demand. During these periods when electricity is cheap, energy is stored as compressed air in the underground tavern [3]. It consists of motor/generator set, air compressor, turbines, cavity and auxiliaries such as heat exchanger units. [9]. Merits: (i) Energy capacity is large and (ii) Can store energy in longer duration. Demerits: (i) Huge investment costs, (ii) Site dependent and (iii) Low efficiency.

2.2.3 Electro-chemical

2.2.3.1 Batteries Storage System

These are also one of the oldest and the most common form of storage in the market [3]. Electricity is converted into electrochemical energy that is stored in the electrolytes. Either these electrolytes can be in liquid or solid form together with electropositive and electronegative electrodes. It is during discharge that electrolytes act with electrodes in the cell and the counter reaction initiates electric current [9].

2.2.3.1.1 Types of Batteries Storage

2.2.3.1.1.1 Lead-acid battery

This the common type of battery in the industry. It mainly made up of electropositive electrode made of lead dioxide, negative electrode as sponge lead and an electrolyte of sulphiric acid. When the battery discharges, the electrodes are deposited with lead sulphite while the electrolyte is converted into water. Merits: (i) Good power and energy densities for immobile utilities, (ii)Intrinsically safe by controlled overcharged anode and electrolyte, (iii)Cell management is simple and (iv)It is comparatively a low investment scheme. Demerits: (i) Limited life cycle, (ii) Non-identical charging/discharge aptness, (iii) Requires provision for venting and (iv) Battery location is restrictive.

2.2.3.1.1.2 Lithium-ion battery storage system

The negative electrode consists of lithium metal oxide; the positive electrode is made up of graphite carbon while the electrolyte has lithium salts dissolved in organic carbonates. As the charging process takes place, the lithium ions migrate from the cathode to the anode to combine with the external electrons and are placed betwixt the carbon layers as lithium atoms [9]. During discharge of the battery the process reverses [9]. Merits: (i) Has good efficiency, (ii) Favourable energy density and (iii) Good cycle longevity. Demerits: (i) Investment costs are high due to the packaging required and (ii) Possibility for internal charge sharing.

2.2.3.1.1.3 Nickel-cadmium Battery Storage System

The electropositive and electronegative electrodes are made of nickel hydroxide and cadmium hydroxide respectively. These electrodes are isolated from each other by a separator in an alkaline electrolyte. Merits: (i) Dependability is resolute, (ii) Favourable energy density and (iii) Manageability costs are low. Demerits: (i) Comparatively expensive and (ii) High battery effect, i.e., holds low charge

2.2.3.1.1.4 Sodium-Sulphur Battery Storage System

The sodium nickel –chloride (zebra batteries) and sodium Sulphur batteries are distinct from other battery technologies in that their electrolyte consist of solid-state material [9]. The positive and negative electrodes constitute of liquid sulphur and liquid sodium respectively. While the charging process takes place, the sodium cations migrate across the electrolyte to fuse with sulphur to form polysulphide [9]. Merits: (i) Low cost of raw material, (ii) Favourable energy density and (iii) Good cycle longevity and durability. Demerits: (i) Heat losses are high, (ii) Operating temperature comparatively high and (iii) Nickel material render it expensive

2.2.3.1.1.5 Sodium-nickel Chloride battery storage system

Another name for sodium-nickel battery is ZE-BRA. The positive electrode is made of nickel-chloride and works at a temperature of approximate 300^0C in the absence of cooling [9].

Merits: (i) Cell voltage is high and (ii) Good cycle longevity and durability

Demerits: (i) Heat losses are high, (ii) Operating temperature comparatively high and (iii) Power and energy densities comparatively low.

2.2.3.1.1.6 Vanadium redox flow battery (VRB)

The power is stored into analytic and catholytic reservoirs containing a solution of sulphiric acid. These analytic and catholytic reservoirs have V^{2+}/V^{3+} and V^{4+} and V^{5+} as electrolyte [9]. Throughout the charging and discharging action the H^+ are swapped in the middle of the two electrolytic reservoirs past the hydrogen-ion permeable polymer membrane [2]. Merits: (i) Economical, (ii) Easily sustainable and manageable, (iii) Enough storage space. Demerits: Power and energy densities comparatively low.

2.2.3.1.1.7 Zinc Bromine Battery Storage System (Zn Br battery)

Similar to VRB case, the Zinc and Bromine are stored into two separate tanks too. As the charging process takes place, the Br^- ions and Zn^{2+} are transformed into Br^-_3 and Zn ions respectively [2]. The Zn and Br^- ions form Zinc-bromide that produces a nominal voltage of 1.8V across each cell [9]. Merits: (i) Low costs, (ii) High energy efficiency and (iii) High reliability. Demerits: Power and energy densities comparatively low.

2.2.3.2 Hydrogen Storage

This fuel cell produces electricity from extrinsic fuel sources such as hydrogen and oxygen, solid oxide, methanol, molten-carbonate and metal air [9]. The electricity is used to disassociate water into hydrogen and oxygen with the hydrogen generated kept under pressure in reservoirs. When required this hydrogen is streamed with air into fuel cell to produce electrons and water [3]. Another name for this type of storage is regenerative fuel cell (RFC) [3]. Merits: (i) Highly modular system and (ii) They have higher levels of energy and power volume. Demerits: (i) Shortened round trip efficiency and (ii) Relatively high cost.

2.2.4 Electrical Energy Storage

2.2.4.1 Supercapacitors storage

They usually constitute parallel plates with dielectric material in the middle that stores the charge. The main distinction of the capacitors and the supercapacitors is the use of the pervious electrodes with large surface area that increases the surface density [3]. This kind of technology narrows the gap between the usual dielectric capacitors and batteries as they can reserve higher capacities of energy compared to the batteries. They are fast, have rapid charge and discharge cycles since they do not involve any conversion process. Whilst the energy stored in supercapacitor is proportionate to their magnitude and square of the voltage between the electrodes, the capacity is directly proportionate to the electrode surface area and is reversely proportionate to the distance between the electrodes [9]. This can be expressed in form of equations (2.2) and (2.3) as;

$$E = \frac{1}{2} CV^2 \tag{2.2}$$

$$C = \varepsilon_o \varepsilon_r \frac{A}{D} \tag{2.3}$$

The supercapacitor configurations are generally symmetrical and asymmetrical where in the former the electropositive and electronegative electrodes are made of similar material. The connection of the supercapacitors to the network is via a two-way converter [14]. The principle is to reserve energy at off-peak period and supply the energy unto the grid at peak periods.

Merits: (i) No conversion losses, (ii) Environmental friendly storage mode, (iii) Can be recycled with ease and (iv) Highly suitable for frequency support utilization

Demerits: (i) More affected by self-discharge, (ii) Low energy density and (iii) High cost per installed design.

2.2.4.2 Super-conducting Magnetic Energy Storage (SMES)

In SMES, energy is stored in the disposition of magnetic field produced by a dc current passing across the conducting coil at low temperature [9]. The system is made of superconductive coil, refrigerator, vacuum insulated vessel and power converter. SMES energy storage is dependent on self-inductance of the coil, square of current through it and the operating temperature of the coil. Addition of current at a maximum the energy stored in SMES is increased. [9]. Merits: (i) Higher efficiency and (ii) Long cycle lifetime. Demerits: (i) Lower energy capacity and power ratings, (ii) High costs due to the cooling system and maintenance of the system and (iii) Complex in design.

2.2.5 Thermal

2.2.5.1 Low and High Temperature Thermal Storage

The thermal storages are categorized as low temperature and high temperature. The material used in thermal storage are those to be kept in low and/or high temperature insulated containments [9]. Further classifications for these thermal storages are (i) industrial cooling which is below -18^{0}C, building cooling at between 0 – 12^{0}C, building heating at between 25-50℃ and industrial heating which is greater than 350℃ [9]. In the process of charging, the electrical energy is transformed into temperatures of high value at 500℃ [9].

2.2.5.2 Molten Salt (Phase Change Materials)

They are defined as substances or mixtures of substances showing a phase transition in an assumed temperature range, which are tend to reversibly store and release thermal energy while facing the phase conversion. The temperature of the phase change material undergoing the phase change remains constant until the change is over. The thermal conductivity of the phase change material needs to be low as possible for it to be functional. Only then will the phase change material be able to quickly absorb or release a significant amount of heat at its phase transition temperature. The basic role of the phase change material is to stabilize the temperature of the system and to eliminate thermal effects caused by contact of the system with the environment. The type of phase change material and the type of phase transformation used are selected for the particular application and desired phase transition temperature. For example, in construction it is necessary to use phase-change materials exhibiting a solid / solid phase transition, while the transition temperature may fluctuate in a relatively wide temperature range [15]. In turn, the so-called hand warmers must show a phase transition at a temperature slightly above the human body temperature, but solid / liquid phase transition may be used [15]. Merits: (i)Suitable for big capacity storages, (ii)Temperature losses are minimum and (iii) Construction – passive technology that does not require additional work and energy expenditure during use, including: offices, housing, passive houses, data centers and server rooms, cooperation with heat pumps (improvement of heat balance). Demerits: (i) High energy density, (ii) Relatively low efficiency and (iii) Uneven group of functional materials that differ in heat quantity and phase transition temperature.

2.3 Reasons for Hybrid Energy Storage System

From the comprehension of energy management perspective, the capacity to invest in energy storage devices is one way to save energy and reduce costs (7], [4]. However, due to sporadic nature of renewable energy it is paramount to have more than one way of storage to meet the power demand at peak times [4]. There will be need to accordingly develop a redundant generation capacity to match the demand. Therefore, a robust energy storage system with a hybrid strategy to relieve peak demand will be beneficial to both power supplies and end consumers. The idea is to work around storage technologies that complement each other with fast and long response times. This is done through either scaling down power consumption or through postponing of power to a later time when the demand of power is low at a favorable cost [4]. From the foregoing, hybrid energy storage is favoured over single storage units among other reasons due to the following:

(i) Long run operational costs by having single hybrid unit that have combined power and energy features over separate single storage units.
(ii) Hybrid unit operating at its peak capacity has increased efficiency.
(iii)The charging and discharging cycles are extensive hence; cycle life of the storage device is prolonged.
(iv) Economizes on space storage ratio as compared to single units

This project proposes to adopt a hybridized energy storage system that will answer the existing gaps in the previous studies in energy storage. The project underscores in having a right mix of energy storage forms to address the challenge of stored power to be utilized when warranted by the demand.

2.3.1 Energy Density vs Power Density

This research largely focuses on choosing the right combination of different forms of energy storage. Attention is drawn to electric energy system with high energy and power densities. To explain this scenario better an example of two ESS devices is presented. ESS device 1 rated at 500 kW takes 30 seconds to deliver energy and ESS device 2 rated at 500 kW delivers energy in 2 hours when fully charged. The energy from device 1 is 4.17 kWh (500 kW x 30 sec) [12]. This implies that the device delivers a large amount of power at shorter duration but has small measure of energy (relative to the amount of power) [12]. On the other hand, ESS 2 energy rating is 1000 kWh (500 kW x 2 hrs.) which is a high amount of energy proportional to the quantity of power [12]. Applications such as those of long durations load shift requiring high energy density capacity makes the energy cost (dollars per kWh or MWh) a vital thought for choosing suitable energy storage technology [12]. In similar way, applications such as grid frequency control and voltage stabilization need storage with ability to deliver high power density to be consumed or added making power cost (dollars per kWh or MWh) a significant aspect too in determining the suitable technology to adopt [12].

2.4 Review of Existing Hybrid Energy Storage

Hybrid energy storage schemes (HESS) is still an ‘exciting’ feature for research within the energy domain and that is still evolving technologically. Though some technologies for the energy storage are still maturing, there are researches who have made some significant strides in this area as will be discussed under this subsection.

Ferreira H.L in [13] gives provisional procedure for identifying a suitable technology mix for different applications. The **strength** in [13] is carrying out multiple comparison of energy storage technologies according to their different characteristics. He compares them according to maturity level, ratings, energy density, durability and costs. The **demerits** in [13] is failure to mention or pair the chosen technologies on account of their different characteristics.

Hajiaghasi et al in [15] considered hybridization of battery and supercapacitor storage systems to improve the performance of microgrid under unbalanced load conditions. The major **strengths** from the research were; (i) there was reduction of battery power fluctuation as a result of the coupling of the two energy storages, (ii) there was better dc bus voltage control for production and load disruptions, (iii) enhancement of system performance under balance load conditions was also noted [15]. The **demerit** was failure to disclose the type of battery used as different batteries have different characteristics such as depth of discharge, capacity, type of electrolyte used and maintainability.

Dekka Apparo et al in [9] postulated on the operation on the myriad energy forms applied in HESS. The drawback noted from the authors work in [9] is failure to comprehensively analyse the different technologies of energy storage that can be combined.

Jing Wu et al in [19] presented an effective prototype for hybrid energy system by coupling wind power and energy storage. The focus of the study was on the economic benefits derived by energy curtailments on optimization model of HES by merging wind power and energy storage. The **strengths** were; (i) hybridization of wind and energy storage acts as a generator that safeguards the stable generation of wind power, (ii) combination of wind power and ESS met the objectives of gaining maximum benefits at minimum energy waste. The **demerits** in [19] were: (i) no specific ESS technology stood out as the storage hybrid with the wind power hence it cannot be convincingly advocated as the alternative hybrid to adopt, (ii) generally assumes that utilization of ESS and curtailed wind energy on the generation side is where there are fluctuations but not on the demand side.

Thilo Bocklisch in [20] discusses the significance of batteries as whether they fall under intense energy or intense power storage. The **strength** in [20] gives principle approaches for the power flow architecture, basic energy consumption control and power flow division based on levelling peaks and having double layer of filters that allows low frequencies only. The **demerits** in [20] are that for the HESS configurations given namely; (i) power for heat unit, battery and hydrogen, (ii) supercapacitor and battery, most of them require intelligent change control and energy management control algorithms that are complex and costly.

Maria Lukatskaya et al in [21] approach was on the microscopic nanoscale level. The miniature materials are responsible for the control, execution and malfunction of the ESS action. The **strengths** presented in [21] were; (i) ESS with fewer content of inactive material have a larger cycle life. (ii) For the design of the supercapacitors the asymmetric electrodes is required for optimal performance, i.e., the electrodes are of different materials thus the energy density $\mathrm{E}= \frac{1}{2}\,\mathrm{C}_{\mathrm{tot}}\mathrm{V}^2$ [21] where $\mathrm{C}_{\mathrm{total}}$ is the stored electric charges of the scheme and V is the active voltage range of the cell. (iii) The typical combination of two dissimilar electrochemical materials leads to generating an unsymmetrical energy storage. The **demerits** in [21] is that in the computational of material science and simulations of electrode architecture requires advance studies on micro-sciences.

Etxberria et al in [1] opined that the changes of the microgrid is sensitive with load and generation supply variance that the storage systems should have scaled up energy and power densities. The **strength** in [1] is that for similar wind-power output the largest power for the battery in the HESS was below half the size in the unitary ESS. The battery depth of discharge was 5-8% lower than that in the HESS resulting to lessened power losses by 15%. The **demerit** found in [1] is that the system develops power losses and the costs involved by using two bidirectional converters to interface the storage devices to the microgrid. Table 2.2 summarizes the aforementioned review work for HESS.

Table 2. 2: Illustration of Existing HESS Applications

Ref	**Existing HESS**	**Method Used**	**Parameters Investigated**
[13]	Multiple ESS	Characterizing various ESS technologies.	(i) Energy density (ii) Ratings of ESS
[15]	Battery / SC	Modelling of ESS components	DC bus voltage & currents when the loads are unbalanced.
[22]	Hydrogen / Lithium ion battery	(i) Determining frequency control of AC power system (ii) Designing hybrid ESS devices	(i) Time scales for frequency response controller (ii) Rated energy for ESS and power for converters
[19]	Wind power/ESS	Optimization by use of PSO algorithm model.	Power output and costs.
[20]	Hybrid Batteries (VRB &Lithium ion	Investigation by experiment of HESS energy management and applicable configurations	Power flow concept of peak shaving and low pass double filtering.
[21]	Batteries & Electro capacitors (EC)	Investigations at nanoscale level on the effect of types of electrodes and electrolyte used.	(i)Effect of ion size of the crystalline material of the SC (ii)Effect of electrodes design (asymmetrical or symmetrical) on the performance of SC
[1]	VRB/SC	Analysing of coupling topologies and energy management algorithms	Load profiles from the different coupling topologies.
Proposed HESS	Lead Acid Battery & Supercapacitor	Modelling and simulations of single ESS & paired ESS	(i) Current, voltage, power and energy (ii) State of charge of ESS

2.4.1 HESS Coupling Topologies

A brief look of the various coupling methods for HESS is as follows:

(i) Passive topology - The simplest topology where the short-term and the long-term ESS devices are connected in parallel and directly coupled to a DC bus. Main advantages are the simplicity in operation and low cost. The disadvantage is lack of control of the power flow [1], [15].

(ii) Semi-active topology - In this method, the converter is used to interface one of the ESS devices to the DC bus. The advantage of this topology is that when interfaced to the long-term storage, the latter can be guarded from power spikes and frequent load dynamics. The cons for this method is the fluctuations of the DC voltage which becomes identical to the short-term ESS [1] [15].

(iii)Full active topology – This method has all the paired ESS interfaced with the power converters. The pros for this mode is that the converter for short-term ESS regulates the voltage of the DC bus, thus, resulting for the ESSs capacity to be optimally harnessed. The cons associated with this mode of coupling is the high power losses and costs compared to other topologies [1] [15].

In this research a semi-active topology was adopted where the battery was coupled to the DC bus and the SC interfaced to the DC bus via a power converter. The trade-off is the benefit of minimal power loss, which is an important aspect in ESS and the bus voltage satisfying an operation range that is dependent on the SoC of the battery therefore, limiting the operation of the system [1].

2.5 Research Gap(s)

Work has been done on the various forms of energy storage schemes but there still exists an opportunity for continuous improvement on the best alternative for pairing different energy schemes of different classification to attain optimal energy storage capacity. This implies having a hybrid pair of a source from say mechanical with that from electrical source. This entails characterizing these energy storage schemes with the objective of achieving a complementing couple of energy storage to build a resilient HESS regime. Previous studies exhibit shortcomings on how the pairing of the various forms of electrical energy storage forms have been characterized and matched. Further, a technologically sound but cost-effective coupling technology for the ESSs pairing requires to be given greater attention that it is currently. Therefore, this study endeavours to present clearly and concisely two forms of energy storage pair namely; the electro-chemical (battery) and electrical (SC) storages respectively, to achieve a hybridized energy storage scheme (HESS). The technology chosen analyses the complementary features of the ESS pair to refine the quality of power, reliability and availability from the renewable energy sources ready for integration to the grid power network that can provide high power density (short-term) and high energy density (long-term) respectively. Table 2.2 gives a summary of the parameters investigated in other studies as well as in this work.

2.6 Chapter Conclusion

The chapter begins by presenting the importance of storing energy in grid connected renewable energy sources. A run through on the application of these energy storages is stated. More to this, a look at the technological trends of the energy reserves has been undertaken. The different forms of energy storages and the respective technologies applied has also been discussed. In order to establish a good hybrid energy storage schemes, an intense study has been done on how to characterize and come up a compatible HESS system that is optimally utilized to support a microgrid network from the power dispensed by the renewable energy sources. To understand how the HESS technology has been trending, a review on previous work by other researches has been carried out. This takes into account the strengths and drawbacks from those works with a view to establish opportunities to improve on. Continuous improvement prospects of this technology in the futuristic years are observed by identifying the research gaps that exist. Clearly, this study has opened horizons on ways to add value to power generation from the renewable energy sources by way of improving energy storage systems through hybridization.

CHAPTER THREE

3.0 METHODOLOGY

This section presents the method to be use in the research study. However, a brief highlight on the methodology approach by previous researchers on their work has been reviewed.

3.1 Review of Previous Methods

Oswaldo A. Arraez et al in [23] method was to model a solar PV backed diesel generator hybridized with batteries. The model had the following characteristics developed; (i) the solar PV gives priority to the signal coming from the battery instead of the load when the diesel generators are put in operation, (ii) the load following strategy was adopted, i.e. the load was supplied by the diesel generators only after the PV and the battery power was inadequate. The **strength** in this method is the adaptation of the particle swarm optimization (PSO) that determines the number installation components to obtain the most cost effective and reliable indicators. The **demerit** [23] is failure to present the algorithm for calculating the reliability indicators for the RE and the costing models.

Ferreira H.L et al in [13] method is the evaluation of the efficiencies of various energy storage systems. The major observation in [13] was that when storage devices undergo transformation processes to convert energy to electricity, significant energy is lost resulting to loss of efficiency. The **strengths** derived in [13] was highlighting: (i) durability for various storage systems are dependent on cycle depths, temperature of the room and ageing of the device, (ii) energy and power ratio capacities is affected by the storage pack and weight of the given technology, (iii) reliability indices of the storage system as MTBF and MTTR so as to evaluate the Availability and Reliability of the storage systems, (iv) response time for the various energy applications. The **demerit** in [13] is insufficient detailed methodology of storage devices chosen or evaluated.

Lukatskaya R. Maria in [21] methodological approach was to investigate the advancement of the electrode architectures at nanoscale level. This approach led in investigation on how the miniature materials and electrolytes are utilized. This found that the reversible reaction of the multi electrons are able to scale up the energy density in more than one electron per oxidoreduction. The **strength** in [21] is the understanding of the microscopic science in the functioning of the electrodes such as cathode transitions and nanostructuring of the cathodes.

The **demerit** in [21] was that the influence of chemistry on the chemical characteristics of the materials nanostructure was not mentioned as it could have an improved material and the device performances.

Etxberria et al in [1] compared active and passive topologies. The method used to analyze these topologies is by simulations. For case 1 under passive topologies, the process had power converters connected to the battery pack resulting the current being scaled down by 40% while the voltage from the DC bus scaled up by 30% and the supercapacitors features were well exploited. For case 2 under the active topology, the procedure was to increase the power density of the functional HESS by factor of $3\frac{1}{5}$ and the decrease of the current emanating from the battery to acquire stable DC bus voltage. Further, this study in [1] conceptualized that employing power conversion system the identical period is boosted as on the direct linking of the battery-super capacitor is attained though using half the number of the supercapacitor cells. The **strength** in [1] was that the power conversion system manages the power outflow of the energy storage in effect reducing the current for the battery thereby increasing its lifecycle. The **demerit** observed in [1] is the procedure presented, as passive topology is not factual since from other literature sources passive topology entails direct connection of the storage devices to the DC link.

Hajiaghasi et al in [15] presented similar method as in [1] but the point of departure was the utilization of the DC/DC converters to the solar PV. In [15] the HESS consisted of PV generator, battery and super capacitor packs, DC and AC loads. The PV was the main generator linked to the DC bus by a DC/DC converter. The AC load was linked to the DC bus by use of three-phase inverter. The battery and the super capacitor were coupled to the main DC bus via bidirectional buck-booster converter [15]. The maximal power point tracking model controlled the PV system converter. Both the Shepherd curve fitting and Stern models respectively described the behavioural characteristics of the energy storages. The **strength** in these models was that the overvoltage is added to the battery discharge to improve the battery state of charge (SoC) and on the performance. The work had the **demerit** that the type of battery technology was not mentioned and how the outcome of would by considering the use of different type of batteries since they have unique characteristics such as depth of discharge, type of electrolyte used, capacity etc.

Thilo Bocklisch work in [20] discusses the significance of batteries utilization in HESS and as to whether they fall under large-scale energy or large-scale power storage capacity. The author approach was to deploy flexible power converter system with utmost of eight bidirectional DC to DC and DC to AC converters. The **strength** in the method used in [20] is the presentation of the power flow decomposition that consist of both the current and voltage controllers. These controllers emanate from either peak shaving or double low-pass filtering which partake in regulating both the bus voltage and the component's voltage (ESS). The study **demerit** is that for the HESS configurations discussed in [20] require investment in intelligent energy management systems capable of estimating the effect of the various functional limits at optimal energy management parameterised model.

3.2 Proposed Method

This research has endeared to present an energy bank system that constitute a hybrid of two kinds of energy storage schemes. These ESSs are sourced from electro-chemical and electrical forms of energy with due consideration of their different properties that supplement each other. As was reviewed in the literature, the desire to have the aforementioned classes of energy is to achieve an ESS with enhanced characteristics of energy capacity and power capacities. The latter are expected to boost the quality of power produced from the renewable production and guarantee continuous power flow to the load (demand) side on the grid. The entire system under probe will have the following main components:

(i) Solar PV array source
(ii) Lead acid battery bank
(iii) Supercapacitor bank
(iv) Power converter device
(v) Inverter

The battery type chosen is preferred due to ease of availability, low cost and good energy reserve while the supercapacitor is favoured for its higher power containment as well as quick discharge and charging abilities. As it was discussed in the previous chapter, the coupling architecture adopted is semi-active topology where only the SC is interfaced to the DC bus by use of the power converter where the latter is expected to control the power flow of the SC. Since the primary source of power required is renewable type, provision is made for the solar PV to supply the power that is inverted as it delivers to the load that is also fed by the grid.

For this work, MATLAB Simulink would be deployed for the set-up of the system and data collection for analysis. The simulations carried out are to induce variability of the power produced by the solar PV and observe generated power reaching the load when both the HESS devices are in-line. Observations are done when singular ESS component is availed as backup storage during periods of power disparity originating from the solar PV supply.

3.2.1 System Arrangement

The power from the renewable source is from the solar PV array. The HESS is the source of the backup storage fed by either the lead acid battery bank or the supercapacitor. A semi-active bidirectional DC/DC converter is considered for the supercapacitor bank. Both the Solar PV and the ESS devices are all connected in parallel to the DC bus as a current source. However, under this study a model in MATLAB Simulink will simulate the power output from the system at a set of parameters given in the sub-sections here under. The arrangement is shown in the block diagram in Figure 3.1.

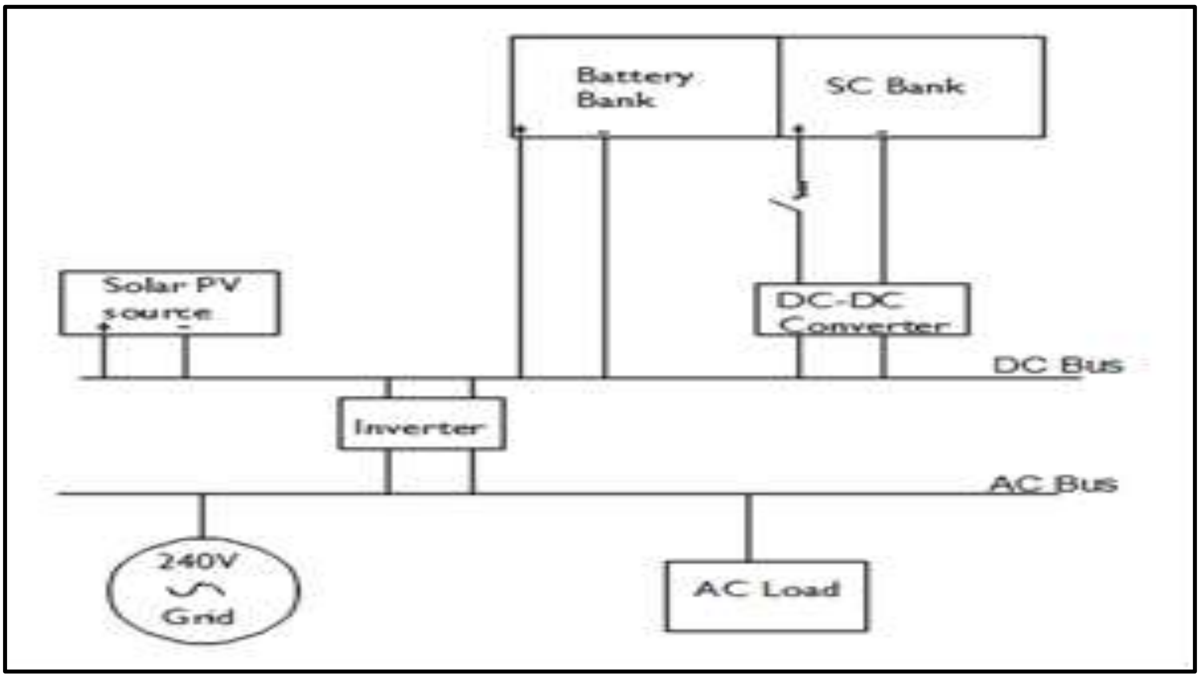

Figure 3. 1: Arrangement of the HESS in a Grid Connected Solar PV

3.2.2 Solar PV

The solar PV system of 9 kW considers parameters from Kyocera panel whose specifications are as shown in Table 3.1. More specifications of the solar panel are given in appendix 1. The capacity of this RES was carefully arrived at after carrying out a design on the energy requirements for the VIP lounge building at Wanguru airstrip, Kirinyaga County.

Table 3. 1: Parameters for Solar PV Module (Kyocera Solar KD320GX-LFB)

P_{max}	V_{mp}	I_{mp}	V_{OC}	I_{sc}	Normal Temp	$P_{tolerance}$
320 W	40.1 V	7.99 A	49.5 V	8.60 A	25^0C	+10/-0 %

3.2.3 Battery Energy Storage (BESS)

The BESS technology considered is Lead acid battery. The parameters used are from Chloride Exide whose specifications are as shown in Table 3.2. More of these specifications are given in appendix 2.

Table 3. 2: Parameters for Battery (Chloride Exide)

Charge Capacity	Output Voltage	Max Charging Current		Internal Resistance	V_{OC}	Float Charging Voltage	Normal Temp
200 Ah	24 V	60A		0.004Ω	25.66 V	27.2-27.6 VDC	25 ^{o}C

From the design, total battery capacity required is **738Ah**. Using the parameters in Table 3.2 of the available charge capacity, the no. of batteries required are $\frac{738}{200}$ = 4 batteries

3.2.4 Supercapacitor Energy Storage

The supercapacitor energy storage considers parameters from Maxwell Technologies whose specifications summary are as shown in Table 3.3. More of these specifications are given in appendix 3.

Table 3. 3: Parameters for Supercapacitor (Maxwell Technologies ultracapacitor)

Initial Rated Capacitance	Rated Voltage	Initial Equivalent Series Resistance(ESR)	Max Peak Current (I_{ACmax})	No. of Series Capacitance	Normal Temp	$C_{tolerance}$	Energy Wh
3400	24V	0.15 mΩ	2800A	8	25^0C	-5% to 20% (+20% ^{o}C)	4.2

3.3 Problem Design

3.3.1 Solar PV Control

This research considers the following two conditions that affect the output of the solar PV array: (i) solar irradiance (W/m2) and (ii) PV cell temperature (ºC).

Solar irradiance

To achieve maximum power from the solar PV, an incremental conductance (IC) MPPT algorithm is commonly deployed in [24] and it is adopted for use in this study.

(1) PV Cell Temperature

Since the temperature of the solar PV and the ambient temperature are never similar the approach adopted is similar to the one formulated in [24]. This formula largely considers factors such as surrounding temperature, PV irradiance and windspeed. The solar PV cell temperature is determined by the relationship in equation (3.1);

$$(T_{module}{}^{\circ}C) = a + T_{ambient} + (b \text{ x Irradiance}) - (c \text{ x wind speed}) + d \quad (3.1)$$

Where, the system constants of regression are a,b,c and d, ℃ is the $T_{ambient}$,PV irradiance given as W/m^2 , wind speed as m/s. Adopting the function used in [24], the constants a,b,c and d were computed by use of solar PV data taken for a year. The predictive formulae became as shown in (3.2), that is,

$$(T_{module}{}^{\circ}C)=0.943 + T_{ambient} + 0.0195 \text{ x Irradiance} - 1.528 \text{ x windspeed} + 0.3529 \quad (3.2)$$

3.3.2 Lead Acid Battery

The lead acid battery characteristics are formulated by the relationships as given in (3.3), (3.4) and (3.5) below;

$$\text{SOC}= \frac{\text{I}_{\text{battery}}\ (t)}{3600\text{Q}_{\text{battery}}} \quad (3.3)$$

$$I_{battery}= V_{oc}R_{in,\ battery} \quad (3.4)$$

$$E_m= V_{oc}-K_e\ (273+T_b)\ (1- \text{SOC}) \quad (3.5)$$

Where; E_m represents the electromotive energy, V_{oc} represents the open circuit voltage, K_e the electron constant, T_b shows the operating voltage temperature, SoC the state of charge which the battery is operating and I is the battery current.

3.3.3 Supercapacitor

A supercapacitor of similar output as that of the lead acid battery is modelled. The model in Figure 3.2 used in [25] was adopted for this work.

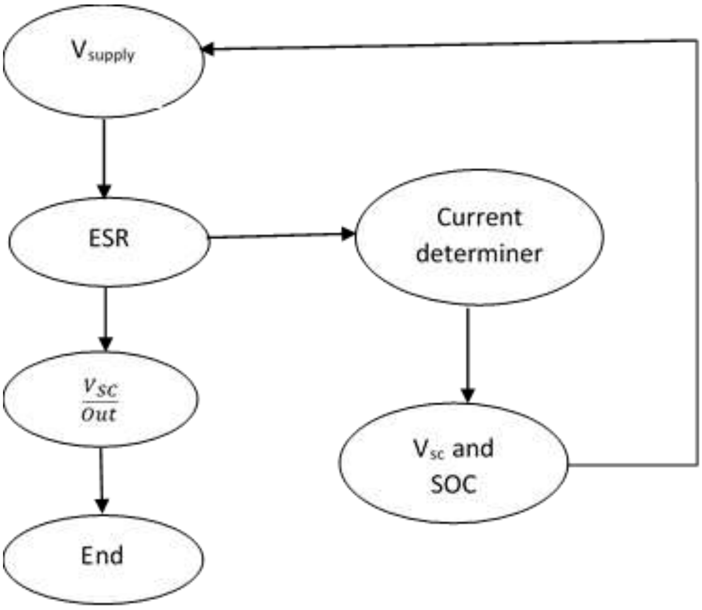

Figure 3. 2: Representation of Supercapacitor Model [25]

The output of the supercapacitor are shown in expressions given in (3.6), (3.7) and (3.8);

$$V_{SC}\,(t) = V_i e\ (\frac{t}{RC}) \qquad (3.6)$$

$$I_{SC} = \frac{P_{SC}}{V_{SC}} \qquad (3.7)$$

$$SOC = SOCo - \int_o^t \frac{\epsilon_f I}{Q}\, dt \qquad (3.8)$$

Where; V_{SC} represents the capacitor voltage, V_i the supply voltage, e represents Euler’s constant 2.7182, t shows the period elapsed after supplying the voltage, RC represent the time constant, SoC the state of charge of the capacitor, I_{SC} shows the supercapacitor current and P_{SC} supercapacitor power.

Marin S. Halper and James C. Ellenbogen (2006) on the review paper of supercapacitors concluded that the factors affecting the internal resistance of the SC are collectors, electrodes and the dielectric material, which is referred to as equivalent circuit resistance (ESR) that determines the voltage, during the discharging process. The maximum power P_{max} for a capacitor (Marin S. Halper and James C. Ellenbogen 2006) is expressed in equation (3.9);

$$P_{max} = \frac{V^2}{4x\ ESR} \tag{3.9}$$

3.3.4 Control of HESS

The study in [24] developed a control structure that is able to maintain HESS power. This study adopted the model in [24] due to its outstanding performance. The HESS reference power is computed using the expression given in (3.10) as shown;

$$P_{HESS,\ ref} = P_{GRID,\ ref} - P_{PVES} \tag{3.10}$$

The power reference of the battery obtained is when the $P_{HESS,\ ref}$ when the components of high frequency are filtered by passing it in a low pass filter. This is also supports in prolonging the battery lifetime.

On the other hand, the power reference of the supercapacitor that is, $P_{SESS,\ ref}$ is calculated as shown in expression (3.11) that was also adopted in [24];

$$P_{SESS,\ ref} = P_{BESS,\ ref} - P_{HESS,\ ref} \tag{3.11}$$

DC to DC power conversion duty ratio is responsible in checking both the proportional and integral error by limiting the ratio of output to input voltage of the system. It is determined by checking the reference signals of the two ESS storage banks with their current output power. A PI controller determines the DC to DC converter's duty ratio in supercapacitor storage source. The Proportional Integral (PI) controller is preferred in this research for its ability to stop the system fluctuating hence stability and rapidity is achieved. The steady state error is also minimized by increasing the control signal with time [24]. As mentioned earlier a semi-active topology was used with the battery directly coupled to the DC bus. This is expressed in equation (3.12) as;

$$PI\ (t) = K_p\ x\ e\ (t) + K_i\ x \int_0^t e(t)dt \tag{3.12}$$

Where; K_p controls the overshoot response sensitivity of the system, e(t) represents the error signal, Ki shows the integral gain constant.

Through numerous tests as found in the study of [24] tested on the converter was found as K_p as $1x10^{-3}$ and K_i as $5x10^{-1}$. When a positive and negative error for the PI converter show up, it signifies the discharge and charging function of the ESS. In the process of the discharge by the ESS, the DC to DC converter functions in boost operation. To prevent ESS input current interruption on buck mode, the voltage for the DC bus is recommended to be about two times the storage (battery/supercapacitor) voltage. According to [24], a perfect duty cycle selected for supercapacitors' state of charge at 100%, 70%, 50% and 25% are given as 0.505, 0.51, 0.485 and 0.46 respectively. ESS is shielded from damage by the extreme PI signal by a limiter module placed at the PI controller. Both the upper and lower limits in [24] for the battery and supercapacitor pack were selected as (0.65 and 0.35), (0.55 and 0.25) respectively. A bidirectional mechanism for the battery storage pack and supercapacitor power transfer adjustment developed in [24] was adopted in this study as presented in Figure 3.3.

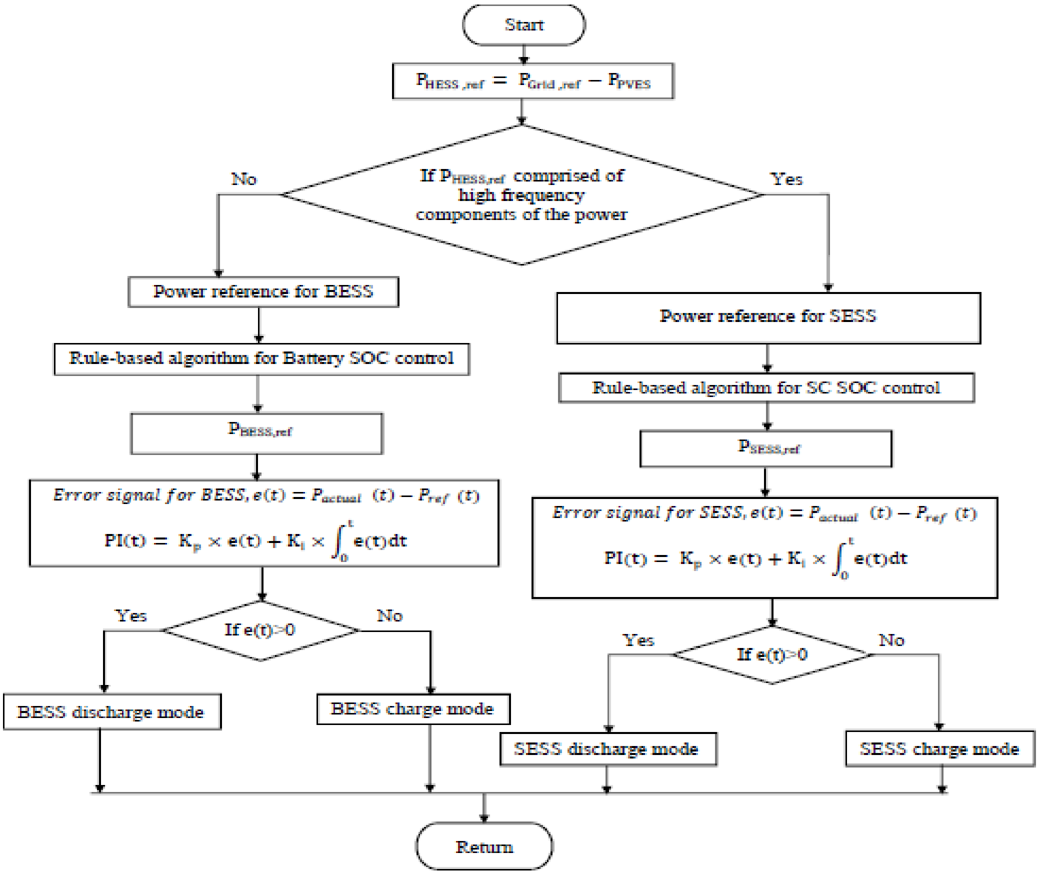

Figure 3. 3: Representation of HESS Power Transfer Tuning [24]

The DC bus voltage control is important for transient condition from the output of solar PV changes, power division between battery and supercapacitor to reduce battery current stress [15]. An expression of power balance was best expressed in [15], which regulates converter and power line losses. This study adopted the expression found in [15] and is shown in equation (3.13) as;

$$P_L(t) - P_G(t) = P_{batt}(t) + P_{SC}(t) = P_{av}(t) + P_{av}(t) + P_{tran}(t) \tag{3.13}$$

Where; $P_L(t)$ is the load power demand, $P_G(t)$ is generated power by the solar PV, $P_{batt}(t)$ is battery power, $P_{av}(t)$ the average power of the storage device, $P_{tran}(t)$ being the transient power of the storage device and $P_{SC}(t)$ the supercapacitor power flow.

The HESS reference currents are disintegrated into battery and supercapacitor reference currents by use of a low pass filter. The battery stress is minimized by adding battery current error to the supercapacitor reference current. The reference values of the battery and supercapacitor-measured values are compared by using two PI controller, which are converted to switching duty ratio. It is worthwhile considering minimum and maximum SOC limits of HESS and the latter decides if the HESS should discharge or charge accordingly to power difference P_{HESS} between P_L and P_G. The expression in [15] is given in equation (3.14) as;

$$\text{State} \quad \begin{array}{l} 1 \text{ if } P_{HESS} > 0 \text{(Discharging)} \\ 0 \text{ if } P_{HESS} \leq 0 \text{ (Charging)} \end{array} \tag{3.14}$$

The indication of SOC is monitored by SOC block that gives flagged signals showing $flag_{SoC+}$ and $flag_{SoC-}$ that indicates the maximum value and minimum value of SOC respectively. These values of SOC are similarly expressed in [15] in equation (3.15) and (3.16) as;

$$Flag_{SoC+} = \begin{cases} 1 \text{ if } SOC \geq \text{SOCmax} \\ 0 \text{ if SOC } < SOC\ max \end{cases} \tag{3.15}$$

and

$$Flag_{SoC-} = \begin{cases} 1 \text{ if SOC } \leq \text{SOCmin} \\ 0 \text{ if SOC } > SOC\ min \end{cases} \tag{3.16}$$

The construction of the control block of SoC is done using logic elements shown in (3.17) as;

$$Gc_{batt} = K_p + K\frac{i}{s} \tag{3.17}$$

Where; C is the DC bus capacitor, K_p and K_i are proportional and integral gains respectively. K_p is proportional gain, K_i is the integral gain and C is dc bus capacitor.

3.4 Conceptual Framework

The research conceptualizes examining the problem and obtaining solutions by undertaking the following tasks:

(i) Ensuring the load side meets the power demand continuously at the periodical loss of RE supply,

(ii) Ensuring the supply side meets healthy power delivery by refining momentary power fluctuations, and

(iii)Ensuring the characteristics of ESS components are analyst for the optimal matching and pairing.

To actualize the above, a clear road map for this work is constructed. (i) Obtaining the energy requirements for the building at Wanguru airstrip, Kirinyaga County. (ii) Obtaining the meteorological data that are applicable for the solar PV since the decision is the latter to be RES. Metrological conditions for Nairobi are used to obtain the size of the solar PV array. (iii) Sizing of the solar PV and the energy storage components. (iv) Identification made for the available devices in the market and comparing the specifications with the parameters obtained in (iii). (v) After obtaining all the required information, the data is fed to the computer software since the concept was validated using MATLAB Simulink with safeguards to the conditions discussed in the previous subsections of this chapter. The solar PV, battery and supercapacitor parameters under test were each simulated for a duration of 1000 sec (approx.16 mins). The procedure is to first input the parameters of the solar PV, battery storage alone then the process repeated with the supercapacitor. Subsequent process was done for the hybrid energy storage component and the results recorded. These single storage components were to compare the hybridized ESSs on the performance of power delivery.

Figure 3.4 illustrates the procedure that was followed when carrying out the research.

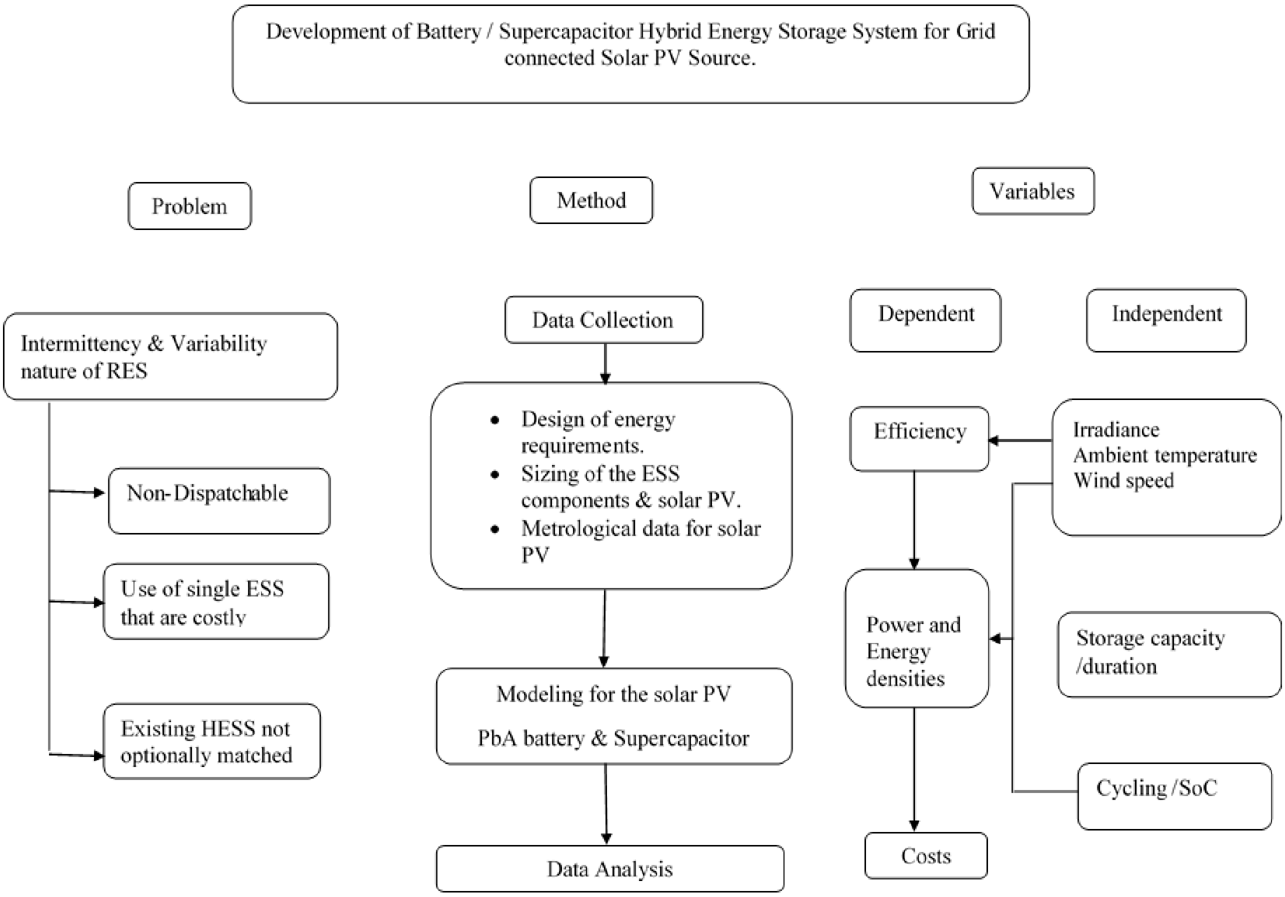

Figure 3. 4: Research framework Illustration

3.5 Chapter Conclusion

The chapter began by reviewing other existing methods for hybrid storage regimes. Different approaches were discussed as well as the pros and cons of each method. Important to note is that since individual research work done by others has unique properties, distinct needs, and distinct production at the load side etc., there is no common solution as each situation has unique consideration. The proposed method for this work has also been discussed extensively. This has been presented by introducing the components required for the RE supported by the HESS. Since the use of software simulations is adopted in this work, the problem to be solved has been formulated by equations and diagrams to be computed by the software. A framework that will govern the methodological approach of solving the research problem has been presented.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.0 Introduction

Here, we look at the results for the three cases that have been simulated. In case one the supercapacitor is used as storage, whereby it is linked to the solar PV grid system by means of DC to DC power converters. In case two, the lead acid batteries only are used as storage where they are linked to the DC bus without an interface device. Lastly for case three, combination of the supercapacitors and the lead acid batteries are used as storage to complement each other. Case three was of utmost importance as it is the subject matter of the study where the hybrid storage of the battery and supercapacitors is compared against the single unit storage devices.

4.1 Solar PV

A 9 kW Solar PV system parameters in Table 3.1 were simulated using MATLAB Simulink. This was the sole purpose of developing a renewable energy source to be dispatched to the grid. The Kyocera solar PV modules were used in this simulation. Further to it, unidirectional power converters and energy control mechanism have been modelled and displayed during the simulation process.

A model presented in Figure 4.1 from the MATLAB 2022a illustrate the power dispatched from the solar PV to the grid with the backup of energy storage back up from the lead acid battery and supercapacitors. From the model, the power output from the solar PV has been measured when there are high and low irradiances from the solar. During high irradiance, the supply to the grid is from the PV and energy storage banks are on standby mode. Whilst during periods of low irradiance signifying shedding of the solar PV modules, the hybridized storage banks in: (i) lead acid battery and (ii) supercapacitors are “kicked–in” and provide support to the solar PV by providing power momentarily to the grid.

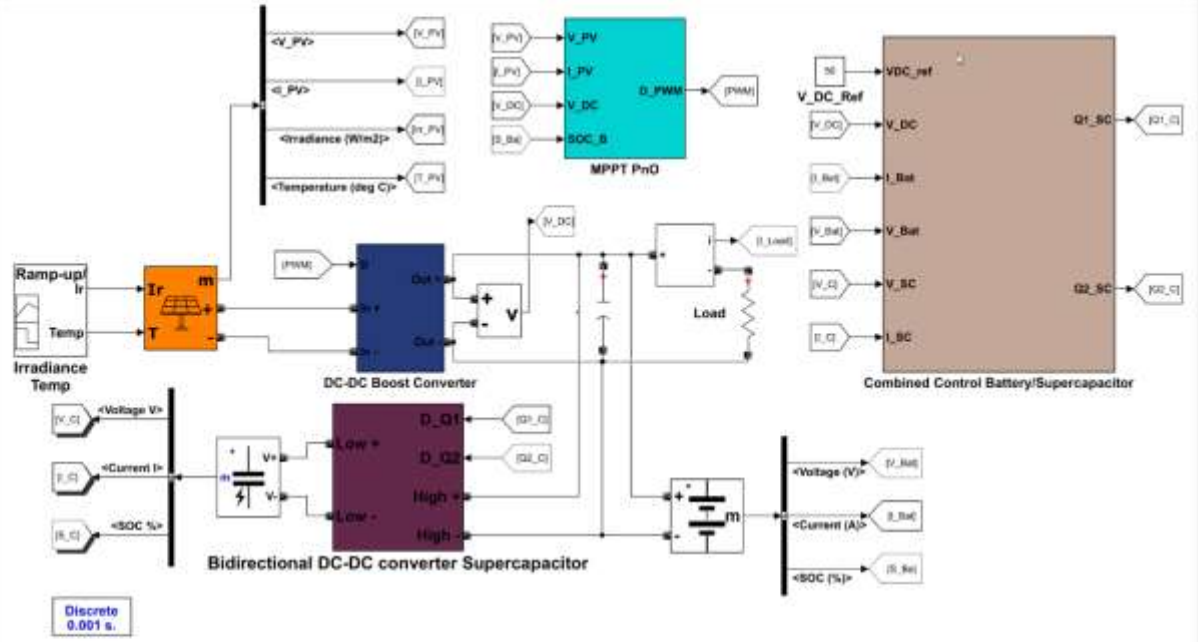

Figure 4. 1: MATLAB 2022a Model for Solar PV and Energy Storage Banks

The graph in Figure 4.1.1 shows the characteristics of the Solar PV (Kyocera Solar KD320GX-LFB) without the energy storage systems. The simulation of the solar irradiances at 1.25 kW/m^2, 1 kW/m^{22}, 0.35 kW/m^2, 0.1 kW/m^2 was carried out to investigate the power output of the various solar insolation. It was observed that below the 1kW/m^2 of the given irradiances, the power production from the solar PV is below the designed output of the solar PV system. A reduction of the solar irradiance shows the variability nature of the solar PV source, which is a power deficit that needs to be compensated by the HESS banks.

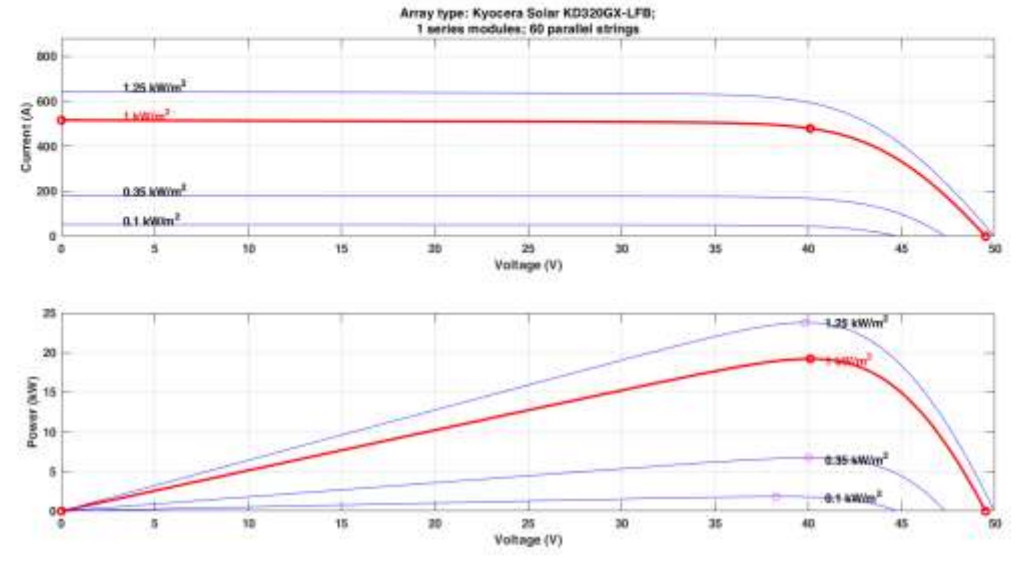

Figure 4.1. 1: Solar PV Characteristics

4.2 Battery Energy Storage System (BESS)

The parameters presented in Table 3.2 simulated the power flow of BESS. The aim was to investigate the effect of having the power backup from the battery bank to the power generation system. This was done by use of the MATLAB Simulink to illustrate the battery performance by displaying power profile characteristics dispatched from the lead acid battery banks in a given time (t) in seconds.

Figures 4.2.1, 4.2.2 and 4.2.4 presents the current, voltage, and power characteristics of the battery when used singularly in the RES power backup. It was observed that power is zero initially until at a time t = 300 s when the power P rises at approx. 7.5 kW. Power drop is observed between time t = 400 s to 600 s before a rise of approx. 10 kW. This signifies when the battery is discharging at its maximum during time t = 300 s and t = 600 s. Figure 4.2.3 illustrates the SoC of the battery is at instances of charging and discharge phases. The SoC is observed to rise when the battery power falls and vice versa. Hence, the lead acid battery is discharging to the power network as expected from theoretical literature. On the other hand, when the SoC drops at its low of 64% the battery is expected to be undergo the charging process. Assumption made is that there are no transmission losses for the battery.

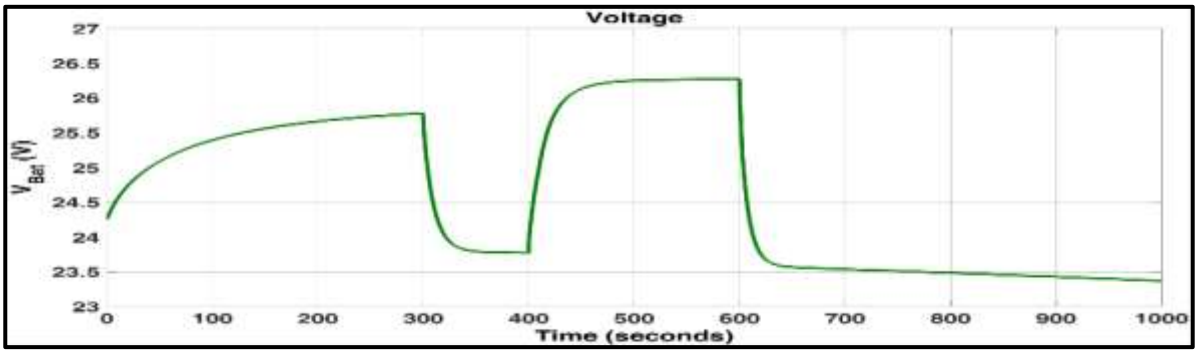

Figure 4.2. 1: Graph of Voltage (V) against Time (sec) for BESS

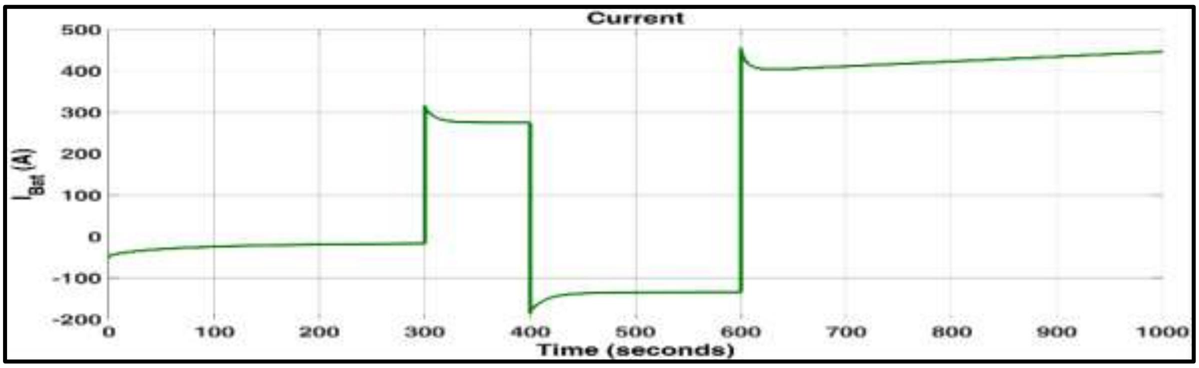

Figure 4.2. 2: Graph of Current (I) against Time (sec) for BESS

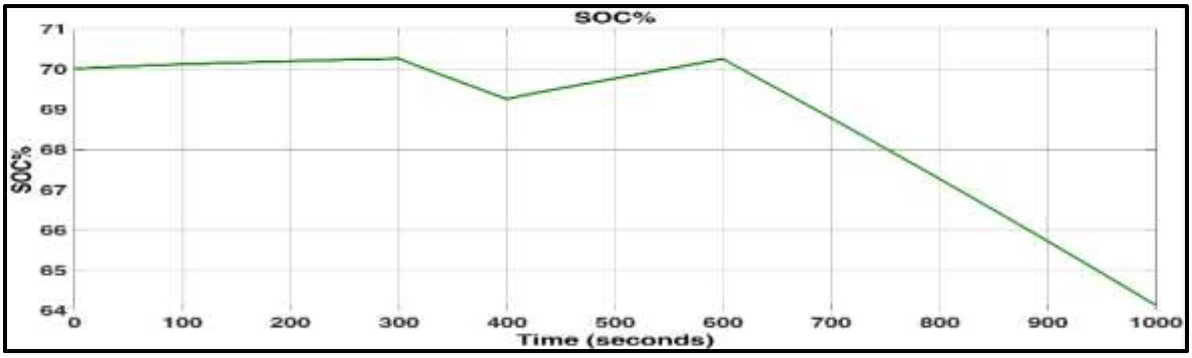

Figure 4.2. 3: Graph of SoC % against Time (sec) for BESS

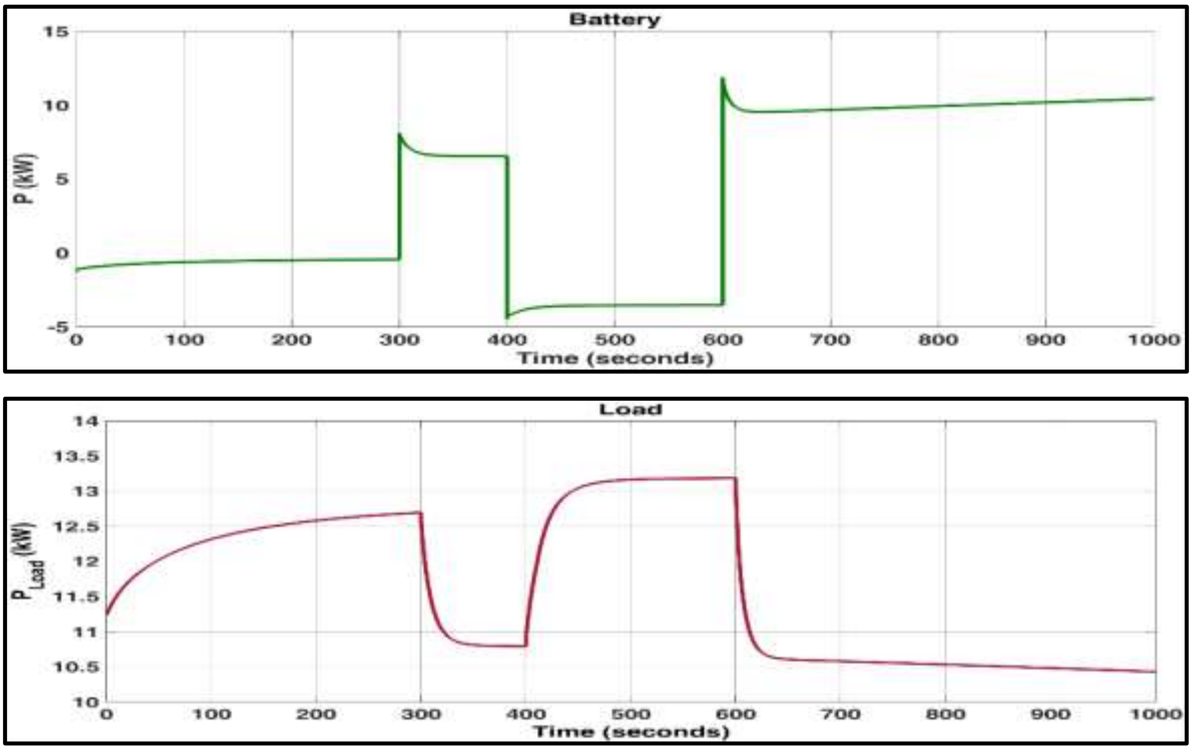

Figure 4.2. 4: Graph of Power (P) against Time (sec) for BESS

4.3 Supercapacitor Energy Storage System (SESS)

Similarly, parameters presented in Table 3.3 simulated the power flow characteristics of SESS. The aim was to investigate the effect of having the power back up from the supercapacitor bank to the power generation system. Figures 4.3.1, 4.3.2 and 4.3.4 presents the current, voltage, and power characteristics of the supercapacitor when used singularly in the RES power backup. The supercapacitor has its power peaks at P = 7 kW and 10 kW for time t = 300s and 600s respectively, but, this is for a very short time as the graph drops rapidly as these peaks are reached. This explains the inherent characteristic of the supercapacitor of attaining high power but for a short period. On the load side, the power output is approx. 20 kW. From the graph in Figure 4.3.3, the SoC of the supercapacitor shows it is at its maximum when it is fully charged up then falls as the supercapacitor discharges. The cyclic nature of the supercapacitor is exhibited by the rapid charging and discharging in short spells thereby discharging all the energy for the subsequent cycles.

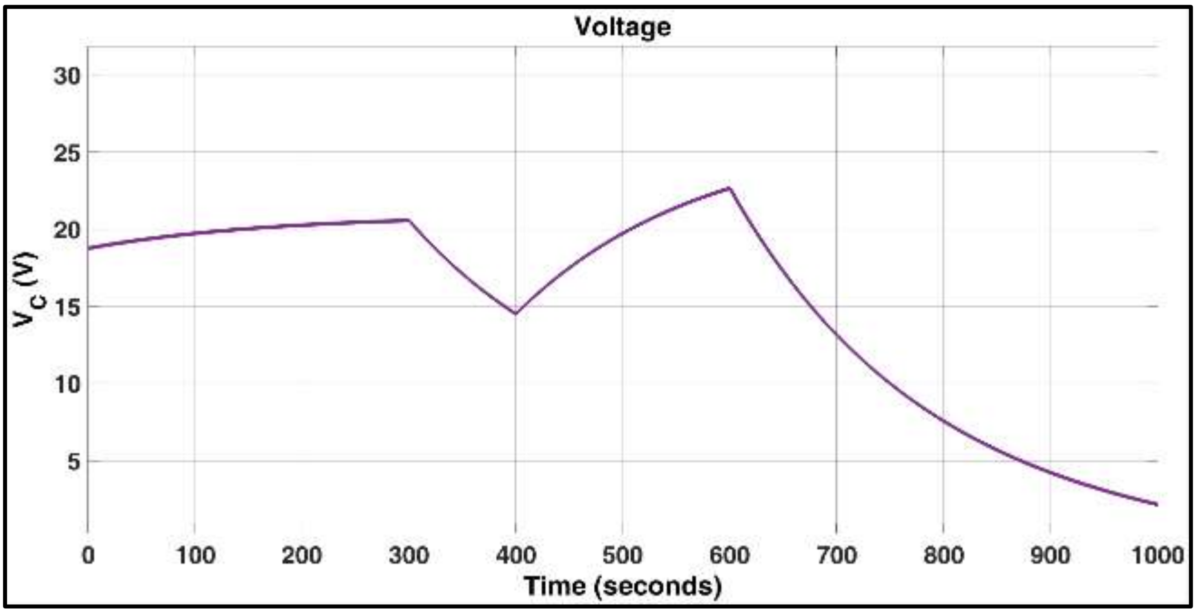

Figure 4.3. 1: Graph of Voltage against Time (sec) for SESS

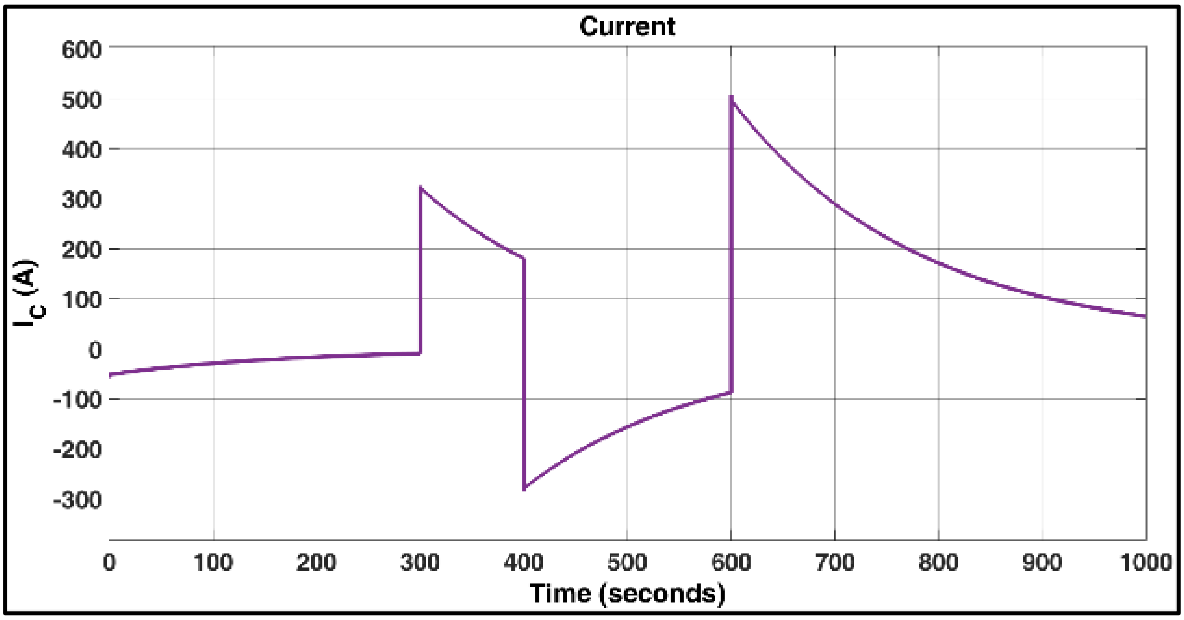

Figure 4.3. 2: Graph of Current (I) against Time (sec) for SESS

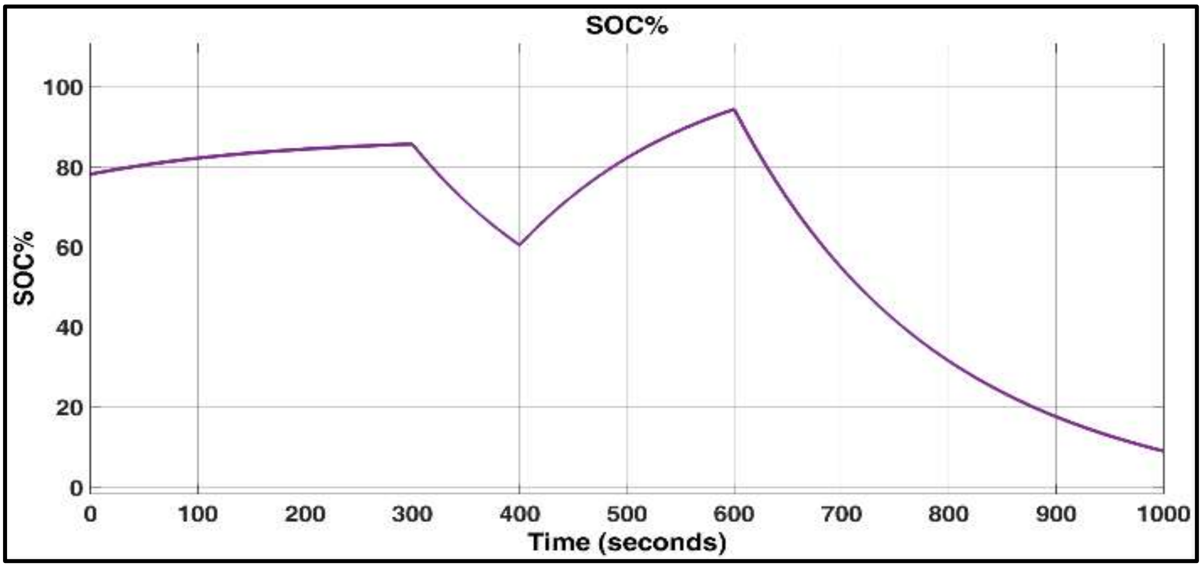

Figure 4.3. 3: Graph of SoC % against Time (sec) for SESS

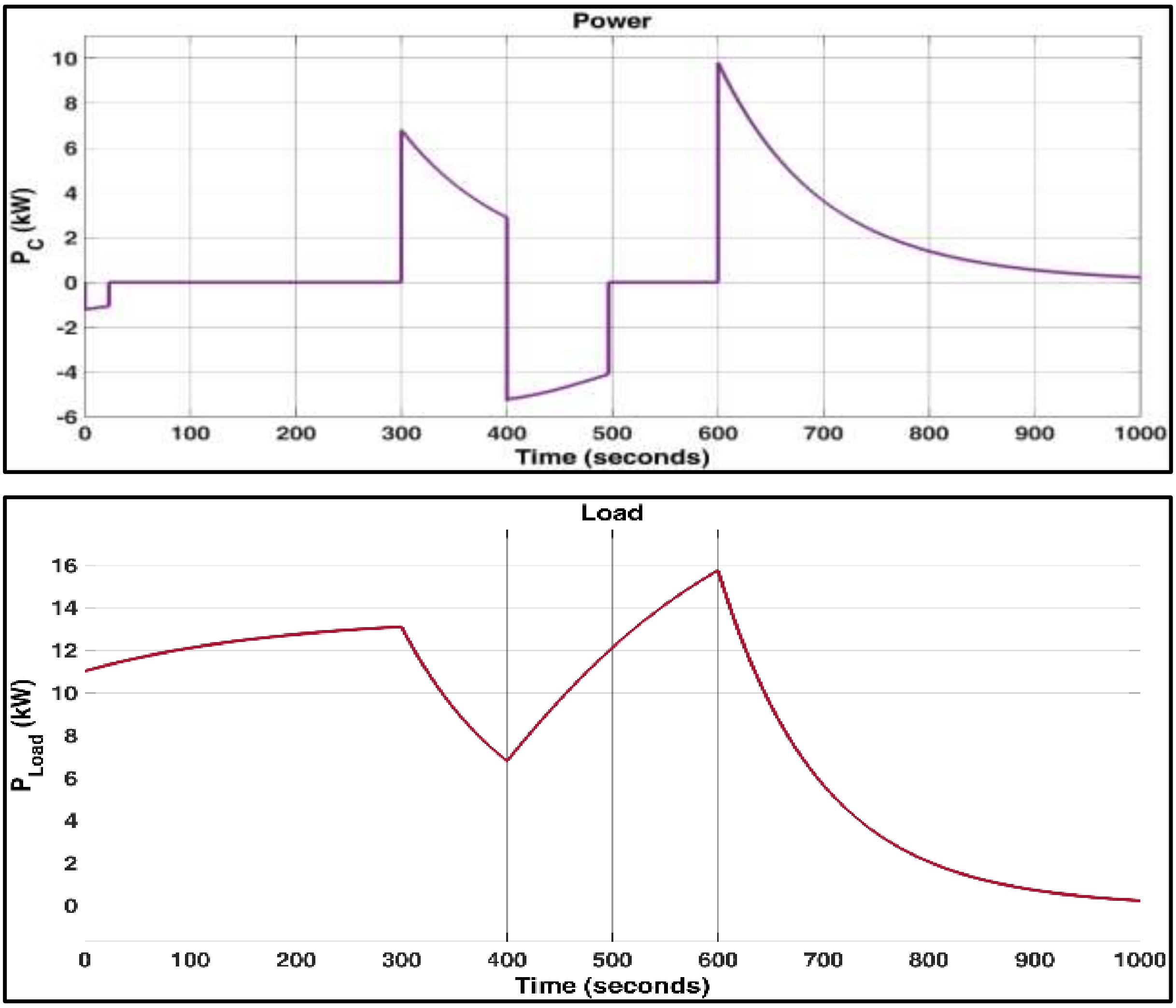

Figure 4.3. 4: Graph of Power (P) against Time (sec) for SESS

4.4 Hybrid Energy Storage System – PbA and SC

Finally, analysis is done for the HESS comprising of the lead acid battery and supercapacitor that is the core study for this work. Figures 4.4.1 and 4.4.2 reflects the currents and voltages for the two ESSs respectively when coupled for the hybrid power network. Comparing Figure 4.4.1 and 4.4.2 with the single ESSs currents and voltages, there is significant improvement on the performances of these devices when coupled. This is also reflected in Figure 4.4.4 that shows the power profile of the PV incorporated with the coupled energy storage devices. From the Figure 4.4.4, the solar PV provides power to the load between 0 to 300 s. This change at two instances when there is drop of solar PV, that is, period between 300s to 400 and 600s to 1000s respectively. The power injected into the network is from the HESS devices. This is portrayed in Figure 4.4.4 that shows how the battery power represented by the green colour outstrips the SC represented by the purple colour. At this point in the absence of solar PV, the HESS sustains the load (4.4.4). The battery storage shows resilience as it sustains power delivery at longer duration compared to the SC. The supercapacitor on the other hand only picks power momentarily before it quickly undergoes the cyclic process of charging and discharging phases. This explains the point that the battery storage is good in high energy for longer duration as opposed to the SC that fairs better in short time intervals.

The combined SoC of the coupled ESSs is in better status than when the ESS are single as shown in Figure 4.4.3. Since the SC resonates at 94% -100% of SoC, the quick charge/discharge of SC provides oscillatory power to the power system and at the same time improve the run time of the battery. The lowest value for SoC of the battery was at 65%, which agreed with universally accepted value of the SoC not dropping beyond 50%. This study postulates that using a semi-active coupling topology for the HESS devices, a good performance of the HESS is achieved.

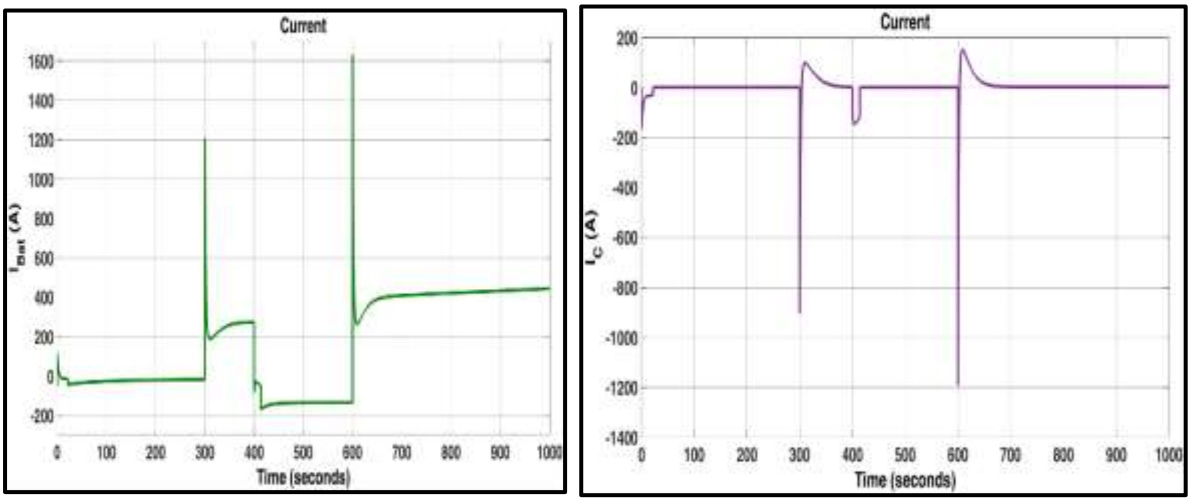

Figure 4.4. 1: Graphs of Current (I) against Time (sec) for Batt and SESS in HESS

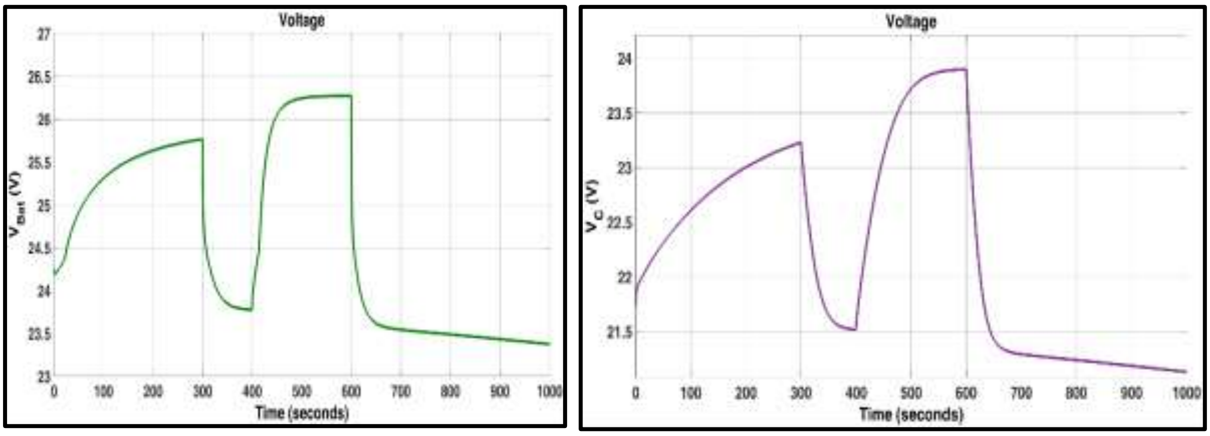

Figure 4.4. 2: Graphs of Voltage (V) against Time (sec) for BATT and SC in HESS

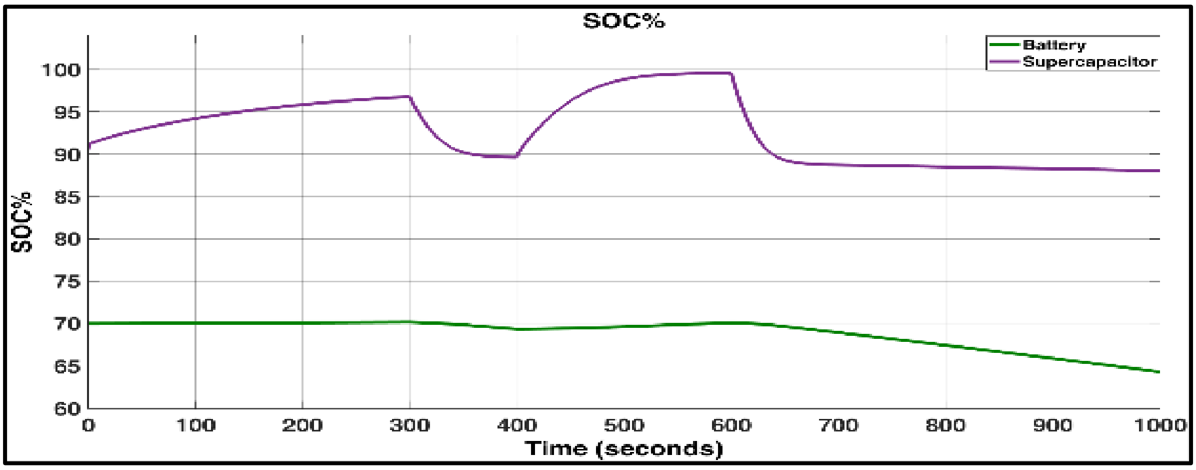

Figure 4.4. 3: Graph of SoC % against Time (sec) for HESS

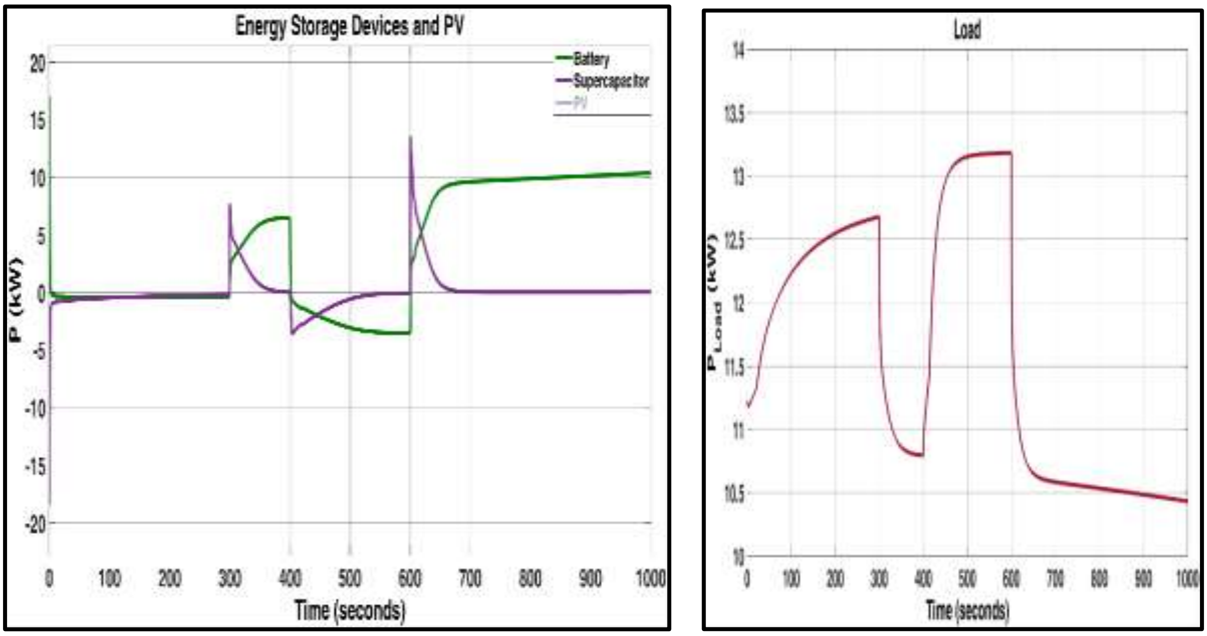

Figure 4.4. 4: Graphs of Power (P) against Time (sec) without load and with load for HESS

4.5 Validation

4.5.1 HESS and Single Storages Capacities

To validate this work, comparison between the HESS and the single ESSs performance is presented in Table 4.1 for the power output and for the energy delivered respectively. The energy in kWh for the ESSs has been computed from the graphs using the MATLAB Simulink software. From Table 4.1 it is observed that when HESS is available the SoC of the SC improves against when the SC is in the singular ESS. When single, the SC minimum status of the SoC is 20% against that of HESS, which is at minimum at 96%. At the same time, comparing the single ESSs, the SC has a larger power capacity than the battery source. It is a logical representation in actual practice where the SC has good power storage capacity while the battery has high-energy storage capacity. Contrarily, the battery has a larger energy capacity than the SC. Further comparison of the two ESSs against HESS shows that the total power of the former when on load is approximately 29.2 kW (13.2 + 16) which is above the HESS power of 13.2 kW. Similarly, the total energy of the two ESSs is computed at 5.597 kWh that is 1.75 times that of the HESS at 3.197 kWh. These readings shows that when the single ESSs are used, more power and energy are used which may result to more costs of devices and energy utilization. The HESS on the other hand utilizes less power and energy signifying economic advantage of one HESS component against two single ESSs.

Table 4. 1: Comparison of Single ESSs against HESS

	Power (kW)		**Energy (kWh)**		**SoC %**
Single ESS	**No Load**	**With Load**	**No Load**	**With Load**	
Battery	12	13.2	1.043	3.23	64 - 70
Supercapacitor	14	16	0.2679	2.367	20 - 100
HESS (PbA+SC)					
Battery	10	13.2	1.021	3.197	64 - 70
Supercapacitor	14		0.01989		96 - 100

4.5.2 HESS and other Hybrids

Comparison between HESS for this study and the study by Thilo Bocklisch in [20] is made. In [20] the findings given of interest to this study are the energy storage for HESS comprising of redox flow battery (long-term storage) and supercapacitor (short-term storage). The HESS in [20] has a greater storage capacity as compared to the HESS in this study. This could be due to redox flow battery having superior properties than lead acid battery. Further, the SoC for this study comparatively matches the findings in [20]. These findings are mentioned in Table 4.2.

Table 4. 2: Comparison of HESS with other Hybrids

Ref	**Type of Storage**	**Power (kW)**	**Energy (kWh)**	**SoC %**
[20]	**HESS (redox flow+SC)**			
	Redox flow battery	-	10	50 -80
	Supercapacitor	-	0.2	20-100
This study	**HESS (PbA+SC)**			
	Battery	10	1.021	64 - 70
	Supercapacitor	14	0.01989	96 - 100

4.6 Chapter Conclusion

The results and analysis for the simulations of the energy storages has been discussed in this chapter. The simulations for the solar PV, battery and the supercapacitor were done using the parameters presented in Chapter 3. The performance of the power delivered by the RES network when single ESSs are integrated in the system has been analysed against the ESS when paired. The results have demonstrated that the battery storage shows resilience as it sustains power delivery at longer duration. On the other hand, the supercapacitor has sharp power peaks momentarily before the later drops after a short time as it undergoes the cyclic process of charging and discharging phases. The outcome of this simulation has underscored the fact that battery energy storage devices are good choice for the long-term duration while the supercapacitor storage devices perform better for short-term durations.

CHAPTER FIVE

CONCLUSION & RECOMMENDATIONS

5.1 Conclusion

First, report began by mentioning few sources of the RE such as hydro, wind, solar and geothermal. However, vulnerability of the weather conditions has had hydro usage not attractive against the increasing popular solar PV source that is readily available in nature. The problem with this RES source was identified as being intermittent in nature thus causing a problem to the generation of power. Traditionally, energy storages have been long in usage but this too has its share of disadvantages, as they cannot reliably sustain power when required. This work therefore has mitigated this issue by hybridizing the energy schemes for integration to a renewable energy system network. Through a series of research questionnaire, the objectives of the study were mooted as well as why it was justified to carry out the research.

Secondly, literature review of researches who have attempted to carry out similar work was discussed as well as the strengths and existing gaps on their work. A background check of the existing energy technologies was done and suitable pairing of the later was identified for implementation in this research work. A hybrid of lead acid battery and supercapacitors was chosen as good pair for HESS technology.

Thirdly, the report highlighted the available methods to carry out the research work by first exploring the available methods. The method used in this work was presented and a design of the HESS system presented. Since the research was to be analysed through software simulations, a proper design was formulated for the systems ready for modelling in the MATLAB software.

Lastly, the analysis of the parameters for the ESSs were done by (i) simulating the battery alone, (ii) simulating the supercapacitor alone and (iii) simulating the paired ESS (hybrid). The results largely agreed with the expectation that the HESS system performs better that individual ESS. From the results, the energy delivered to the load by HESS was 3.197 kWh while the battery and SC alone delivered 3.23 kWh and 2.367 kWh respectively.

The study was largely a success as it achieved its intended objectives of modelling and simulating solar PV source with hybrid energy storages to attain continuous flow of power during periods of low production from the solar PV.

5.2 Contribution

Three scenarios were presented in the cause of the research work. Case 1 was to simulate solar PV with the singular battery storage. Case 2 was simulated solar PV with the singular supercapacitor storage and case 3 had the paired energy storages with the solar PV. The study successfully demonstrated that for the choice of semi-active coupling topology for the HESS components, availability of continuous power would be achieved at the demand side. This signifies that having one power converter to the ESS will reduce cost of the system and the power losses, thus, responding to the old adage of cost verses technology.

5.3 Recommendations of Further Work

This study has provided opportunities for future researchers to work on:

(i) For instance, this work considered that the solar PV with HESS backup deliver power to a constant load. The recommendation therefore is for future research work to consider the aspect of having a varying load to HESS coupled system.

(ii) Due to the technological advancement on energy storage devices, more research work is recommended on the type of supercapacitors used for HESS coupling. This work considered electrochemical double layer capacitors (ELDC) hence more openings for research may be explored for other types of SC used for HESS.

(iii) Periodic time for simulations for dispatching solar PV and ESSs power may also be recommended for further investigations on the effect of HESS.

(iv) It is further recommended for more study on the temperature impact on the optimal working of the energy schemes. This study only considered the temperature control for the solar PV but made assumptions that the ESS are operating at a standard operating conditions.

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APPENDICES

Appendix 1: Kyocera Solar Panel Specifications

KYOCERA

KD 150 F GX Series

KD150GX-LFU

CUTTING EDGE TECHNOLOGY

As a pioneer with four decades of experience in the development of photovoltaic systems, Kyocera drives the market as a leading provider of PV products. We demonstrate our *Kaizen* philosophy, or commitment to continuous improvement, by setting the industry standard in the innovation of best-in-class solar energy equipment.

QUALITY BUILT IN

- UV-stabilized, anodized aluminum frame in black
- Supported by major mounting structure manufacturers
- Easily accessible grounding points on all four corners for fast installation

PROVEN RELIABILITY

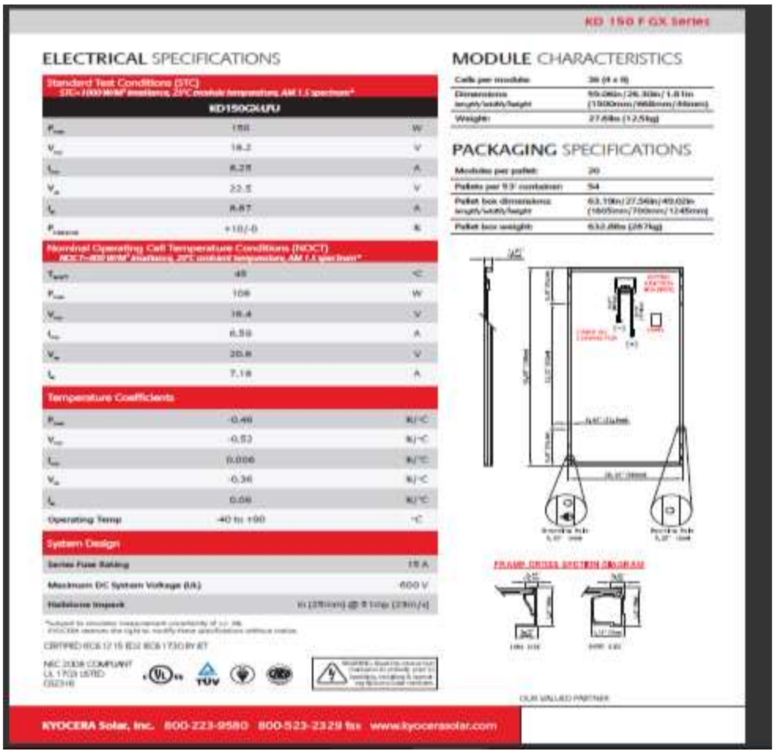
- Kyocera modules confirmed by the Desert Knowledge Australia Solar Centre to have the highest average output of any crystalline module
- First module manufacturer in the world to pass long-term sequential testing performed by TÜV Rheinland
- This series construction also passed TÜV Rheinland's Salt Mist Corrosion Test at Severity Level 6, the most intense test conditions available
- Only module manufacturer to achieve the rank of "Performance Leader" in all six categories of GTM Research's 2014 PV Module Reliability Scorecard

CERTIFICATIONS

- UL1703 Certified and Registered, UL Fire Safety Class C
- Applicable to hazardous location, Class I Div. II
- NEC2008 Compliant, IEC 61215/61730, and ISO 14001
- IEC61701 Ed.2 Severity 6 (Salt Mist Corrosion Test)

HIGH EFFICIENCY MULTICRYSTAL PHOTOVOLTAIC MODULE

SOLAR by KYOCERA



KD 150 F GX Series

ELECTRICAL SPECIFICATIONS

Standard Test Conditions (STC) STC=1000 W/m² irradiance, 25°C module temperature, AM 1.5 spectrum*	KD150GX-LFU	
P_{max}	150	W
V_{mpp}	18.2	V
I_{mpp}	8.25	A
V_{oc}	22.5	V
I_{sc}	8.87	A
$P_{tolerance}$	+10/-0	%
Nominal Operating Cell Temperature Conditions (NOCT) NOCT=800 W/m² irradiance, 20°C ambient temperature, AM 1.5 spectrum*		
T_{NOCT}	45	°C
P_{max}	108	W
V_{mpp}	16.4	V
I_{mpp}	6.59	A
V_{oc}	20.6	V
I_{sc}	7.18	A
Temperature Coefficients		
P_{max}	-0.46	%/°C
V_{mpp}	-0.52	%/°C
I_{mpp}	0.006	%/°C
V_{oc}	-0.36	%/°C
I_{sc}	0.06	%/°C
Operating Temp	-40 to +90	°C
System Design		
Series Fuse Rating		15 A
Maximum DC System Voltage (UL)		600 V
Hailstone Impact		1 in (25mm) @ 51mph (23m/s)

*Subject to simulator measurement uncertainty of +/- 3%.
KYOCERA reserves the right to modify these specifications without notice.

CERTIFIED IEC61215 ED2 IEC61730 BY ET

NEC 2008 COMPLIANT
UL 1703 LISTED
[illegible]

MODULE CHARACTERISTICS

Cells per module:	36 (4 x 9)
Dimensions length/width/height	59.06in/26.30in/1.81in (1500mm/668mm/46mm)
Weight:	27.6lbs (12.5kg)

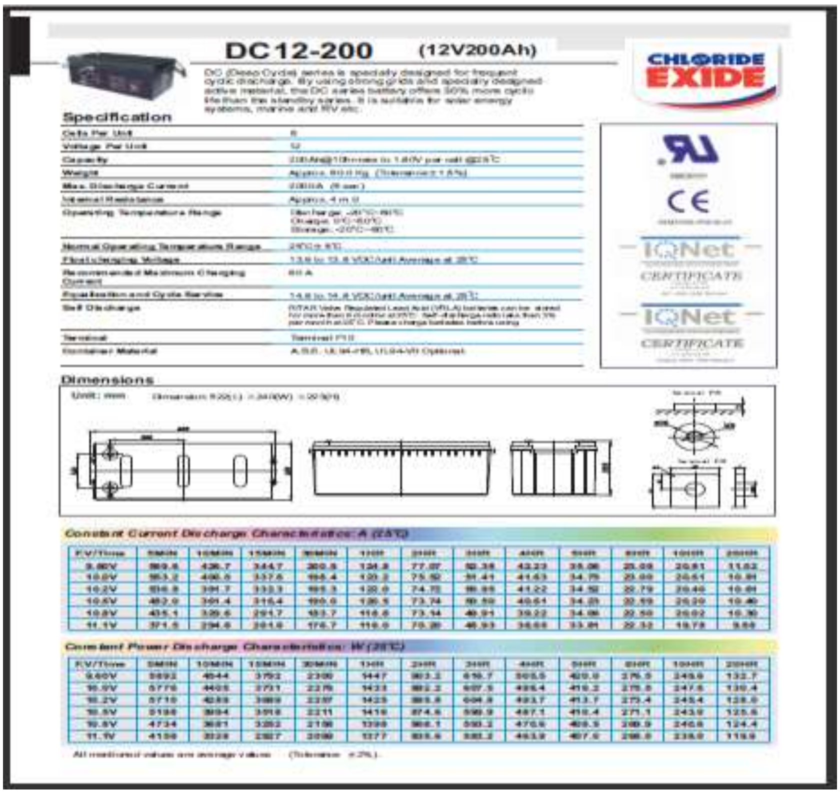
PACKAGING SPECIFICATIONS

Modules per pallet:	20
Pallets per 53' container:	54
Pallet box dimensions length/width/height	63.19in/27.56in/49.02in (1605mm/700mm/1245mm)
Pallet box weight:	632.8lbs (287kg)

OUR VALUED PARTNER

KYOCERA Solar, Inc. 800-223-9580 800-523-2329 fax www.kyocerasolar.com

Appendix 2: Chloride Exide Specifications



DC12-200 (12V200Ah)

DC (Deep Cycle) series is specially designed for frequent cyclic discharge. By using strong grids and specially designed active material, the DC series battery offers 30% more cyclic life than the standby series. It is suitable for solar energy systems, marine and RV etc.

Specification

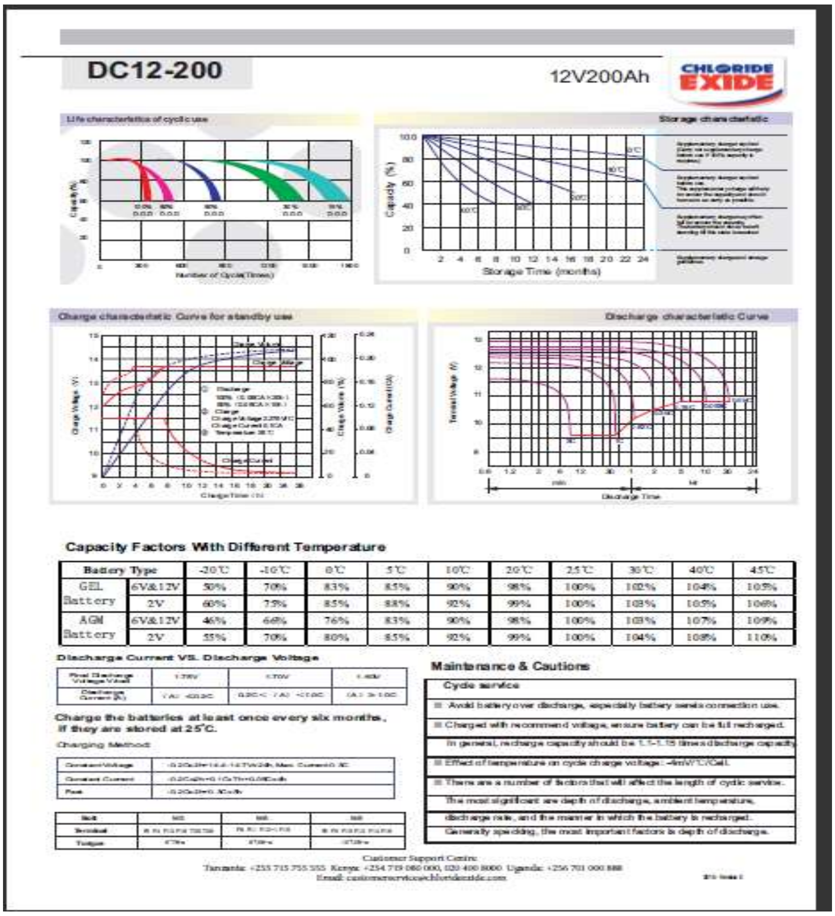
Cells Per Unit	6
Voltage Per Unit	12
Capacity	200Ah@10hr-rate to 1.80V per cell @25°C
Weight	[illegible]
Max. Discharge Current	[illegible]
Internal Resistance	Approx. 4 mΩ
Operating Temperature Range	[illegible]
Normal Operating Temperature Range	[illegible]
Float charging Voltage	[illegible]
Recommended Maximum Charging Current	[illegible]
Equalization and Cycle Service	[illegible]
Self Discharge	[illegible]
Terminal	[illegible]
Container Material	[illegible]

Dimensions

Unit: mm

Constant Current Discharge Characteristics: A (25°C)

Constant Power Discharge Characteristics: W (25°C)



DC12-200

12V200Ah

Capacity Factors With Different Temperature

Battery Type		-20°C	-10°C	0°C	5°C	10°C	20°C	25°C	30°C	40°C	45°C
GEL Battery	6V&12V	50%	70%	83%	85%	90%	98%	100%	102%	104%	105%
	2V	60%	75%	85%	88%	92%	99%	100%	103%	105%	106%
AGM Battery	6V&12V	46%	66%	76%	83%	90%	98%	100%	103%	107%	109%
	2V	55%	70%	80%	85%	92%	99%	100%	104%	108%	110%

Discharge Current VS. Discharge Voltage

Charge the batteries at least once every six months, if they are stored at 25°C.

Charging Method:

Maintenance & Cautions

Cycle service
Avoid battery over discharge, especially battery series connection use.
Charged with recommend voltage, ensure battery can be full recharged.
In general, recharge capacity should be 1.1-1.15 times discharge capacity
Effect of temperature on cycle charge voltage: -4mV/°C/Cell.
There are a number of factors that will affect the length of cyclic service.
The most significant are depth of discharge, ambient temperature,
discharge rate, and the manner in which the battery is recharged.
Generally speaking, the most important factors is depth of discharge.

Customer Support Centre
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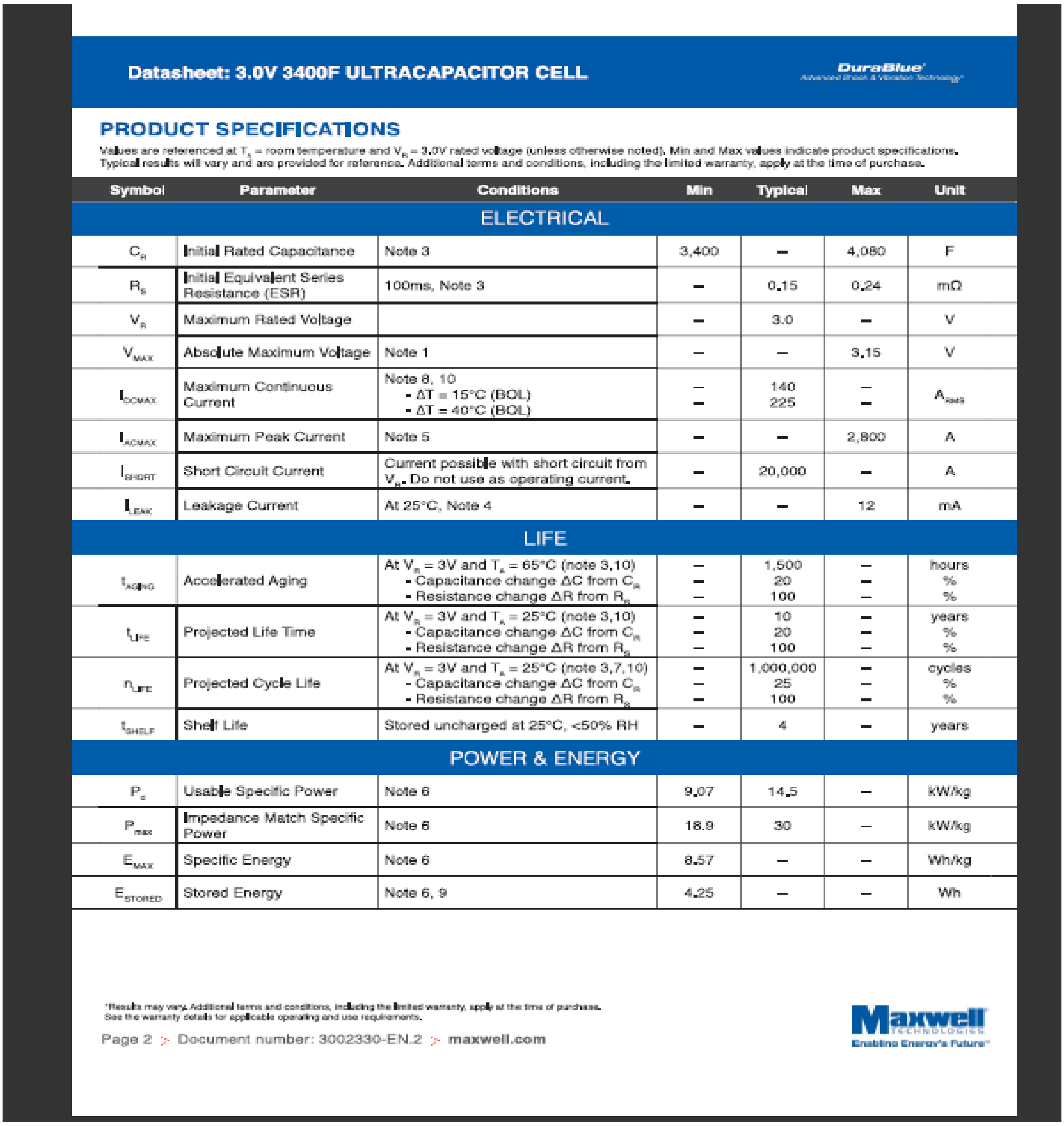
Email: customerservice@chlorideexide.com

Appendix 3: Supercapacitor Specifications



Datasheet: 3.0V 3400F ULTRACAPACITOR CELL

DuraBlue®
Advanced Shock & Vibration Technology®

PRODUCT SPECIFICATIONS

Values are referenced at T_A = room temperature and V_R = 3.0V rated voltage (unless otherwise noted). Min and Max values indicate product specifications. Typical results will vary and are provided for reference. Additional terms and conditions, including the limited warranty, apply at the time of purchase.

Symbol	Parameter	Conditions	Min	Typical	Max	Unit
		ELECTRICAL				
C_R	Initial Rated Capacitance	Note 3	3,400	–	4,080	F
R_S	Initial Equivalent Series Resistance (ESR)	100ms, Note 3	–	0.15	0.24	mΩ
V_R	Maximum Rated Voltage		–	3.0	–	V
V_{MAX}	Absolute Maximum Voltage	Note 1	–	–	3.15	V
I_{DCMAX}	Maximum Continuous Current	Note 8, 10 - ΔT = 15°C (BOL) - ΔT = 40°C (BOL)	– –	140 225	– –	A_{RMS}
I_{ACMAX}	Maximum Peak Current	Note 5	–	–	2,800	A
I_{SHORT}	Short Circuit Current	Current possible with short circuit from V_R. Do not use as operating current.	–	20,000	–	A
I_{LEAK}	Leakage Current	At 25°C, Note 4	–	–	12	mA
		LIFE				
t_{AGING}	Accelerated Aging	At V_R = 3V and T_A = 65°C (note 3,10) - Capacitance change ΔC from C_R - Resistance change ΔR from R_S	– – –	1,500 20 100	– – –	hours % %
t_{LIFE}	Projected Life Time	At V_R = 3V and T_A = 25°C (note 3,10) - Capacitance change ΔC from C_R - Resistance change ΔR from R_S	– – –	10 20 100	– – –	years % %
n_{LIFE}	Projected Cycle Life	At V_R = 3V and T_A = 25°C (note 3,7,10) - Capacitance change ΔC from C_R - Resistance change ΔR from R_S	– – –	1,000,000 25 100	– – –	cycles % %
t_{SHELF}	Shelf Life	Stored uncharged at 25°C, <50% RH	–	4	–	years
		POWER & ENERGY				
P_d	Usable Specific Power	Note 6	9.07	14.5	–	kW/kg
P_{max}	Impedance Match Specific Power	Note 6	18.9	30	–	kW/kg
E_{MAX}	Specific Energy	Note 6	8.57	–	–	Wh/kg
E_{STORED}	Stored Energy	Note 6, 9	4.25	–	–	Wh

*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.

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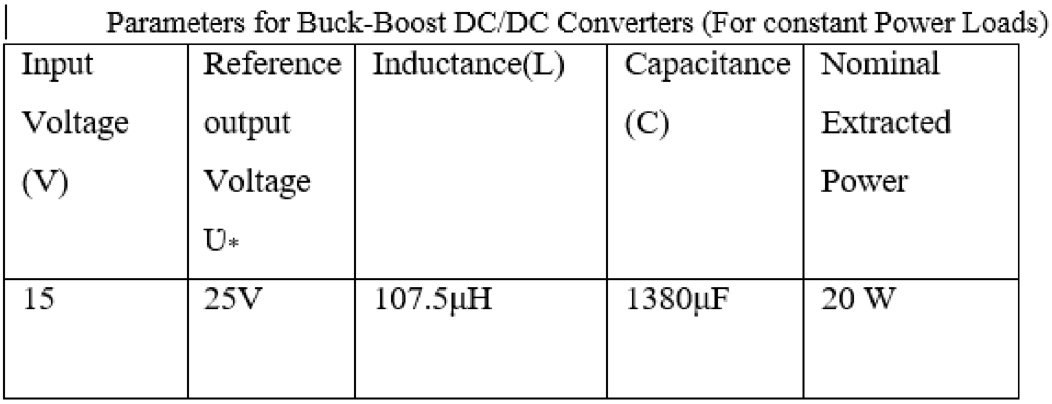
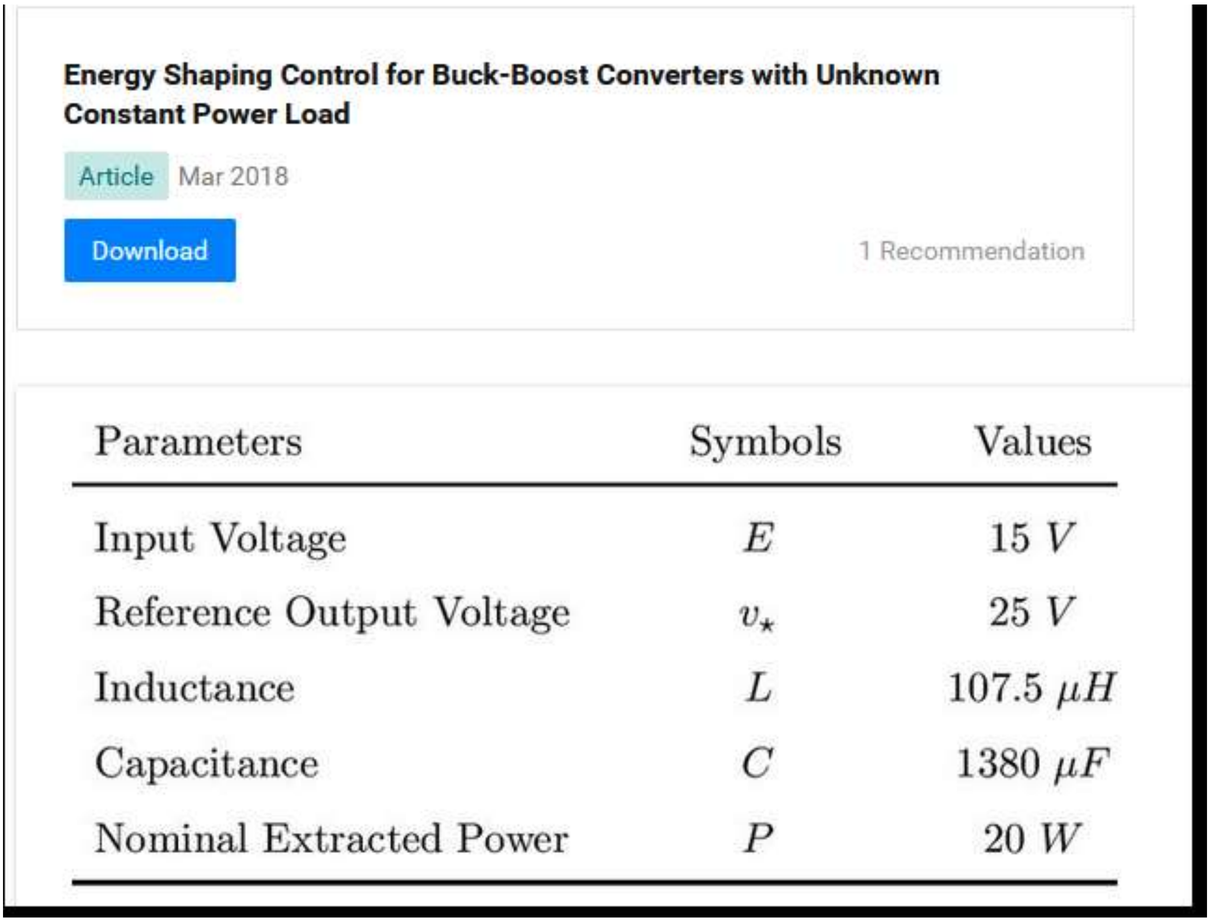
Appendix 4: Buck-Boost DC/DC Converters



Parameters for Buck-Boost DC/DC Converters (For constant Power Loads)

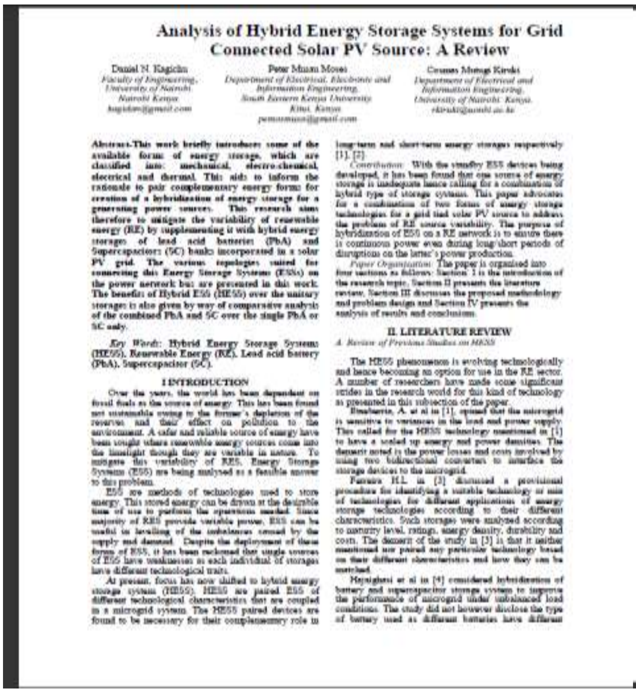
Input Voltage (V)	Reference output Voltage U*	Inductance(L)	Capacitance (C)	Nominal Extracted Power
15	25V	107.5µH	1380µF	20 W



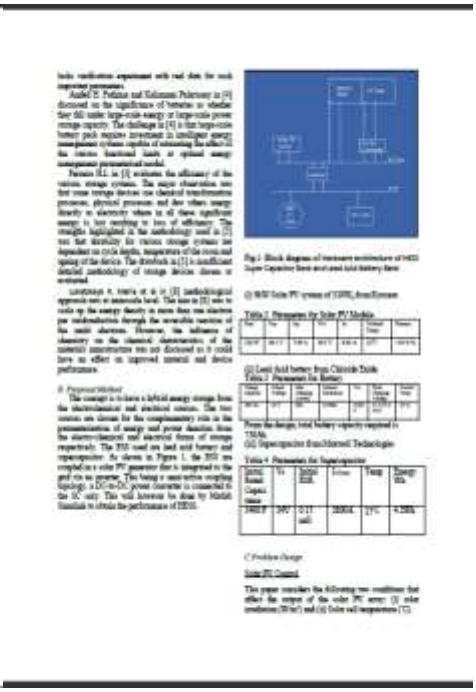
Energy Shaping Control for Buck-Boost Converters with Unknown Constant Power Load

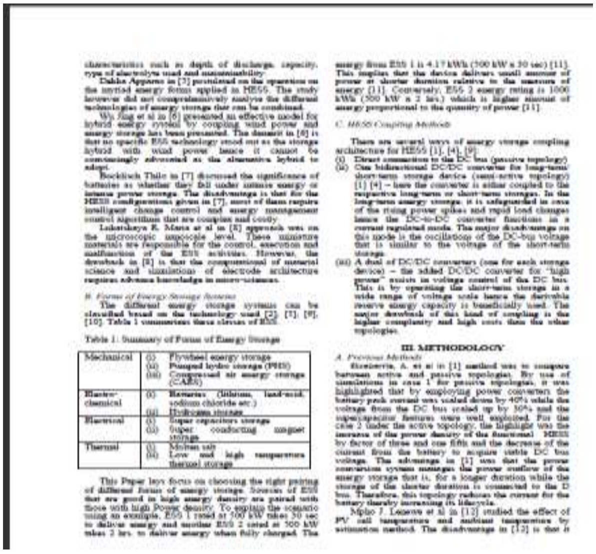
Parameters	Symbols	Values
Input Voltage	E	$15\ V$
Reference Output Voltage	$v_\star$	$25\ V$
Inductance	L	$107.5\ \mu H$
Capacitance	C	$1380\ \mu F$
Nominal Extracted Power	P	$20\ W$

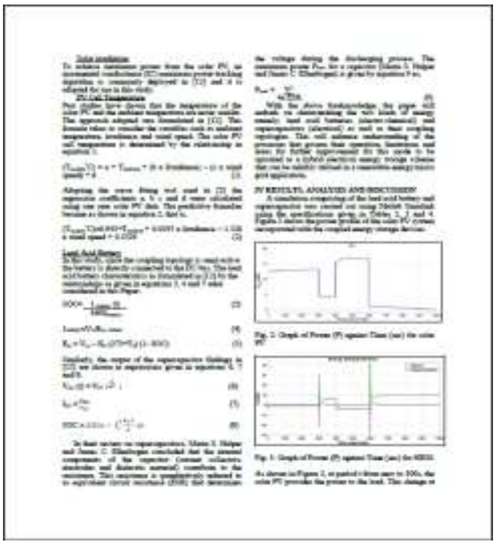
Appendix 5: Paper

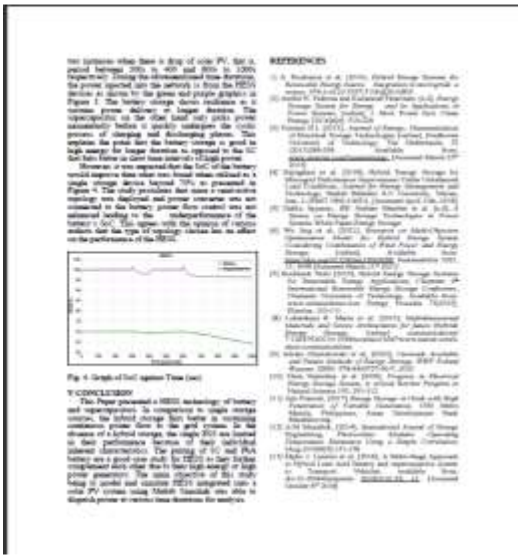


Analysis of Hybrid Energy Storage Systems for Grid Connected Solar PV Source: A Review



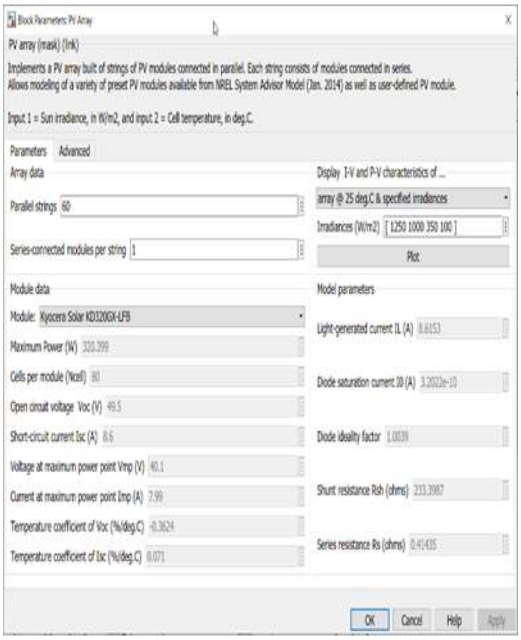






Appendix 6: Selected MATLAB Models & Parameters used

(i)Kyocera KD320GX-LFB



Block Parameters: PV Array

PV array (mask) (link)

Implements a PV array built of strings of PV modules connected in parallel. Each string consists of modules connected in series.
Allows modeling of a variety of preset PV modules available from NREL System Advisor Model (Jan. 2014) as well as user-defined PV module.

Input 1 = Sun irradiance, in W/m2, and input 2 = Cell temperature, in deg.C.

Parameters | Advanced

Array data

Parallel strings 60

Series-connected modules per string 1

Display I-V and P-V characteristics of ... array @ 25 deg.C & specified irradiances

Irradiances (W/m2) [1250 1000 350 100]

Module data

Module: Kyocera Solar KD320GX-LFB

Maximum Power (W) 320.399

Cells per module (Ncell) 80

Open circuit voltage Voc (V) 49.5

Short-circuit current Isc (A) 8.6

Voltage at maximum power point Vmp (V) 40.1

Current at maximum power point Imp (A) 7.99

Temperature coefficient of Voc (%/deg.C) -0.3624

Temperature coefficient of Isc (%/deg.C) 0.071

Model parameters

Light-generated current IL (A) 8.6153

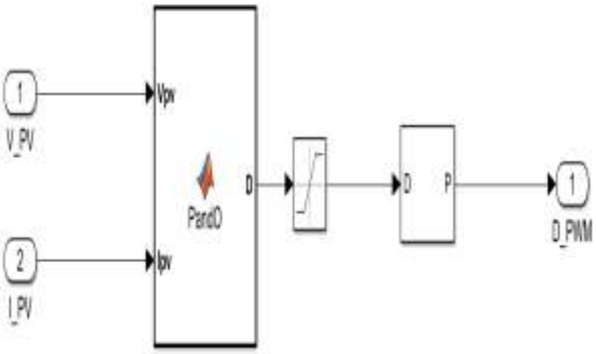
Diode saturation current I0 (A) 3.2022e-10

Diode ideality factor 1.0039

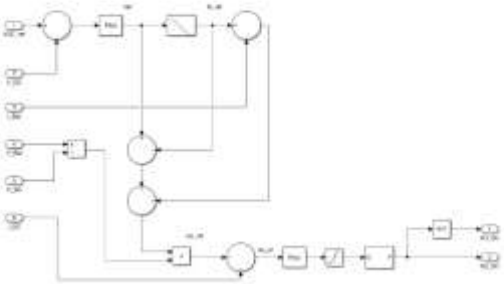
Shunt resistance Rsh (ohms) 233.3987

Series resistance Rs (ohms) 0.41435

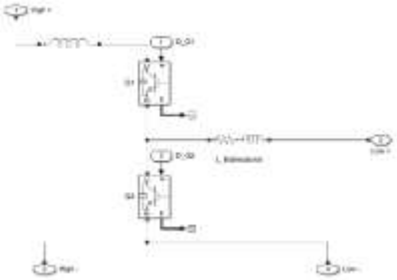
(ii)PV Array Converter Pulse Generator



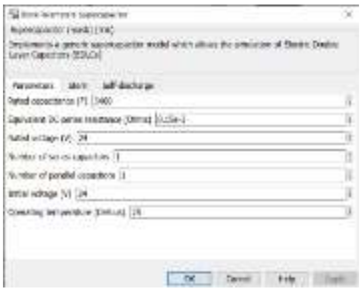
(iii)SC 1 DC/DC Converter



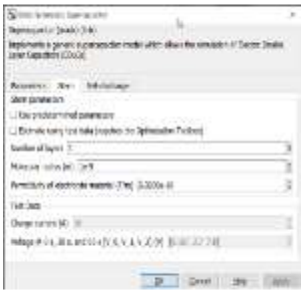
(iv)SC 2 DC/DC Converter



(v) SC 1 Parameters



SC 2 Parameters

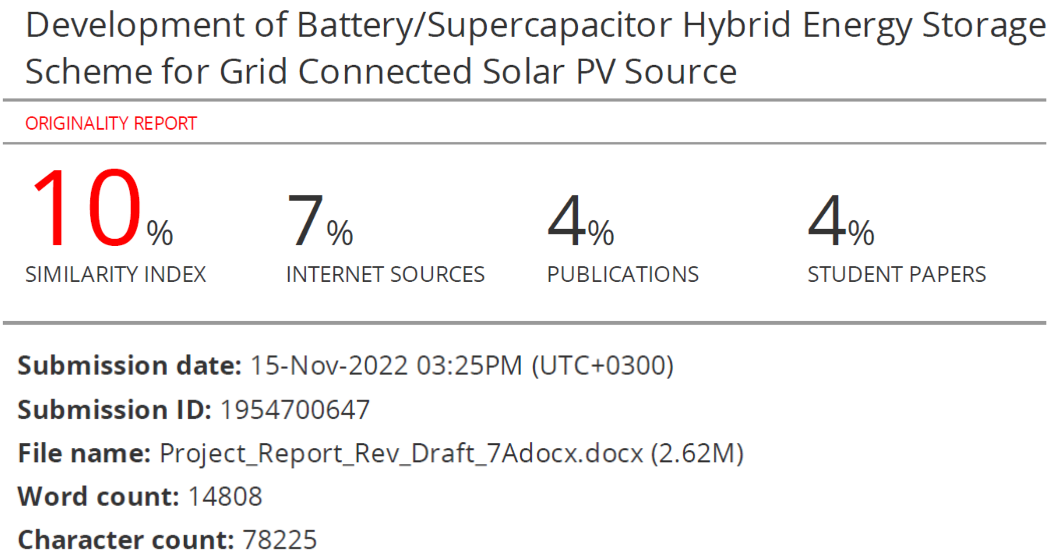


SC 3 Parameters

Appendix 7: Table of Corrections

Section/ Chapter	Comments from Panel	Corrective Actions
Project Title	To check on the title (to capture what is being hybridized),	Title changed to: **“Development of Battery/Supercapacitor Hybrid Energy Storage Scheme for Grid Connected Solar PV”.**
1.3.2	To consider re-writing objective no. (iii)	Re-written as To compare the economic value of HESS over that of single ESSs.
3.3.1	To check equation 3.1 in chapter 3	Details on the equation provided under the sub-section
3.4	To check on the conceptual framework Figure	Figure 3.4 revised
4.5.1	To re-frame the explanation on comparison of data of single ESS and HESS under the validation section	Wording on the explanation revised
5	To include the heading for Chapter Five	Heading given as: Conclusion & Recommendations
From chapters 2 to 4	Naming of Tables and Figures to rhyme with the chapter numbers.	Caption on Tables and Figures amended according to the Chapter numbers.

Appendix 8: TURNITIN Originality Report- Similarity Index



Development of Battery/Supercapacitor Hybrid Energy Storage Scheme for Grid Connected Solar PV Source

ORIGINALITY REPORT

10%	7%	4%	4%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

Submission date: 15-Nov-2022 03:25PM (UTC+0300)
Submission ID: 1954700647
File name: Project_Report_Rev_Draft_7Adocx.docx (2.62M)
Word count: 14808
Character count: 78225

Signed by:

Dr. Mutugi Kiruki

Date: 18/11/2022