Comparative Study of DC–DC Converters Performance for Standalone Solar Water Pumping Systems (Case Study: - Ciro Rural Community)

Takele Alemayehu Abebe
A Thesis Submitted to department of Electrical Power and Control Engineering
School of Electrical Engineering and Computing

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Electrical Power and Control Engineering (Specialization in Power Engineering)

Office of Graduate Studies

Adama Science and Technology University

August, 2024

Adama, Ethiopia

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Declaration

I hereby declare that this Master Thesis entitled "Comparative Study of DC–DC Converters Performance for Standalone Solar Water Pumping Systems (Case Study: - Ciro Rural Community)" is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

Name of student	Signature	Date

Recommendation of Advisor

I, the advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled “Comparative Study of DC–DC Converters Performance for Standalone Solar Water Pumping Systems (Case Study: - Ciro Rural Community)” prepared under my guidance by Takele Alemayehu submitted in partial fulfillment of the requirements for the degree of Mater’s of Science in Electrical Power and Control Engineering. Therefore, I/we recommend the submission of revised version of the thesis to the department following the applicable procedures.

________________________ ______________________ _______________

Advisor Signature Date

Approval Sheet

I, the advisor of the thesis entitled "Comparative Study of DC–DC Converters Performance for Standalone Solar Water Pumping Systems (Case Study: - Ciro Rural Community)" and developed by Takele Alemayehu. hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Advisor	Signature	Date

We, the undersigned, members of the Board of Examiners of the thesis by Takele Alemayehu have read and evaluated the thesis entitled "Comparative Study of DC–DC Converters Performance for Standalone Solar Water Pumping Systems (Case Study: - Ciro Rural Community)" and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Electrical Power and Control Engineering.

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Final approval and acceptance of the thesis is contingent upon submission of its final copy to the Office of Postgraduate Studies (OPGS) through the Department Graduate Council (DGC) and School Graduate Committee (SGC).

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Table of contents

LIST OF TABLES

List of Figures

List of Abbreviations

Symbols	Description
AC	Alternating Current
BLDC	Brushless Direct Current
CCM	Continuous Conduction Mode
DC	Direct Current
DCM	Discontinuous Conduction Mode
DGC	Department Graduate Council
DNI	Direct Normal Irradiance
FL-INC	Fuzzy Logic based Incremental
GHI	Global Horizontal Irradiance
GPV	Global Photovoltaic
ICEEE	International Conference on Electrical and Electronic Engineering
IEEE	Institute of Electrical and Electronics Engineers
IoT	Institute of Technology
ISCAS	International Symposium on Circuits and Systems
M-INC	Modified Incremental Conductance
MATLAB	Matrix Laboratory
MDPI	Multidisciplinary Digital Publishing Institute
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
OPGS	Office of Postgraduate Studies
PV	Photovoltaic
PID	Proportional Differential Integrator
PMDC	Permanent Magnet Direct Current
PWM	Pulse Width Modulation

SEPIC	Single Ended Primary Inductor Converter
SGC	School Graduate Committee
STC	Standard Test Condition
SWPS	Solar Water Pumping System
TDH	Total Dynamic Head

Abstract

In rural Ethiopia, agriculture and water are vital for food security and income, necessitating efficient irrigation systems to enhance productivity. This study addresses the challenge of implementing a standalone solar water pumping system in the remote community of Chorora, West Harerghe. Using MATLAB/Simulink, a solar water pumping system was designed, incorporating a photovoltaic (PV) array connected to a permanent magnet DC motor via various DC-DC converters: buck, buck-boost, Cuk, SEPIC, and Zeta. The objective was to identify the most efficient converter for this application under variable irradiance conditions, utilizing a Perturb and Observe Maximum Power Point Tracking (MPPT) strategy. Key findings revealed that the Zeta converter achieved the highest efficiency at 96.2%, while the buck converter exhibited the lowest at 90%. Additionally, the system performed effectively under variable load torque conditions. These results underscore the potential of optimized solar-powered solutions to improve irrigation practices in rural Ethiopia.

Keyword: Chorora, DC-DC converter, Maximum power point tracking, Perturb and Observe, Permanent magnet dc motor, Photovoltaic, Standalone, Water pumping system.

CHAPTER ONE

1. INTRODUCTION

1.1. Background of the study

When considering the development of every country, energy is an important consideration. Energy sources can be produced from both non-renewable, like fossil fuels, and renewable sources, such as solar, wind, and hydro. Fossil fuels, as non-renewable or conventional energy sources, have negative environmental effects, are expensive, and deplete quickly, presenting significant challenges when using them for power generation. Across the world, one renewable energy source that is commonly used to generate electricity is solar energy. Among the technologies that directly use solar energy and convert it into direct current, photovoltaic (PV) technology is the most widely used. PV water pumping systems are also among the most common applications of PV power systems, gaining increasing attention as a viable solution for irrigation and drinking water supply in remote rural communities.

Recent studies show that the use of solar water pumping systems in remote rural communities improves the availability of irrigation water for agriculture and enhances the livelihoods of smallholder farmers. For instance, a study in Ethiopia finds that the adoption of solar water pumping systems increases crop yields and reduces the use of traditional fuels for irrigation (Assefa, et al., 2021). Similarly, a study in Kenya shows that the use of solar water pumping systems improves the productivity of smallholder farmers and reduces their reliance on rain-fed agriculture (annual-report, 2022).

The study area, Ch'orora, is a rural district located in the West Harerghe Zone of the Oromia Region in Ethiopia. The district has a population of approximately 150,000 people and is characterized by high potential for solar radiation, making it an ideal location for solar water pumping systems. However, the district faces challenges such as access to clean water, limited irrigation water, high levels of poverty, and limited access to electricity. In areas like this, where grid electricity is unavailable, standalone solar water pumping systems offer a promising solution to meet the water needs of communities.

This study focuses on the comparative performance of DC-DC converters for standalone solar water pumping systems without battery storage and an inverter in Ch'orora, West Harerghe, Oromia, Ethiopia, using a DC motor. These systems use photovoltaic (PV) panels to harness solar energy, with maximum power point tracking (MPPT) algorithms ensuring that the solar panels operate at their maximum power point, maximizing power output and system efficiency. DC-DC converters ensure that the maximum power generated by the solar panels is utilized effectively to power the pump, optimizing power transfer (Derbel, Said, & Zhu, 2023), Direct current (DC) motors drive the water pumps and are specifically designed to operate on DC power generated by the PV panels, making them suitable for direct connection to solar panels without needing an inverter. Additionally, due to their efficiency, reliability, and compatibility with solar power, DC motors are well-suited for this application. A storage tank stores water, ensuring a continuous water supply.

The performance of DC-DC converters plays a crucial role in the overall efficiency and reliability of standalone solar water pumping systems. These converters match the varying power output of the PV panels with the load requirements of the DC motor (Kalita, Emilia, Borah, & Pradhan, 2019). Therefore, it is essential to evaluate and compare the performance of different DC-DC converters to identify the most suitable option for the specific requirements of the target rural community in Ch'orora.

The focus is on evaluating the efficiency, reliability, and cost-effectiveness of various converter topologies under the given conditions (Kalita, Emilia, Borah, & Pradhan, 2019).To achieve the objectives of this thesis, a comprehensive design, modeling, and simulation approach is adopted using the MATLAB/Simulink environment (Aissaoui, Kacimi, Assia, & Mohamed, 2019). This environment provides a flexible and accurate platform for analyzing the dynamic behavior of the system components and evaluating their performance metrics (Kalita, Emilia, Borah, & Pradhan, 2019). By performing simulations under different operating conditions and using various DC-DC converter topologies, valuable insights are gained to guide the selection and optimization of the system components.

The outcome of this study contributes to the knowledge base of standalone solar water pumping systems for remote rural communities. The findings inform decision-makers, system designers, and stakeholders about the most suitable DC-DC converter options for the specific context of Ch'orora, West Harerghe, Oromia, Ethiopia. Ultimately, the research aims to facilitate the implementation of sustainable and efficient water pumping systems, improving the livelihoods and well-being of the community residents.

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1.2. Motivation

Access to clean water and reliable energy is fundamental to the socio-economic development of any community, yet many remote rural areas, particularly in developing countries like Ethiopia, continue to face significant challenges in both. Ch'orora, located in the West Harerghe Zone of Oromia, Ethiopia, is one such region where limited access to electricity and water hinders agricultural productivity and the well-being of its inhabitants. The high cost of extending the national electricity grid to such remote areas makes off-grid, renewable energy solutions essential for addressing these critical needs.

Solar energy, with its abundance in regions like Ch'orora, offers a sustainable and reliable solution. Photovoltaic (PV) water pumping systems, which harness solar power to provide water for drinking and irrigation, have proven to be highly effective in similar rural settings. These systems not only reduce dependence on traditional fuel-powered pumps but also promote environmental sustainability by utilizing clean energy. However, maximizing the efficiency and reliability of solar water pumping systems requires careful consideration of key components, particularly DC–DC converters, which regulate and optimize the power flow from PV panels to water pumps.

DC–DC converters play a crucial role in ensuring that the energy generated by the PV panels is efficiently used to drive the water pump, especially in systems that use DC motors without the need for inverters or batteries. Given the variety of converter topologies available, understanding their performance under different environmental and operational conditions is essential for designing cost-effective and reliable solar water pumping systems.

The motivation for this study arises from the need to evaluate and compare the performance of different DC–DC converter topologies for standalone solar water pumping systems in Ch'orora, where such systems can have a transformative impact on the community. By identifying the most efficient, reliable, and cost-effective converter options, this research aims to contribute to the broader goal of improving water access, agricultural productivity, and overall livelihoods in rural Ethiopia. The study also seeks to provide insights that can be applied to similar rural communities facing challenges related to water and energy access, promoting sustainable development in off-grid areas.

1.3. Statement of problem

Despite the growing recognition of solar energy as a viable solution for addressing water scarcity and energy access in remote rural communities, significant challenges remain in optimizing the performance of standalone solar water pumping systems. In regions like Ch'orora, West Harerghe, Oromia, Ethiopia, where access to clean water is critical for agricultural productivity and overall community well-being, the lack of efficient and reliable water pumping solutions hampers development.

Current solar water pumping systems often rely on various DC–DC converter topologies to manage the power generated by photovoltaic (PV) panels and supply it effectively to direct current (DC) motors driving the water pumps. However, the performance of these DC–DC converters can vary significantly based on factors such as environmental conditions, load requirements, and system design. As a result, many existing systems fail to maximize energy conversion efficiency, leading to inadequate water supply and reduced reliability.

Furthermore, the absence of a systematic comparative analysis of different DC–DC converter topologies in the context of standalone solar water pumping systems limits the ability of stakeholders, including decision-makers, system designers, and local communities, to select the most suitable components for their specific needs. Without a clear understanding of the efficiency, reliability, and cost-effectiveness of these converters, the implementation of solar water pumping systems in Ch'orora and similar rural areas may not achieve their full potential.

This research addresses these critical gaps by evaluating and comparing the performance of various DC–DC converter topologies in standalone solar water pumping systems. By identifying the most effective solutions tailored to the unique conditions of Ch'orora, the study aims to contribute to improved water access, enhanced agricultural productivity, and the overall well-being of the community.

1.4. Objectives

The following describes the general and specific objectives of this thesis work:

1.4.1. General Objective

The general objective of this thesis is to evaluate and compare the performance of various DC–DC converter topologies for standalone solar water pumping systems without battery storage and an inverter in Ch'orora, West Harerghe, Oromia, Ethiopia. This study aims to identify the most efficient, reliable, and cost-effective converter options that optimize the energy transfer from photovoltaic (PV) panels to direct current (DC) motors, ultimately enhancing the performance of solar water pumping systems and improving water access and agricultural productivity in remote rural communities.

1.4.2. Specific Objectives

The following are the specific objectives of this thesis work:

- To review the existing literature on standalone solar water pumping systems, DC-DC converters, PV panels, MPPT techniques, PMDC motors, and motor speed controllers
- To identify and select suitable DC-DC converter topologies for standalone solar water pumping systems without battery storage and inverters, considering the specific requirements and constraints of the rural community in Ch'orora, West Harerghe, Oromia, Ethiopia
- To design and simulate the selected DC-DC converter topologies using MATLAB SIMULINK software, taking into account the characteristics of the PV panels, MPPT techniques, and PMDC motor
- To evaluate and compare the performance of the designed DC-DC converter topologies in terms of efficiency, power output, voltage regulation, and reliability for standalone solar water pumping systems in the target rural community.
- To analyze the impact of different operating conditions, such as solar irradiance and water demand, on the performance of the DC-DC converters and the overall system

1.5. Scope of Thesis

This thesis focuses on the design and analysis of a standalone solar water pumping system for rural communities in Ethiopia, emphasizing the selection of a suitable Permanent Magnet DC (PMDC) motor. It conducts a comparative study of five step-down DC-DC converter topologies—buck, buck-boost, Cuk, SEPIC, and Zeta—analyzing their efficiency through theoretical calculations and experimental evaluations. The research addresses the specific challenges faced by these communities in accessing clean water and reliable electricity, utilizing simulation models to predict system performance under varying conditions. Additionally, the thesis provides recommendations for the optimal selection and implementation of DC-DC converters, as well as identifying future research directions to enhance solar water pumping solutions.

1.6. Significance of the Study

This study holds significant importance for several key areas:

- By optimizing solar water pumping systems through efficient DC-DC converters, this research directly contributes to improving access to clean water in rural Ethiopian communities. This is crucial for public health and overall well-being.
- The study emphasizes the potential of solar energy as a sustainable power source for rural areas. By focusing on the efficiency of different DC-DC converters, it highlights innovative approaches to harnessing renewable energy effectively.
- The comparative analysis of various DC-DC converter topologies provides valuable insights for engineers and practitioners in the field. It aids in informed decision-making regarding the design and implementation of efficient solar water pumping systems tailored to local conditions.
- Improved access to clean water and electricity can stimulate local economies by enhancing agricultural productivity, enabling small businesses, and creating job opportunities. This study contributes to the broader goal of economic empowerment in rural regions.
- The outcomes of this research can serve as a foundation for future studies in renewable energy systems. By documenting the efficiencies and performance of various DC-DC converters, it paves the way for further innovations and improvements in solar technology.

1.7. Limitation of the Study

This thesis is subject to several limitations that may affect the scope and applicability of the findings:

- Geographical Focus: The study is limited to the specific context of Ch'orora, West Hareerghe, Oromia, Ethiopia. While the findings may offer valuable insights for similar rural communities, their applicability may be constrained by differing environmental conditions, resource availability, and local practices in other regions.
- Technical Constraints: The evaluation of DC–DC converters in this study relies on simulations conducted within the MATLAB/Simulink environment. While simulations provide useful insights into system performance, they may not fully replicate real-world

operational conditions, including variations in solar irradiance, temperature, and load demands that can impact converter efficiency and reliability.

- Component Availability: The performance comparison of different DC–DC converter topologies may be limited by the availability of certain components in the local market. This could affect the feasibility of implementing the most effective solutions identified in the study.
- Focus on DC–DC Converters: While this research emphasizes the performance of DC–DC converters, it does not address other critical components of solar water pumping systems, such as PV panel selection, motor specifications, and system integration. This narrow focus may overlook the influence of these factors on overall system performance.
- Financial Considerations: The cost-effectiveness analysis may be limited by the availability of current market data and pricing for components. Fluctuations in material and labor costs may also affect the feasibility and implementation of the recommended solutions.
- User Adoption: The success of solar water pumping systems is not solely dependent on technical performance. Community acceptance, user training, and maintenance practices are critical for long-term sustainability but are not the primary focus of this study.

1.8. Thesis Organization

This thesis is organized into five chapters.

Chapter 1 will introduce the study, including the background, objectives, and research methodology.

Chapter 2 will provide a literature review of DC-DC converters for solar water pumping systems.

Chapter 3 will detail the design and modeling of the whole system using MATLAB SIMULINK software. Chapter 4 will present the results of the simulations and discussion.

Finally, Chapter 5 will provide conclusions and recommendations based on the study's findings.

CHAPTER TWO

2. LITERATURE REVIEW AND RELATED WORKS

2.1. Introduction

For human life and sustained growth, having access to clean, sufficient water is essential. yet millions of people in remote rural communities around the world continue to face challenges in securing a consistent water supply. In regions like Ch'orora, West Harerghe, Oromia, Ethiopia, the absence of grid electricity and limited access to conventional water pumping solutions further exacerbate these challenges. To address this pressing issue, standalone solar water pumping systems have emerged as promising alternatives, employing the sun's available energy to produce sustainable water access.

This literature review seeks to explore and analyze existing research on standalone solar water pumping systems, with an emphasis on the extent to which DC-DC converters perform in maximizing system dependability and efficiency. The comparative study aims to provide valuable insights into the selection and utilization of DC-DC converters for enhancing the performance of solar water pumping systems in remote rural communities like Ch'orora.

The first part of the literature review investigates at its fundamental concepts and components used in stand-alone solar water pumping systems. Prior studies emphasized how crucial system design is to guaranteeing peak performance and dependability. This includes choosing appropriate solar panels, pumps, and control mechanisms. Studies by Patel et al. (2018) and Khan et al. (2019) underscore the potential of standalone solar water pumping systems to provide sustainable water access in off-grid environments, laying the groundwork for further investigation into system optimization.

Solar water pumping systems are gaining significant attention as a sustainable solution for remote rural communities lacking access to reliable electricity grids. The efficient utilization of solar energy, along with suitable DC–DC converters, plays a crucial role in the performance and viability of these systems. This literature review aims to explore the existing research on the comparative study of DC–DC converters' performance in standalone solar water pumping systems, specifically focusing on the case of Ch'orora, West Harerghe, Oromia, Ethiopia. The integration of photovoltaic (PV) panels, motor speed control, maximum power point tracking (MPPT) methods, and the use of permanent magnet DC (PMDC) motors are all further studied in this study. It is important to note that this research solely relies on the analysis, modeling, and simulation of the systems using MATLAB SIMULINK software.

In summary, this literature review sets the stage for a comprehensive investigation into the performance of DC-DC converters in standalone solar water pumping systems for remote rural communities. By synthesizing existing research and identifying gaps in knowledge, this comparative study aims to contribute valuable insights and practical recommendations for improving water access and sustainability in regions like Ch'orora, West Harerghe, Oromia, Ethiopia.

2.2. Solar Water Pumping Systems in Rural Communities

Solar water pumping systems refer to the use of solar energy to power water pumps in rural communities. These systems are designed to provide a sustainable and reliable source of water for various purposes such as drinking, irrigation, and livestock watering.

In rural communities, access to electricity is often limited or unreliable, making traditional electric water pumps impractical. Solar water pumping systems offer an alternative solution by harnessing the power of the sun to generate electricity and operate the water pumps.

A controller, a pump, a water storage tank, and solar panels are main components of these systems. Sunlight is converted into electricity by the solar panels, which powers the water pump. The controller controls the flow of electricity from the panels to the pump, guaranteeing peak performance and avoiding system damage. The pump transports water from a river or well and stores it in the storage tank for later use. This ensures a steady supply of water even at night or during low light conditions.

Solar water pumping systems are particularly beneficial in rural communities where access to clean and reliable water is limited. These systems reduce the reliance on traditional fuel-powered pumps, which can be expensive to operate and maintain. Furthermore, since they don't emit greenhouse gases or contribute to air pollution, solar water pumping systems are environmentally friendly (healingwaters, 2021)

2.2.1. Overview of solar based water pumping technology in Developing Countries

Developing regions are areas that are still in the process of economic and social development, often characterized by limited access to electricity and water resources. Solar water pumping technology is a sustainable and environmentally friendly alternative to traditional water pumping methods that rely on fossil fuels or grid electricity. With this method, sunlight is converted into electricity using solar panels, and that electricity powers the water pump.

Photovoltaic cells, which make up the solar panels, collect sunlight and convert it into direct current (DC) electricity. An inverter that works with the water pump is then used to transform this direct current (DC) electricity into alternating current (AC) electricity. Depending on the water source and intended use, a submersible or surface pump is usually used for the water pump. Surface pumps are used when the water source is a river, lake, or pond, whereas submersible pumps are used when the water source is underground, such as a well or borehole. The solar water pumping system also includes other components such as a controller, battery, and storage tank. The controller controls how much power is transferred from the solar panels to the pump, which ensures peak efficiency and preventing damage. The battery allows the pump to run at night or in overcast conditions by storing additional power produced by the solar panels during the day. The storage tank stores the pumped water for later use, providing a reliable water supply for various purposes such as irrigation, livestock watering, and domestic use.

Solar water pumping technology has numerous advantages in developing regions, including reduced reliance on fossil fuels, lower operating costs, and increased access to clean water. It can help improve agricultural productivity, enhance livelihoods, and contribute to poverty alleviation in these regions. However, there are also challenges associated with the adoption and implementation of solar water pumping technology in developing regions, such as high upfront costs, limited technical expertise, and maintenance requirements. To meet the objectives of sustainable development, governments, non-governmental organizations, and international agencies have to take steps to encourage the application of solar water pumping technology and get over these challenges.

2.2.2. Applications and Impact in Rural Ethiopia

Systems known as solar water pumping systems use solar energy to run water pumps, which draw water from subterranean sources like boreholes and wells.

Applications: Solar water pumping systems have various applications in rural Ethiopia. They are primarily used for irrigation purposes, where the water is used to irrigate crops and increase agricultural productivity. These systems are also used for domestic water supply, providing clean and safe drinking water to rural communities. Additionally, they can be used for livestock watering, providing water for animals in remote areas.

Impact: The use of solar water pumping systems has had a significant impact in rural Ethiopia. Firstly, it has improved agricultural productivity by enabling farmers to irrigate their crops, leading to increased yields and income. This has helped to reduce food insecurity and poverty in these communities. Secondly, the availability of clean and safe drinking water has improved public health, reducing the incidence of waterborne diseases. Lastly, the provision of water for livestock has improved animal health and productivity, benefiting the livelihoods of pastoral communities.

Rural Ethiopia: This refers to the rural areas of Ethiopia, which are characterized by limited access to electricity and water infrastructure. These areas often rely on traditional methods of water extraction, such as manual labor or diesel-powered pumps, which can be costly and inefficient. The development of solar water pumping devices has given these communities a cheap and environmentally friendly way to satisfy their water needs.

2.3. Solar Photovoltaic (PV) Systems

Solar PV systems have grown significantly in both size and technology in recent years, making solar energy a more adaptable, economical, and efficient source of renewable energy. They are renewable energy source, which can convert sunlight (abundant and freely available resource) into electricity by using solar panels, which have the ability to convert sunlight into electricity, resulted in higher energy yields and reduced wastage of sunlight (8msolar, 2023), and the cost of solar panels and associated components has significantly decreased, making solar energy more affordable and accessible (Linkedin, 2024). Since these systems don't release greenhouse gases or other pollutants when they're operating, they can provide clean energy. Furthermore, by reducing reliance on fossil fuels, these systems can help create a more environmentally friendly and sustainable energy system. Solar Photovoltaic (PV) systems are composed of several components as shown figure 2.1., that work together to generate electricity from sunlight. These components include photovoltaic cells, module, panel and arrays.

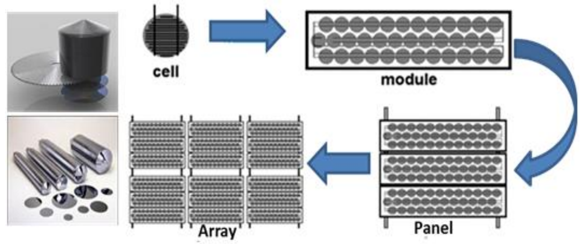

FIGURE 2. 1. Component of Solar PV Systems (Sheir, 2024).

A photovoltaic module is made from of several solar cells placed on a support structure or frame and electrically connected to one another in series or parallel circuits to generate larger voltages, currents, and power levels. As one of the essential components of photovoltaic systems, photovoltaic modules are made up of a sequence of connected PV cell circuits that are covered to protect the environment. A pre-wired, field-installable unit comprising one or more PV modules is what makes up a PV panel. When combined with some PV modules and panels, a PV array can generate power in its whole. (Sheir, 2024). These arrays consist of multiple modules or panels connected together to generate higher power output and the size and configuration of the arrays can vary depending on the specific application, whether it's residential, commercial, or utility-scale solar installations (Alternative, 2024).

Solar panels are critical components in renewable energy systems, transforming sunlight into electricity through the photovoltaic effect. They primarily consist of solar cells made from semiconductor materials, with three main types widely used: monocrystalline, polycrystalline, and thin-film solar panels. Each type has distinct characteristics, advantages, and applications..

Monocrystalline silicon PV panels: Monocrystalline solar panels are made from single-crystal silicon, which gives them a uniform appearance and high efficiency. They typically boast the highest energy conversion rates, often exceeding 20%. This efficiency is due to the purity of the silicon used, which allows for better electron movement and higher power output. Monocrystalline panels are also space-efficient, making them ideal for installations with limited space. Their longevity and performance stability in various environmental conditions make them a popular choice, albeit at a higher cost compared to other types (Foundation, 2021).

Polycrystalline silicon PV panels: Polycrystalline solar panels are composed of multiple silicon crystals melted together. This manufacturing process results in a less uniform appearance and slightly lower efficiency, typically ranging between 15% and 18%. However, polycrystalline panels are generally more affordable to produce, making them a cost-effective option for large-scale installations. They perform well in moderate temperatures but may lose efficiency in extreme heat. Polycrystalline panels are widely used for residential and commercial applications, balancing cost and performance effectively.

Thin-film based solar panels: Thin-film solar panels are made by depositing a thin layer of photovoltaic material on a substrate, which can include glass, plastic, or metal. This technology allows for lightweight and flexible panels that can be integrated into various surfaces, including building materials. Although thin-film panels have lower efficiency levels, typically ranging from 10% to 12%, they can perform better in low-light conditions and high temperatures. Their versatility and lower production costs make them suitable for applications where space and weight are considerations, such as in portable solar devices and building-integrated photovoltaics (BIPV).

Table 2.1 Summary of solar panel (Foundation, 2021).

Type	Advantage	Disadvantage
Monocrystalline	❖ Highest efficiency (up to 22%) ❖ Takes lesser space ❖ Higher durability ❖ More efficient in warm weather	Higher Cost
Polycrystalline	❖ Relatively easier to make ❖ Cost-effective as compared to Monocrystalline panels ❖ Higher temperature coefficient, therefore impact of temperature on power output is less	Efficiency of panels is around 15%
Thin-film based solar panels	❖ Mass production is easier ❖ High temperature and shading have lesser impact on power output	❖ Lowest space efficiency ❖ Faster degradation as compare to mono & poly panels

In summary, monocrystalline, polycrystalline, and thin-film solar panels each offer unique benefits and limitations. The choice of solar panel type depends on factors such as efficiency requirements, installation space, budget, and specific application needs. In the context of solar water pumping systems, understanding these differences is crucial for selecting the most suitable technology to optimize energy generation, enhance system performance, and meet the water supply needs of remote rural communities. Based on the technology's end-use application, solar photovoltaic systems can be divided into two categories: standalone (off-grid) and grid-connected (grid-tied) systems. (Foundation, 2021).

2.3.1. Grid-tied solar PV systems

Grid-tied solar PV systems, also known as grid-connected solar systems, are solar energy systems that are connected to the main electricity grid. These systems are increasingly being used in water pumping applications, providing a sustainable and reliable source of power (Mahinda, Wanjiru, & Njiri, 2023). Grid-tied solar PV systems offer several advantages in water pumping applications. Because these systems are cost-effective as they utilize the sun's energy to power water pumps, eliminating the need for expensive fuel or electricity (AptechAfrica, 2022). This results in lower operating expenses and a higher return on investment. Additionally, grid-tied solar PV systems are environmentally friendly, producing clean and renewable energy while reducing reliance on fossil fuels and minimizing greenhouse gas emissions (AptechAfrica, 2022). However, these systems rely on the availability of grid power to operate. This means that if there is a power outage or grid failure, the water pumping system will not function, even if there is ample sunlight to generate electricity from the solar panels. So, installing these systems for rural area community where is no electricity grid cannot be possible, a significant disadvantage of grid-tied solar water pumping in areas with unreliable electricity grid power (ParadiseSolarenergy, 2024) and requires additional equipment for such application such as inverters, which can increase the initial installation costs compared to standalone (without battery storage and inverters) systems (EnergyTheory, 2023). Additionally, these systems connected to the utility grid, which means that they do not have the ability to operate independently. In the event of a grid outage, the system cannot continue to pump water, even if there is sufficient solar energy available. This lack of autonomy can be a drawback in remote or standalone (off-grid) locations where access to reliable grid power is limited (EnergyTheory, 2023). The block diagram of grid-connected Solar PV system is depicted in figure 2.2.

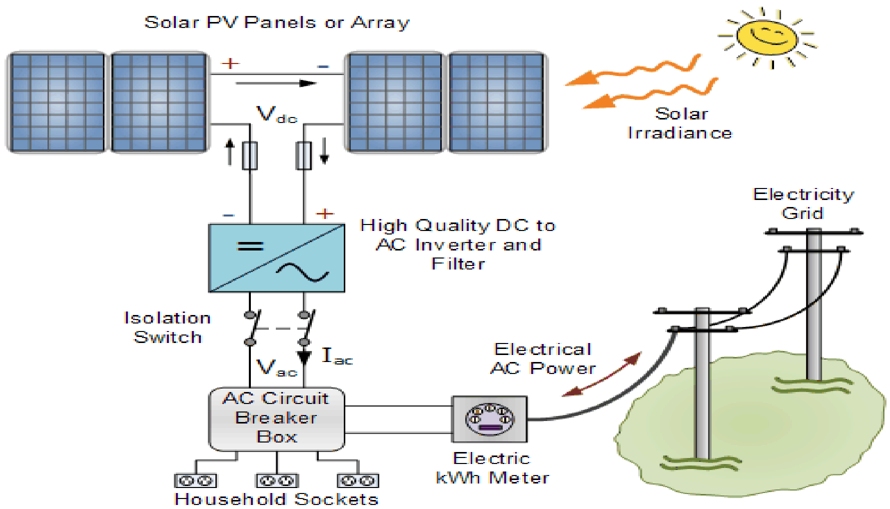

FIGURE 2. 2. Block diagram of grid tied PV system (electricalacademia, 2024)

2.3.2. Standalone solar PV systems

Standalone solar PV systems, also known as off-grid photovoltaic systems shown in figure 2.3, which are a clean and renewable energy source, these systems are a great solution for providing power to both DC and AC appliances in remote areas or locations where grid connection is unavailable (AlternativeEnergy, 2023). However, for AC appliance the generated DC electricity from solar panel must be converted to AC electricity using an inverter which add an additional cost on the systems. In other case in both of AC and DC appliance the generated DC electricity from solar panel can be stored in batteries for later use, which also resulting additional cost to the systems. So, standalone photovoltaic systems without battery storage and inverters can be a suitable solution for locations no access to the grid, especially in water pumping applications which is commonly referred to as a direct-coupled solar water pumping system using DC water pump which is used to draw water from a source, such as a well or a borehole, and deliver it to the desired location. These pumps are designed to operate directly on DC power (AlternativeEnergy, 2023). In conclusion, Standalone PV Systems without battery storage and inverters which commonly referred to as direct-coupled solar water pumping systems can provide several advantages over Grid-Tied PV Systems in water pumping applications. These advantages include independence from the grid, simplicity and cost-effectiveness, higher efficiency, lower maintenance requirements, and flexibility in system sizing. These factors make Standalone PV Systems a viable and attractive option for water pumping in remote areas or locations with no grid access.

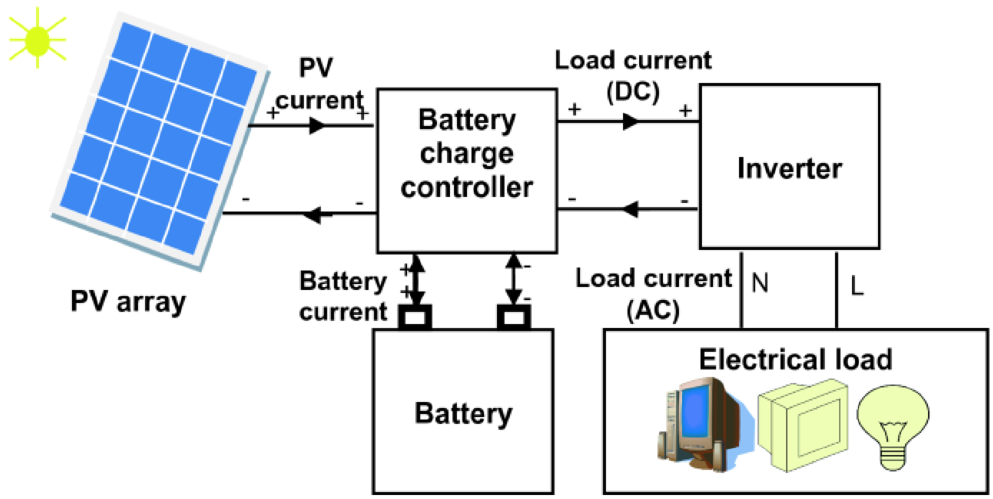

FIGURE 2. 3. Standalone Solar PV System Block Diagram(Touahri, Aoun, Maouedj, & Laribi. S. & Ghaitaoui, 2018)

2.4. Overview of Solar Water Pumping System

Solar PV water pumping systems operate through the use of solar panels which convert solar radiation into electricity. This electricity is then used to run a water pump that extracts water from a stream or well. The main parts are the solar panels, the pump motor, and frequently an inverter to change the electricity from the panels' direct current (DC) to alternating current (AC) for the pump. Because they provide a reliable, renewable, and low-maintenance water source, these systems are suitable for isolated locations without access to the electrical grid. Solar PV pumps are economical to operate, environmentally friendly, and can increase agricultural productivity by enabling reliable irrigation (healingwaters, 2021).

For the purpose of optimizing the amount of water pumped, solar pumping system installations usually require for the following parts: a motor pump assembly, a static power converter to improve system performance and efficiency, and a GPV. These elements mentioned above are coupled in two ways. The basic architecture possible is called direct coupling, as seen in Figure 2.4a, where a motor pump unit is connected directly to the GPV.

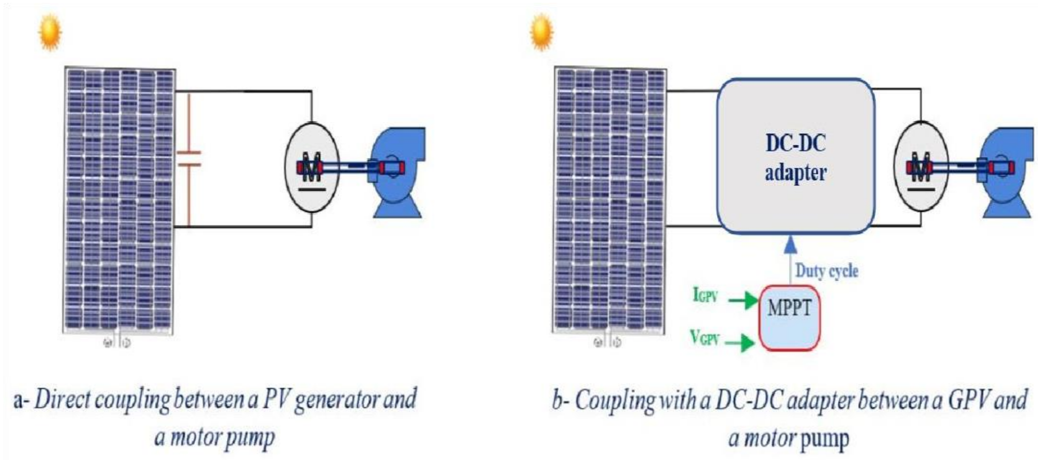

FIGURE 2. 4. Types of couplings between the GPV and the motor pump (Hilali, El Ouanjli, Mahfoud, Al-Sumaiti, & Mossa, 2022)

2.5. Classification of DC-DC converters

Due to its flexibility to step up or down the PV panel's output voltage, DC-DC converters are the most commonly used in PV systems. Step-down DC-DC converters are essential parts of solar water pumping systems that make them work efficiently. The DC water pump motor requires a specific voltage, which is achieved by means of these converters from the high voltage output of the solar panels. These non-isolated DC-DC power converters, also known as step-down/step-up converters, include Buck-Boost, SEPIC, Zeta, and Cuk. They can provide an output voltage that is greater or lower than the magnitude of the input voltage. In comparison to step-down and step-up topologies, step-down/step-up converters are able to cover the entire I–V characteristics of a PV panel. This fact helps MPPT operation to be conducted perfectly in a PV system, regardless of variations in atmospheric and load conditions. (Seguel, Seleme, & Morais, 2022)

This converter acts like an "automatic transmission," allowing the pump to start and run efficiently even in low light conditions like overcast skies or early morning/evening. When compared to connecting the solar panels directly to the pump, the converter increases the flow by 25–50% and maximizes the daily water output by increasing the current to the pump. This helps ensure reliable water delivery, even when sunshine is limited. The step-down converter is an important part of making solar-powered water pumps a practical and economical solution for remote or off-grid applications. In (Seguel, Seleme, & Morais, 2022), (Hayat, et al., 2023) & (Venkat, et al., 2020) these literatures, different dc-dc converters are compared, however in this thesis five dc-dc converters (buck, buck boost, Cuk, SEPIC and zeta) for standalone solar water pumping system are compared based on their efficiency. The detail theory of these converters is presented below;

2.5.1. Buck Converter

Buck converters are highly efficient DC-to-DC converters as shown in figure 2.5 (Venkat, et al., 2020), which have the ability to increase current while stepping down voltage. Because of this, they are ideal for use in solar PV water pumping systems, where the water pump motor requires a lower voltage to be obtained from the high voltage output of the solar panels (stackexchange, 2024). The main components are a capacitor, a switch (usually a MOSFET), an inductor, and a diode. The Buck converter adjusts the output voltage by adjusting the MOSFET's pulse-width modulation (PWM) duty cycle (Hertz, 2023).

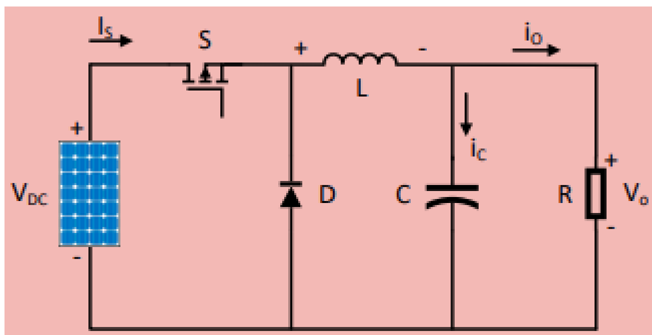

FIGURE 2. 5. Buck converter for the PV application (Venkat, et al., 2020)

Buck converters have three main advantages when used in solar PV water pumping systems: they can match the operating voltage of the pump to the maximum power point voltage of the panel, which increases efficiency to almost 90%, and they can provide more current to the pump than the solar panel alone can. As a result, the system can run more effectively and use the solar panels' optimum output. Due to its ability to control the current drawn from the panels, buck converters also aid in preventing damage to solar panels caused by abrupt variations in load (mberg, 2016). Buck converters are crucial for optimizing the voltage and current characteristics of solar PV water pumping systems, which is reasons for these components are essential for achieving maximum performance and efficiency.

2.5.2. Boost Converters

DC boost converters are used in water pumping systems to increase the voltage from a low-voltage DC source, such as a solar panel, to a higher voltage required by the water pump motor. The boost converter uses an inductor and a switching circuit to step up the voltage, while reducing the current (diysolarforum, 2024). This is accomplished by allowing energy to be stored in an inductor while the switch is in the on state and releasing it to the output while the switch is in the off state. The schematic diagram of the DC–DC boost converter is shown in Figure 2.6, where the PV source is connected to the load through a converter to meet the requirements of the load (Hayat, et al., 2023).

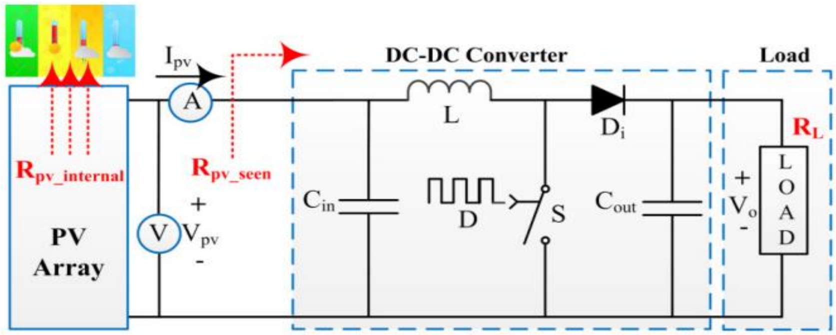

FIGURE 2. 6. Boost converter with Ci converter for the PV application (Hayat, et al., 2023).

2.5.3. Buck-Boost Converter

The Buck-Boost converter is simple and inexpensive to implement because it only contains a capacitor and a coil as energy storage elements (Dursun & Gorgun, 2017). Buck boost converter in Figure 2.7 is formed by integrating basic buck and boost converter topology and that can be used in various applications as standalone/grid-connected PV systems and motor drives (Venkat, et al., 2020)

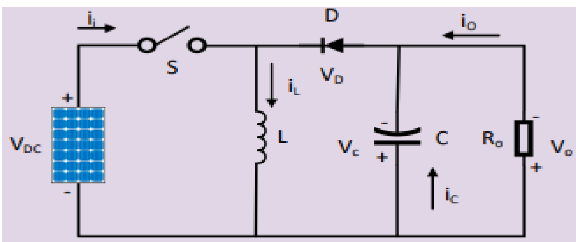

FIGURE 2. 7. Buck–Boost converter for PV application (Venkat, et al., 2020)

It has the ability to both step up and step down the voltage, which is useful for interfacing the variable voltage from the solar panels with the fixed voltage requirements of the water pump. This flexibility allows the system to operate efficiently over a wide range of solar irradiance conditions. Moreover, in a conventional Buck-Boost converter, the output voltage has opposite polarity than the input voltage, which represents its main issue (Veerachary, 2019). For this research work a buck boost converter is used for step down application.

2.5.4. Cuk Converters

A Cuk converter is a DC-to-DC converter that operates similarly to a buck-boost converter but with a negative capacitive output. However, The Cuk converter differs in that it transfers power and stores energy using a capacitor rather than an inductor. A conventional Cuk converter's basic circuit is shown in Figure 2.8.

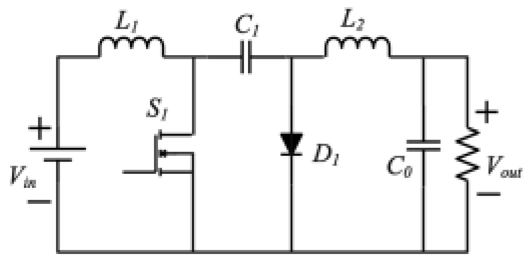

FIGURE 2. 8. A conventional Cuk converter's basic circuit (Priyadarshi, et al., 2022)

The Cuk converter delivers more or less output voltage than the supply voltage with reversed polarity (Priyadarshi, et al., 2022). The source side inductor L_1 acts as a filter, and the amount of energy sent to it is determined by the source side capacitor C_1. Extra circuit needs with reduced noise, increased transient response, and decreased electromagnetic interference are due to the presence of the load-side inductor and capacitor.

2.5.5. SEPIC Converters

The SEPIC is a direct-voltage-to-direct-voltage converter that will allow the output to be greater than, less than, or equal to the input voltage (Rais, Aroudi, Zakriti, & Khamlichi, 2022). Since this converter, like the Cuk converter, contains an inductor at the input, the input current waveform is continuous and has little ripple. Therefore, it is appropriate to attain excellent MPPT performance. The isolation provided by capacitor C_1 between the input and output, as seen in Figure 2.9, is another advantage of this configuration. capacitor C1 protects against a short circuit or an overload of the output (Necaibia, Samira, Labar, Necaibia, & Castronuovo, 2019)

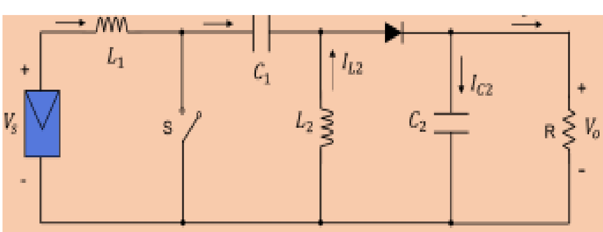

FIGURE 2. 9. SEPIC converter configuration for PV system (Seguel, Seleme, & Morais, 2022)

2.5.6. Zeta Converter

Zeta converter is another type of dc-dc converter, which produces a non-inverted voltage at the output that is either greater or less than the input voltage. In PV system, zeta converter has the ability to track the entire area of the PV curve. A typical configuration of zeta converter is shown in figure 2.10, the parameters in this configuration such as reduced input and output current ripple, enhanced voltage conversion ratio and operated well in both the CCM and the DCM modes (Venkat, et al., 2020).

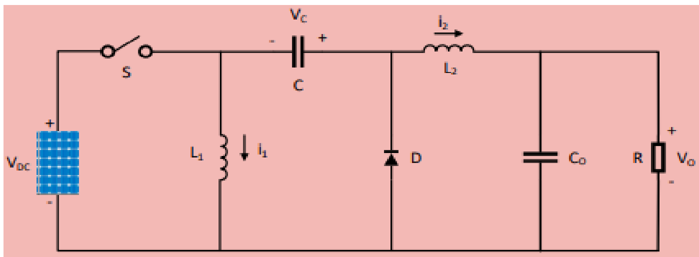

FIGURE 2. 10. A typical configuration of Zeta converter for PV application (Venkat, et al., 2020)

2.6. Maximum Power Point tracking

Maximum power point tracking controllers are necessary since it is highly challenging to track the maximum power from solar panels due to their nonlinear current-voltage (I-V) characteristics. In the literature various MPPT controllers are referred, however, in this research work perturb and observe MPPT algorithms are used due to its lower cost and simple operation.

2.6.1. Perturb and Observe MPPT

Due to its low cost and ease of implementation, the P&O approach is widely used. This method involves varying the duty cycle (ΔD) of the DC-DC converter to cause a perturbation in the PV panel voltage in a particular direction, and then monitoring the output power behavior. The system is disturbed in the opposite direction if the power is reduced; if it is increased, the disturbance persists in the same direction. A portion of the PV panel's energy is wasted as a result of the process' periodic repetition, which causes the power to oscillate around the MPP in a steady state. An appropriate size for ΔD has to be chosen with attention in order to ensure correct behavior both dynamically and in steady state. The primary flaw with this approach is that MPP can occasionally alter as a result of abrupt changes in the weather, like moving clouds. The flowchart for this method is displayed in Figure 2.11.

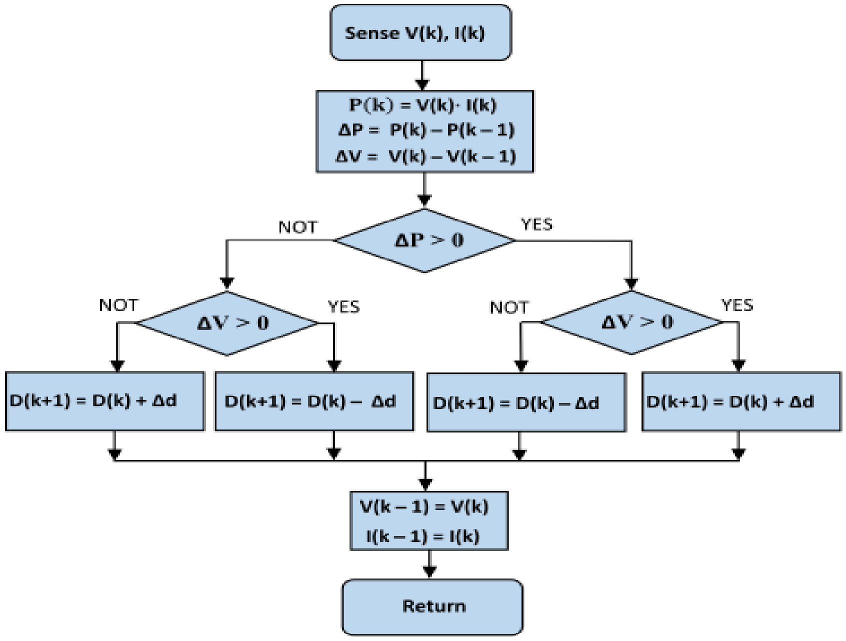

FIGURE 2. 11. P&O MPPT technique flowchart (Hilali, El Ouanjli, Mahfoud, Al-Sumaiti, & Mossa, 2022)

2.6.2. Incremental conductance MPPT

Incremental conductance MPPT is a technique used in photovoltaic (PV) systems to maximize the energy extraction from solar panels. The flow chart of incremental conductance MPPT is depicted in figure 2.12. In order to maintain the maximum power point (MPP) even when environmental factors like temperature and sunlight intensity fluctuate, it continually adjusts the PV array's electrical operating point. By comparing the PV array's incremental conductance to its instantaneous conductance, the incremental conductance method adjusts the voltage to keep the system operating at the MPP. When compared to simpler MPPT techniques, this enables the system to quickly follow changes in the MPP and produces higher energy yields. High efficiency, quick response times, and the capacity to manage partial shade of the PV modules are the main benefits of incremental conductance MPPT (greenlancer, 2014). Incremental conductance MPPT improves the solar PV system's overall performance and return on investment by optimizing the power production (Sun, Ling, & Wang, 2022).

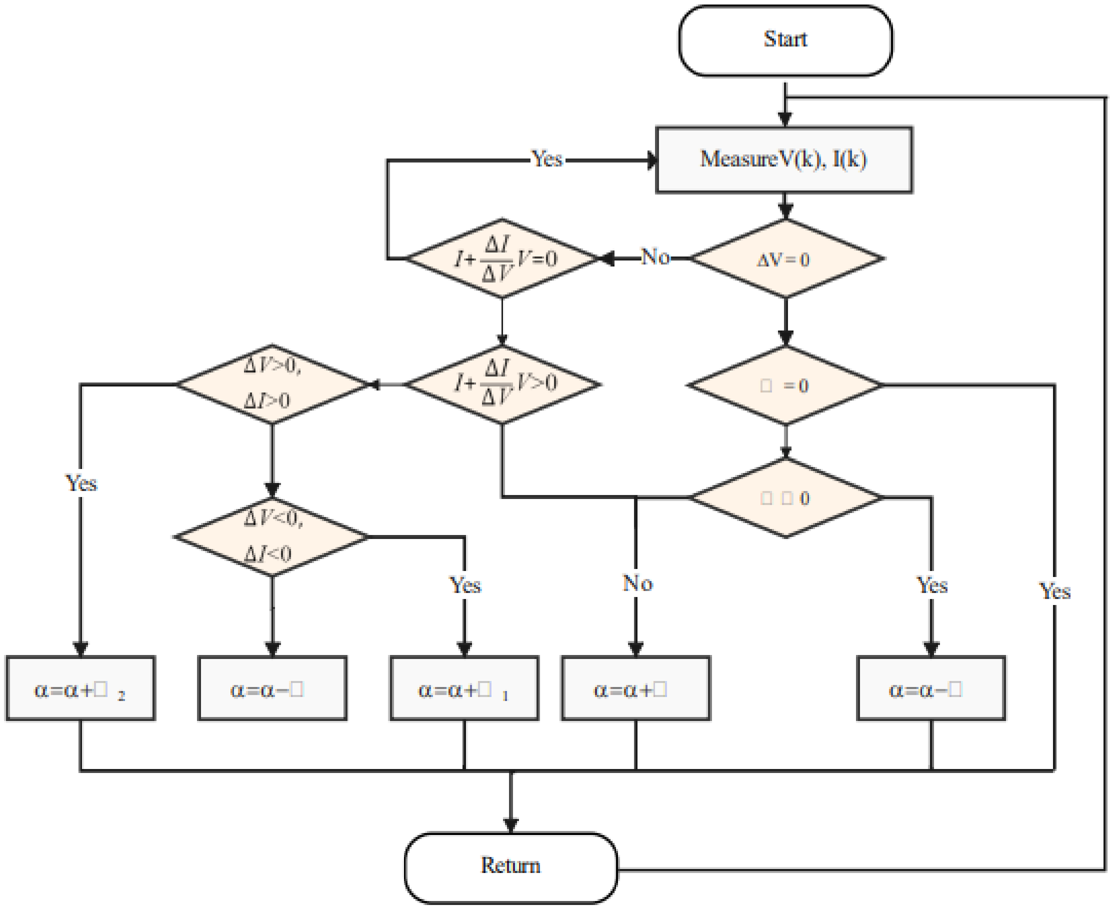

FIGURE 2. 12. An incremental conductance MPPT flowchart (Hilali, El Ouanjli, Mahfoud, Al-Sumaiti, & Mossa, 2022)

2.7. DC Motor

A DC motor is an electrical machine that converts electrical energy into mechanical energy or an electric motor that runs on direct current (DC) as opposed to an induction motor, which runs on alternating current (Byjus, 2024) & (Electrical4u, 2020). In general, the Different Parts of a DC Motor construction diagram was shown in figure below.

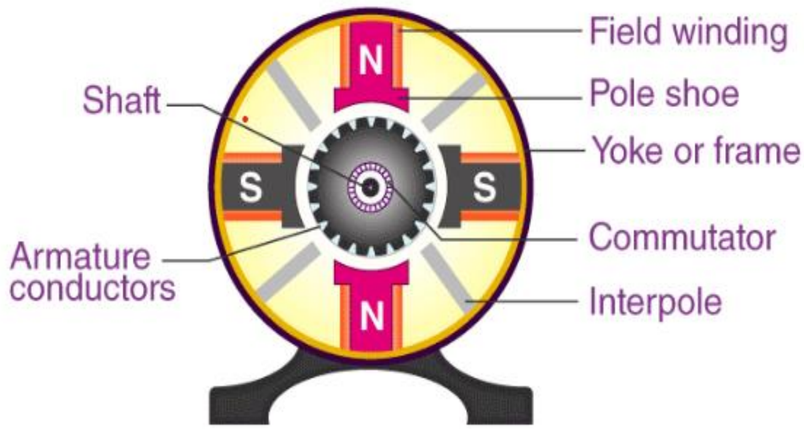

FIGURE 2. 13. DC motor construction diagram (Byjus, 2024).

Armature or Rotor: A DC motor's armature consists of an insulated cylinder filled with magnetic laminations. The armature is orientated perpendicular to the cylinder's axis. There is an air gap separating the armature, which is a revolving component on its axis, from the field coil.

Field Coil or Stator: The non-moving component of a DC motor field coil is wound with winding to create a magnetic field within. A cylindrical hollow is located between the poles of this electromagnet.

Commutator and Brushes: The commutator of a DC motor is a cylindrical structure that is made of copper segments stacked together but insulated from each other using mica. The primary function of a commutator is to supply electrical current to the armature winding.

The brushes of a DC motor are made with graphite and carbon structure. These brushes conduct electric current from the external circuit to the rotating commutator. Hence, we come to understand that the commutator and the brush unit are concerned with transmitting the power from the static electrical circuit to the mechanically rotating region or the rotor.

There are four main types of DC motors, each with its own unique characteristics and applications (Linquip, 2023). These are shunt DC Motors, series DC Motors, compound DC Motors & Permanent Magnet DC Motor.

2.7.1. DC Shunt Motor

Shunt DC motors are a type of direct connection motors in which the shunt field winding is only parallel to the armature winding and not the series field winding as shown in figure 2.14. Shunt DC motors are also known as compound wound DC motors. Shunt DC motors provide excellent speed regulation, as the shunt field can be excited separately from the armature windings. This feature of shunt direct connection motors provides simplified reversing controls (Linquip, 2023).

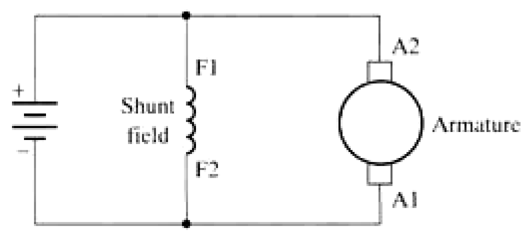

FIGURE 2. 14. DC shunt motor (Linquip, 2023).

The speed vs. armature current characteristic of DC shunt motor can be predetermined from Equations (2.1) & (2.2).

$$\omega = \frac{V - I_a V_a}{K_e \phi} \tag{2.1}$$

Where, Ke = is a constant for the machine. When ϕ is constant ω, A, and B can be expressed respectively in the form:

$$\omega = A - BI_a \tag{2.2}$$

$$A = \frac{V}{K_e \phi} \tag{2.3}$$

$$B = \frac{R_a}{K_e \phi} \tag{2.4}$$

Hence,

$$\omega = f(I_a) \tag{2.5}$$

should be a straight line.

In general speed-current curve and torque-current curve of shunt motor are shown below respectively.

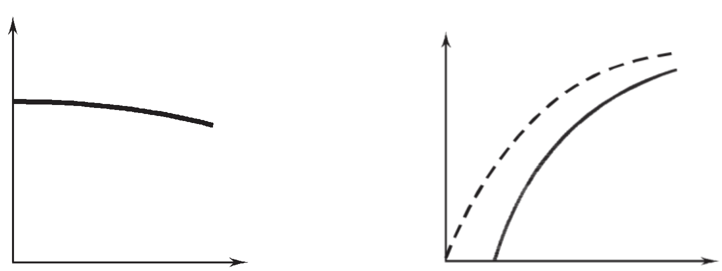

FIGURE 2. 15. Speed-current curve and Torque-current curve of shunt motor

Shunt DC motors are used for applications where you need constant speed, and the starting conditions are not severe. The shunt direct connection motors applications are in lathe machines, centrifugal pumps, fans, blowers, conveyors, lifts, waving machines, spinning machines, etc.

2.7.2. DC Series Motor

A DC series motor is a type of electric motor that operates on direct current (DC) power. It is characterized by the following.

The field winding and armature winding are connected in series, the armature current flows through both the field winding and the armature winding as shown in figure bellow, the torque produced by the motor is directly proportional to the armature current, it has high starting torque, making it suitable for applications requiring high initial torque, it has a simple and compact design.

In the series DC motors or series-wound DC motors, the entire armature current flows through the field winding. Usually, this DC motor type creates a large amount of starting torque, but it can't regulate speed, and even running with no load can damage it. Therefore, these limitations make series DC motors, not a good option for variable speed drive applications (Linquip, 2023).

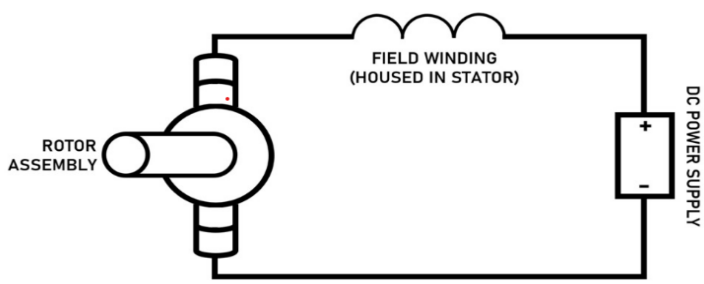

FIGURE 2. 16. Electric circuit of a series-wound DC motor

Series DC motors are typically employed in situations where a high starting torque and potential for speed changes are needed. For example, the traction system, cranes, air compressors, hoover cleaners, sewing machines, etc. all employ these kinds of direct connection motors.

2.7.3. Compound DC Motors

Compound DC motors or compound wound motors have both series and shunt field windings. These types of motors offer good starting torque, but they may have control problems in variable speed drive applications. These motors can be connected to two arrangements: cumulatively and differentially. The cumulative type connects the series field to aid the shunt field, providing higher starting torque but less speed regulation. The differential type has good speed regulation and usually operates at a constant speed.

Compound wound motors are usually used where you need higher starting torque and relatively constant speed. The compound DC motors applications are in presses, shears, conveyors, elevators, rolling mills, heavy planners, etc.

2.7.4. Permanent Magnet DC Motor

Electric motors known as permanent magnet DC (PMDC) motors generate their magnetic field not by field windings but by permanent magnets themselves. Compared to conventional DC motors, this makes them more compact and efficient (Cotton, 2024). PMDC motors are widely utilized in many different applications, such as electric vehicles, power equipment, and home appliances (pranshu, 2023). PMDC motors work especially well in PV systems to power solar tracking systems, which align PV panels to extract the maximum power possible during the day. PMDC motors are a great option for solar tracking applications because of its large starting torque and small size, which are crucial for accurate placement and low power consumption (cookierobotics., 2024).

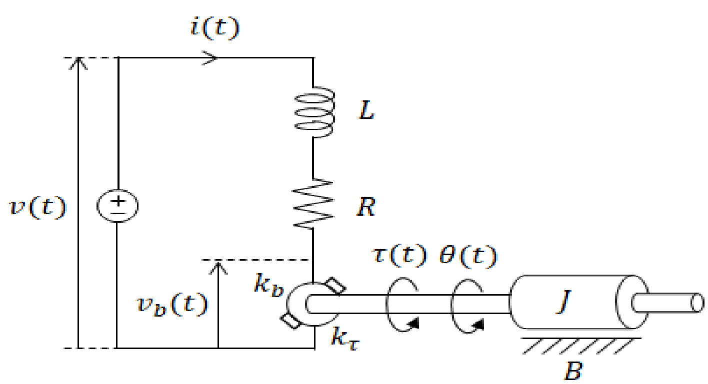

FIGURE 2. 17. Block diagram of PMDC motor (cookierobotics., 2024)

The permanent magnet motors work by a permanent magnet to make a field flux. A PM direct connection motor does not have a field winding on the stator frame. Instead, it uses permanent magnets to provide a magnetic field against which the rotor field interacts to produce torque (Linquip, 2023). This type of direct connection motor makes excellent starting torque, and it has good speed regulation.

2.8. Related Works

In this section numerous articles and scholarly researches publications related a comparative study of dc-dc converters for standalone solar water pumping systems have been reviewed and a research gap have been identified.

The authors (Girma, Assefa, & Molinas, 2015) investigates the feasibility of using a solar photovoltaic (PV) water pumping system to provide clean drinking water for rural communities in Ethiopia. They used PVsyst software to design and analyze the performance of solar PV water pumping system. The study used the PVsyst software to design a system capable of supplying 10.5 m^3, 7 m^3, and 6.5 m^3 of water per day for 700, 467, and 433 people respectively, at an average cost of \$0.10-\$0.16 per m^3 without any subsidies. However, the study does not provide detailed information and configuration of the solar PV system components (e.g., number of panels, battery capacity, etc.) for the different sites.

The authors (Venkat, et al., 2020) provides a detailed analysis of various DC-DC converter topologies and modulation strategies used in solar photovoltaic (PV) systems. The authors classify DC-DC converters into isolated and non-isolated types, and discuss the operating principles and applications of converters like buck, boost, buck-boost, SEPIC, Cuk, and multi-element resonant converters. The review also covers Maximum Power Point Tracking (MPPT) techniques and compares the performance of different converter topologies. However, technical aspects of the converters, but does not provide much insight into the practical implementation challenges, cost, and commercial availability of these topologies.

The authors (Livinti, Culea, Banu, & Vernica, 2024) presents a comparative study of a buck DC-DC converter controlled by the maximum power point tracking (MPPT) algorithm using the perturb and observe (P&O) method, with and without a fuzzy logic controller. The authors designed and simulated the buck converter in MATLAB-Simulink, implementing the conventional P&O MPPT algorithm as well as a hybrid MPPT algorithm that incorporates a fuzzy logic controller. The results show that the hybrid MPPT algorithm with fuzzy logic provides better performance and can harvest a higher quantity of electrical energy compared to the conventional P&O MPPT algorithm. However, the authors only use buck DC-DC converter topology, and the applicability of the FLC-based MPPT approach to other converter topologies is not discussed.

The authors (Seguel, Seleme, & Morais, 2022) provides a detailed analysis of various DC-DC converter topologies and maximum power point tracking (MPPT) techniques for photovoltaic

(PV) applications. The paper compares the performance of buck-boost, SEPIC, Cuk, and Zeta converters under different MPPT methods such as perturb and observe, incremental conductance, and fuzzy logic control. The study evaluates the MPPT tracking efficiency, converter efficiency, and transient tracking time under varying solar radiation and temperature conditions. The results show that the SEPIC converter with a fuzzy logic MPPT method offers the best overall performance in terms of efficiency and tracking capability. The article did not provide a detailed analysis of the design considerations and trade-offs for each converter topology and MPPT method.

The authors (Hilali, El Ouanjli, Mahfoud, Al-Sumaiti, & Mossa, 2022) presents a new hybrid algorithm called FL-INC (Fuzzy Logic - Incremental Conductance) for optimizing the performance of a solar water pumping system (SWPS) under varying weather conditions. The hybrid approach combines fuzzy logic and the incremental conductance technique to improve the SWPS's efficiency, tracking speed, power quality, and ability to track the maximum power point under different environmental changes. The performance of the SWPS using the SEPIC converter and the proposed FL-INC algorithm is compared to direct coupling and other conventional optimization techniques like P&O and modified incremental conductance (M-INC). The results show that the new FL-INC hybrid method outperforms the other approaches in terms of key metrics like efficiency, tracking speed, and water flow rate. However, the study focuses on the optimization of the SWPS, but it does not address other important aspects, such as the economic feasibility, environmental impact, or scalability of the system for different applications and locations.

The literature review reveals that while several studies have investigated the use of different DC-DC converters in solar water pumping systems, there is a lack of comprehensive comparative analysis of these converters regarding standalone solar water pumping systems for rural Ethiopia. Most existing studies have focused on general solar water pumping applications, without specific consideration for the unique challenges and requirements of the rural Ethiopian community

To address this research gap, the proposed thesis aims to conduct a comparative study of five step-down DC-DC converters (buck, buck-boost, Cuk, SEPIC, and Zeta) in the design of a standalone solar water pumping system for a rural community in Ethiopia. The study will evaluate the efficiency and performance of these converters under varying operating conditions, with the goal of identifying the most suitable converter for this application.

CHAPTER THREE

3. METHODOLOGY

3.1. Introduction

A standalone solar water pumping system is a promising renewable energy solution for providing water in remote areas without access to the electrical grid. The feasibility of such a system involves assessing factors like water demand, solar resource availability, pump characteristics, and system sizing to meet the required water needs. Mathematical modeling of the system components, such as the photovoltaic array, power electronics, and water pump, allows for optimizing the system design and predicting its performance under different operating conditions. Key considerations include maximizing energy extraction from the solar panels, efficiently converting and controlling the power to the pump, and ensuring the system can reliably meet the water demand throughout the year. By combining feasibility analysis and mathematical modeling, an optimal standalone solar water pumping system can be designed to provide a sustainable, cost-effective water supply in off-grid locations.

3.2. Feasibility study and data collection

3.2.1. Chorora Town

Chorora town currently use bore hole (deep well) water supply scheme as a source of water supply. Its discharge is 5litre/se. As information obtained from Chorora town Well Completion Report. they mention that fuel supply is the great challenge to them. Because of the fuel price increase from time to time some poorest households were couldn't afford the water tariff for the domestic consumption and for their livestock. This water supply system is driven by diesel generator & it works a minimum of 5 hours in a day. The fuel consumption for this generator in a day is 30 litres. The water tariff rate of this water supply scheme is 30birr/m^3.

3.2.2. Site selection

Chorora town is located in the West Hararge region of Ethiopia as shown in figure 3.1, approximately 400 km from the capital city of Addis Ababa. The region has a diverse landscape, with highlands, deep river gorges, and rift valley lakes. The average temperature in the area ranges from $20℃ - 30℃$, and the region receives moderate sun irradiance. The altitude of Chorora town is around 1,500 meters above sea level, and its latitude is approximately 9°N. The population of the West Hararge region is estimated to be around 1.9 million, with the Oromo ethnic group making up the majority. The region faces challenges such as limited access to electricity, low road density, and a high risk of drought.

FIGURE 3. 1. Chorora town map

3.2.3. Solar radiation

Significant solar radiation is received in the Ethiopian town of Chorora, which is located in the West Hararge region. Throughout the year, the direct normal irradiance (DNI) and global horizontal irradiance (GHI) vary. The transparency of the atmosphere to solar radiation is measured by the clearness index, which normally varies from approximately 0.8 in clear sky circumstances to nearly 0 in cloudy conditions. Figure 3.2 depicts the monthly solar radiation for the town of Chorora.

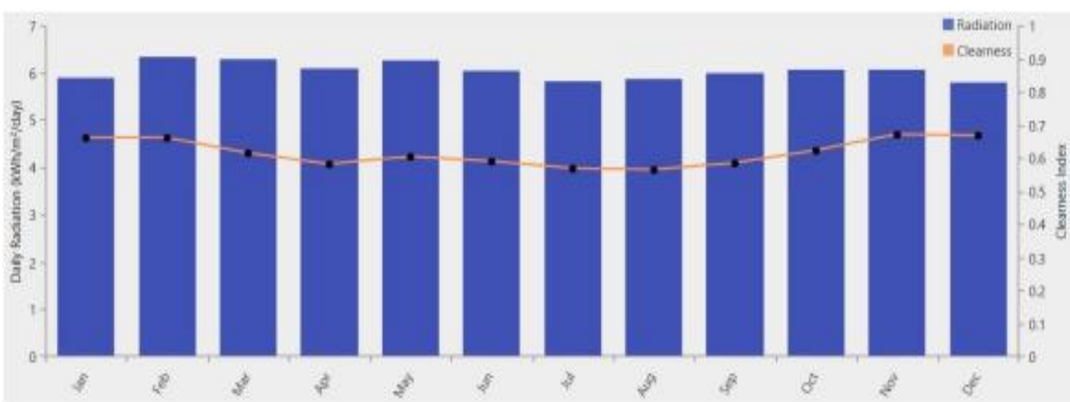

FIGURE 3. 2. Chorora town monthly solar radiation

3.2.4. Temperature

The town of Chorora, located in Ethiopia's West Hararge region, experiences a moderate climate year-round, with typical temperatures of between 20°C and 30°C. While higher temperatures may negatively affect the efficiency and power production of PV modules, this temperature range is generally favorable to the operation of photovoltaic (PV) systems. Figure 3.3 displays the monthly temperature of Chorora town.

FIGURE 3. 3. Chorora town average Monthly Temperature Resource

3.2.5. Data Collection

According to the data obtained from the Chorora town Administration Office, 2021 the number of populations directly benefited from the project are 950.

The growth rates adopted in this project document are adopted from CSA, 2008. Which is 2.9%.

The overall demand for water supply is determined from.

$$Q_i = q_i \times POP_i \tag{3.1}$$

$$POP_i = POP(1 + AAGR)^i \tag{3.2}$$

Where; Q_i is water demand of the people served in $^{litre}/_{day}$ for year i

q_i is the specific consumption in $^{litre}/_{day}$ for year i (if specific demand does not change over time, it will be constant)

POP_i is the population in year i

AAGR is the annual average growth rate of population (2.9%)

Projected population for 15 years is determined as follows.

$$POP_i = POP \times (1 + AAGR)^i = 950 \times (1.029)^{15} = 1459 \tag{3.3}$$

Gathered basic information

The first step in the design process is the compilation of basic data for the water source, water demand, and the required lift. The data collection form shown below can be used to collect this information. Note that information required in this form will be available from water source development reports (water well drilling and testing reports), water source developer estimates (e.g., water demand levels from Wareda Water Offices), and from observations and estimates to be made by the pumping system designer (you, for distances, locations and elevations of main pumping components).

TABLE 3. 1. Chorora town water supply scheme of well data

Population size	1459
Total Daily Water Requirement	44880 L/day = 44.88 m^3/day ≈ 45m^3/day
Static water level	31m
Lift from surface	10m
Draw down	21.5m
Friction losses	5% of Static head (Total vertical lift)
Additional percentage of daily water supply in order to compensate loss	2%
Reservoir capacity	3 times Total water required per day
Type of water source	Deep Well
Type of pump	Submersible pump

3.4. Design of Standalone Solar water pumping system

In order to design solar photovoltaic water pumping systems, the following values have to be calculated: water need, total head requirement, solar pump power selection and PV array requirement. Water need is the total water required by population size every day. The pump choice has to be determined depending on the source of water. The lower limit of the pump is the drawdown level of the water and the upper limit of the pump is the maximum height of the outlet pipe. The pump selected should be capable of delivering the water above the static head, which is calculated as follow.

$$\text{Static head} = \text{Drawdown level} + \text{Static water level} + \text{Lift from surface} + \text{Losses} \quad (3.4)$$

$$\text{Static head} = 21.5 + 31 + 10 + 3 = 65.5\text{m}$$

$$\text{Total Dynamic Head (TDH)} = 1.05 \times \text{Static head} = 1.05 \times 65.5 = 68.7 \cong 69\text{m} \quad (3.5)$$

$$H_e = \frac{\rho V g TDH}{3600} = \frac{1000\ {}^{Kg}/_{m^3} \times 9.81\ {}^{m}/_{s^2} \times 69\text{m}}{3600} = 8461.125\ \text{watt} - \frac{\text{hour}}{\text{day}} \quad (3.6)$$

Where; ρ is the density of water $= 1000\ ^{\mathrm{Kg}}/_{\mathrm{m}^3}$

V is the volume of water in $^{\mathrm{m}^3}/_{\mathrm{day}}$

g is acceleration due to gravity $= 9.81\ ^{\mathrm{m}}/_{\mathrm{s}^2}$

$^1/_{3600}$ is used to convert seconds in to hours

The solar radiation of proposed location is $5.71\ h/day$ (peak of $1000 w/m^2\ equivalent$), actual day length is longer.

The total power of the PV panel is calculated as;

$$\mathrm{E_{pv}} = \frac{\mathrm{H_e}}{\text{Number of hours of peak} \frac{\text{sunshine}}{\text{day}}} \tag{3.7}$$

$$\mathrm{E_{pv}} = \frac{8461.125\ \mathrm{wh/day}}{5.71} = 1481.8\ \text{Watts}$$

By considering system losses and operating factor for PV panel. Mismatch factor = 0.85 (PV panel usually don't operate at maximum power point, should be 1 if MPPT circuit is used, however P/O MPPT used in this thesis work).

Pump efficiency = 30% or 0.30 (it is typically between 0.25 to 0.40) and PV operating factor= 0.75 (PV panel mostly does not operate at peak rated power)

The total PV panel system losses can be expressed as;

$$\mathrm{P_{loss}} = \frac{\mathrm{E_{pv}}}{\text{pump efficiency} \times \text{mismatch factor} \times \text{operating factor}} \tag{3.8}$$

$$\mathrm{P_{loss}} = \frac{1481.8\mathrm{wh/day}}{0.3 \times 1 \times 0.75} = 6585.77\ \text{watts}$$

Where; $P_{loss}\ is$ Total wattage of PV Panel with system losses

The right choice of SPV panel is important to get a better output with the minimum number of panels and in a smaller area. This will reduce the panel cost, installation cost, maintenance cost, controller requirements, etc. For higher power requirements, it is optimal to select a PV panel with a higher wattage and higher efficiency. On comparing the 200, 300- and 400-Wp PV panels in Table below, it is evident that the 400-Wp panel requires fewer panels, uses the optimal space and provides better efficiency.

Therefore, Number of 400-Wp solar PV panels required is calculated as.

$$\text{Number of PV panels} = \frac{\mathrm{P_{loss}}}{\mathrm{P_{pv}}} = \frac{6585.77\mathrm{w}}{400\mathrm{w}} = 16.46 \cong 17 \tag{3.9}$$

However, there is 18 panel is available on the market.

TABLE 3. 2. PV array requirement for different pump ratings

Pump power rating	Solar power required	No. of 400-Wp, 36-V PV arrays	Area required
5.5 KW	7.2KW_p	18(6x3)	38m^2

3.3. Design and mathematical modelling of Standalone solar water Pumping system

In this section the design and mathematical modelling of standalone solar water pumping system is presented. The detailed design and mathematical modelling of this system is presented below:

3.3.1. SOLAR PV DESIGN

The PV panel has been designed to deliver a wattage of $P_{pv} = 6.5KW$ at $V_{pv} = 292.38V$ and $I_{pv} = 23.26A$. The design of the solar PV is done with reference to the data sheet BYD_220- 250P. A panel of the power rated at 250W has been chosen from the data sheet, whose specifications are given below in the Table 3.3.

TABLE 3. 3. Specifications of PV system from the data sheet

Specification	value
Open-circuit voltage (V_{oc})	38.00 V
Maximum operating voltage (V_{mpp})	30.40 V
Short circuit current (I_{sc})	8.98 A
Maximum operating current (I_{mpp})	8.22 A
Maximum power in STC (P_{mpp})	250 W
No. of cells (N_{cell})	60

The number of panels connected in series and in parallel is expressed as:

$$N_{ser} = \frac{V_{pv}}{V_{mpp}} = \frac{292.38V}{30.40V} \cong 10 \quad (3.10)$$

$$N_p = \frac{I_{pv}}{I_{mpp}} = \frac{23.26A}{8.22A} \cong 3 \quad (3.11)$$

The total maximum power and the voltage at maximum power of series connected PV panels are expressed as

$$P_{max\_ser} = P_m N_{ser} = 250W \times 10 = 2500W \quad (3.12)$$

$$V_{max} = V_{mpp} \times N_{ser} = 30.40V \times 10 = 304V \quad (3.13)$$

Similarly, the total maximum power and the current at maximum power of parallel connected PV panels are expressed as

$$P_{max\_p} = P_m N_p = 250W \times 3 = 750W \quad (3.14)$$

$$I_{max} = I_{mpp} N_p = 8.22A \times 3 = 224.66A \quad (3.15)$$

Selecting the solar physical model in MATLAB, the above designed values are to be entered in the solar module given in the utility's icon of the MATLAB software. The values of the series resistance (Rs), saturation current (ISO), temperature coefficient (Ct), etc., can be calculated in the solar module itself, by adjusting the values of R_s I_{so}, C_t, etc., in the solar module we can obtain the desired P-V and I-V curves. The whole design of the PV panel is done at the standard operating conditions of irradiance and temperature, S =1000 W/m^2 and T= 25°C respectively. The I-V and P-V curves of the designed PV panel are shown in Figure 3.4 and Figure 3.5.

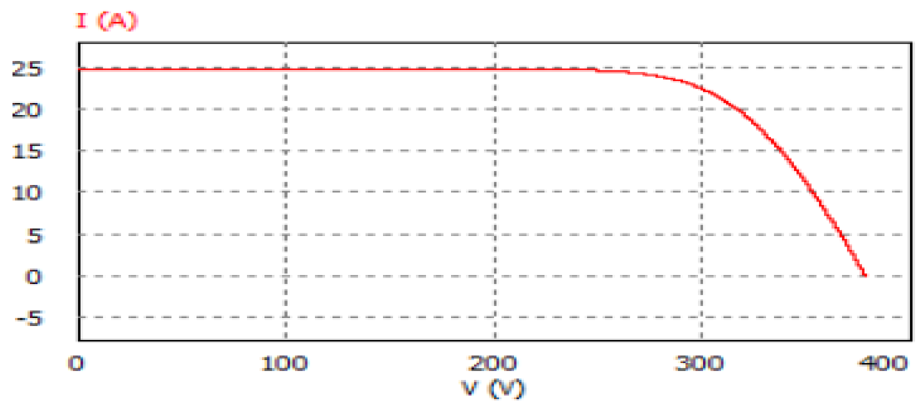

FIGURE 3. 4. I-V curve of the PV Panel

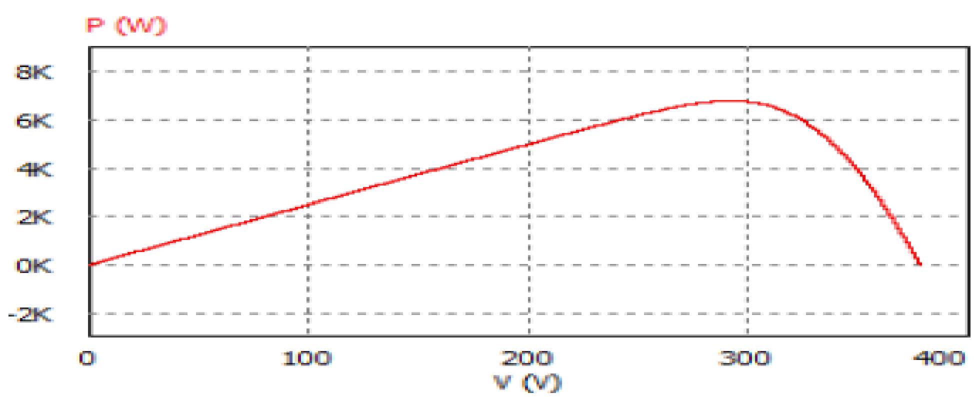

FIGURE 3. 5. P-V curve of the PV panel

3.3.2. DC to DC Converter

The design of five step down dc-dc converter such as buck, buck boost, Cuk, SEPIC and Zeta converter are presented below;

1. Design of buck converter

A buck converter, also referred to as a step-down dc-dc converter, is depicted in Figure 3.6. It consists of dc input voltage source U_s, controlled switch SD, diode D, filter inductor L, filter capacitor C, and load resistance R_L.

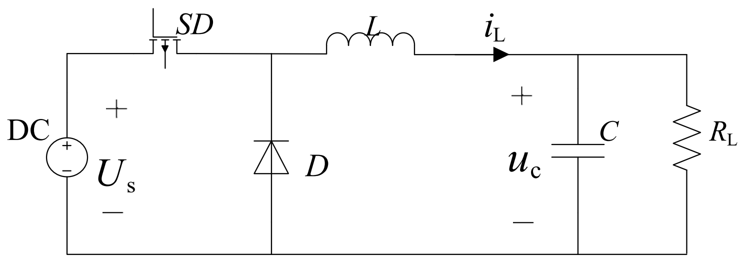

FIGURE 3. 6. buck converter circuit diagram

The value of output voltage, U_o depends on the duty cycle. Equation (3.16) can be used in calculating duty cycle based on the input and output voltage

$$D = \frac{U_o}{U_s} \tag{3.16}$$

Equation (3.17) and (3.18) are used to calculate the value of inductor while designing the buck converter.

$$L_{min} = \frac{(1-D)R}{2f} \tag{3.17}$$

In calculating the value of inductor, it must be 25% greater than the minimum value of inductor, L $_{min}$ obtained in Equation (3.18) to make sure that the circuit will be operated continuously

$$L = 1.25L_{min} \tag{3.18}$$

the maximum inductor current, I $_{max}$ and minimum inductor current, I $_{min}$ can be calculated by using Equation (3.19), (3.20) and (3.21).

$$I_L = \frac{U_o}{R} \tag{3.19}$$

$$I_{max} = I_L + \frac{\Delta i_L}{2} \tag{3.20}$$

$$I_{min} = I_L + \frac{\Delta i_L}{2} \tag{3.21}$$

The value of I $_{min}$ must be positive in order to sustain the continuous current. The value of capacitor can be calculated by using Equation (3.22) with the output ripple voltage which can be defined as a fraction of the output voltage

$$C = \frac{(1 - D)U_o}{8U_r L f^2} \tag{3.22}$$

2. Buck-Boost Converter

A nonisolated (transformerless) topology of the buck-boost converter is shown in Figure 3.7. The converter consists of dc input voltage source V_s, controlled switch S, inductor L_1, diode D, filter capacitor C_1, and load resistance R.

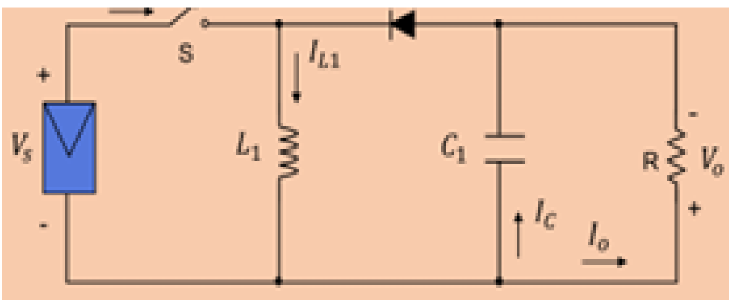

FIGURE 3. 7. Dc buck boost converter circuit diagram

The SPV array voltage at MPP, V_{pv} =V_{mpp} = 290.3V appears as the input voltage source, whereas V_{dc} appears as the output voltage of the buck–boost converter. The duty ratio, D of buck–boost converter is estimated, using the input–output relationship as

$$D = \frac{V_s}{V_s + V_o} \tag{3.23}$$

Neglecting the buck–boost converter losses, an average current flowing through DC motor, I_o is as

$$I_s = \frac{P_{mpp}}{V_s} \tag{3.24}$$

An addition of the two currents, I_s and I_o flow through the inductor, L_1. The inductor, L_1 is estimated as

$$I_o = I_{mpp} + I_s \tag{3.25}$$

The inductor, L_1 is estimated as

$$L_1 = \frac{DV_s}{f_{sw}\Delta I_o} \tag{3.26}$$

Where f_{sw} is the switching frequency of the buck–boost converter and ΔI_o is an amount of ripple permitted in the inductor current.

3. Cuk converter

The circuit of the Cuk converter is shown in Figure 3.8. It consists of dc input voltage source V_s, input inductor L_1, controllable switch S, energy transfer capacitor C_1, diode D, filter inductor L_2, filter capacitor C, and load resistance R.

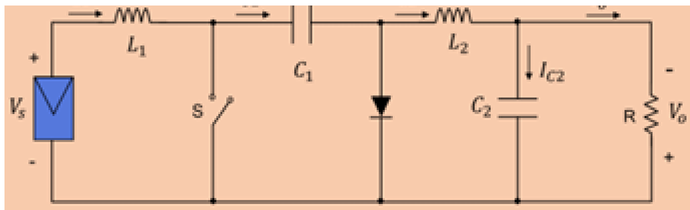

FIGURE 3. 8. Dc Cuk converter circuit diagram

To obtain the dc voltage transfer function of the converter, we shall use the principle that the average current through a capacitor is zero for steady-state operation. Let us assume that inductors L_1 and L_2 are large enough that their ripple current can be neglected. Capacitor C_1 is in steady state if

$$I_{L2} D T_{sw} = I_{L1}(1-D)T_{sw} \tag{3.27}$$

For a lossless converter

$$P_s = V_s I_{L1} = -V_o I_{L2} = P_o \tag{3.28}$$

Combining these two equations, the dc voltage transfer function of the

$$M_V = \frac{V_o}{V_s} = \frac{D}{1-D} \tag{3.29}$$

The boundaries between the CCM and DCM are determined by

$$L_{b1} = \frac{(1-D)R}{2D f_{sw}} \tag{3.30}$$

for L_1 and

$$L_{b2} = \frac{(1-D)R}{2 f_{sw}} \tag{3.31}$$

for L_2.

The output part of the Cuk converter is similar to that of the buck converter. Hence, the expression for the filter capacitor C is

$$C_{min} = \frac{(1-D)V_o}{8 V_r L_2 f_{sw}^2} \tag{3.32}$$

The peak-to-peak ripple voltage in the capacitor C_1 can be estimated as

$$V_{r1} = \frac{DV_o}{C_1 R_f} \tag{3.33}$$

4. SEPIC Converter

Single-ended primary inductor converter (SEPIC) is a type of DC-DC converter, that allows the voltage at its output to be more than, less than, or equal to that at its input. The output voltage of the SEPIC is controlled by the duty cycle of the MOSFET. A SEPIC as shown in figure 3.9 is similar to a traditional buck-boost converter, but has advantages of having non-inverted output, by means of coupling energy from the input to the output is via a series capacitor. When the switch is turned off output voltage drops to 0 V. SEPIC is useful in applications like battery charging where voltage can be above and below that of the regulator output.

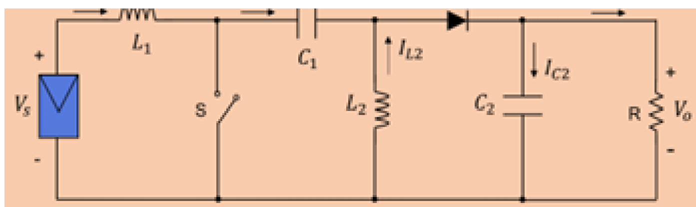

FIGURE 3. 9. Circuit diagram of SEPIC Converter

Duty cycle, D of the SEPIC is estimated as

$$D = \frac{V_o}{V_o + s} \tag{3.34}$$

where V_{dc} is the average value of DC motor voltage. An average current flowing through the DC motor, I_{dc} is estimated as

$$I_o = \frac{P_{mp}}{V_o} \tag{3.35}$$

The design of various components of SEPIC such as an input inductor, L_1; an output inductor, L_2; an intermediate capacitor C_1 and C_2 are designed as

$$L_1 = \frac{DV_s}{f_{sw}\Delta I_{L1}} \tag{3.36}$$

$$L_2 = \frac{(1 - D)V_o}{f_{sw}\Delta I_{L2}} \tag{3.37}$$

$$\omega_h = 2\pi f_h = 2\pi \times \frac{N_{rated} P}{120} \tag{3.38}$$

$$\omega_L = 2\pi f_L = 2\pi \times \frac{NP}{120} \tag{3.39}$$

$$C_h = \frac{I_{dc}}{\delta\omega_h \Delta V_{dc}} \quad (3.40)$$

$$C_L = \frac{I_{dc}}{\delta\omega_L \Delta V_{dc}} \quad (3.41)$$

5. Zeta Converter

The circuit diagram of Zeta converter is depicted in figure 3.10

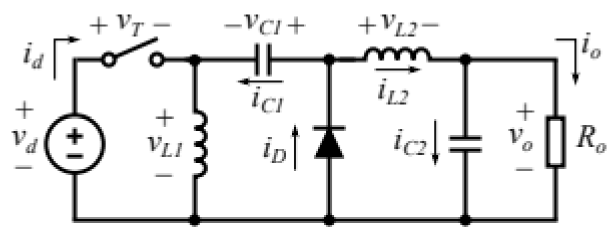

FIGURE 3. 10. Diagram of the Zeta converter

The design equations of the zeta converter are as follows

$$I_{dc} = 21.935A, \delta = 0.514, f_{sw} = 20Kz, V_{pv} = 292.38V, V_{dc} = 310V$$

$$\begin{cases} V_{c1} = V_{dc} = 310V \\ I_{L1} = I_{pv} = 23.26A \\ I_{L2} = I_{dc} = 21.935A \end{cases} \quad (3.42)$$

The capacitor C_1 is expressed as:

$$C_1 = \frac{\delta I_{dc}}{f_{sw} \Delta V_{c1}} = 18.397\mu F \quad (3.43)$$

The inductor L_1

$$L_1 = \frac{\delta V_{pv}}{f_{sw} \Delta I_{L1}} = 10.644mH \quad (3.44)$$

The inductor L_2

$$L_2 = \frac{(1-\delta) V_{pv}}{f_{sw} \Delta I_{L2}} = 11.306mH \quad (3.45)$$

The capacitor C_2 is expressed as:

$$C_2 = \frac{I_{dc}}{\delta\omega_h \Delta V_{dchh}} = 312.7\mu F \quad (3.46)$$

$\varphi_h = \frac{2\pi NP}{120}$

3.3.3. Mathematical modelling of PMDC motor

A permanent magnet DC motor's circuit diagram is shown in Figure 3.11. This is the formula for

$$U = E + IR + U_b \qquad (3.47)$$

Where, U: is the applied voltage

E: is the motor emf

I: is the armature current

R: is the armature resistance

U_b: is the brush dc motor

The PM dc motor emf can be described by:

$$E = K_E\omega \qquad (3.48)$$

Where; $K_E: is\ the\ voltage\ constant$

$\omega: motor\ angular\ speed$

The shaft torque can be expressed as:

$$T = T_{em} - T_o \qquad (3.49)$$

Where; $T: motor\ shaft\ torque$

T_{em}: electromagnetic torque

$T_{em} is\ the\ torque\ (friction\ and\ windage)\ and\ non\ losses.$

The electromagnetic torque is related with armature current as follows

$$T_{em} = K_T I \qquad (3.50)$$

Where: $K_T: the\ torque\ constant$

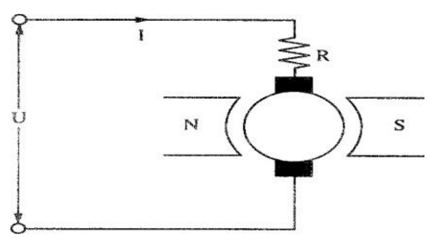

FIGURE 3. 11. schematic diagram of permanent magnet dc motor

The motor losses at load current k can be expressed as:

$$\sum \Delta P = \Delta P_{cu} + \Delta P_b + \Delta P_{Iron} + \Delta P_{mech} + \Delta P_s \qquad (3.51)$$

Where; $\Delta P_{cu} = I^2R$: is the armature copper loss

$\Delta P_b = IU_b: brush\ loss$

$\Delta P_{iron}: armature\ iron\ loss$

$\Delta P_{mech}: fractional\ windage\ loss$

$\Delta P_s: stray - load\ loss$

For a permanent magnet motor the mechanical and iron losses are approximately independent of the armature current and may be estimated from a no-load motor test. The no-load motor losses consist of

$$\sum \Delta P_o = I_o^2 R + I_o U_b + \Delta P_{Iron} + \Delta P_{mech} = U I_o \qquad (3.52)$$

Where; I_o: *no load current*

Since at no-load, the armature losses are very small approximately less than 1% so neglect it. The motor efficiency is expressed as follows:

$$\eta_{motor} = K_T \left(\frac{I - I_o}{I}\right)\left(\frac{\omega}{U}\right) \qquad (3.53)$$

3.3.4. Design of Water Pump

A water pump is selected and is designed using its torque–speed characteristics as:

$$K_p = \frac{T_L}{\omega_m^2} = \frac{7}{(2\pi \times 1750/60)^2} = 0.03821656 \frac{Nm}{(rad/sec)^2} \qquad (3.54)$$

Where; K_p is a constant for selected water pump;

T_L is the load torque offered by pump; and

ω_m is the rated mechanical speed of the rotor in rad/sec.

This designed value of centrifugal water pump is selected for the proposed water pumping system.

CHAPTER FOUR

4. RESULT AND DISCUSSION

4.1. Introduction

This section presents the result and discussion of a comparative study of DC-to-DC converters for solar water pumping systems. The system has been simulated by using MATLAB/Simulink software. The Simulink model of Standalone Solar water pumping system has been shown in figure 4.1.

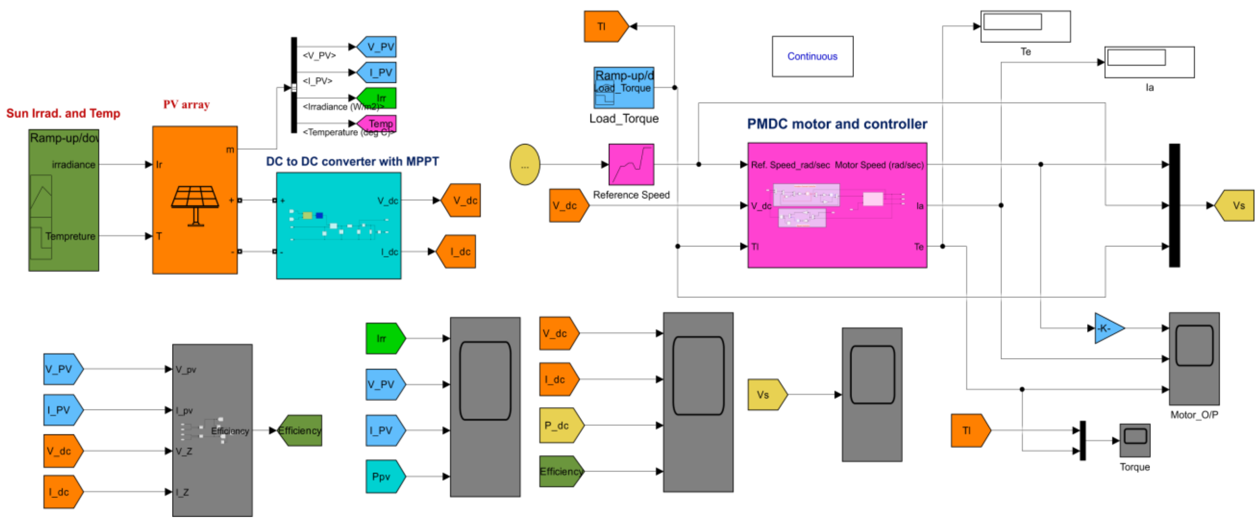

FIGURE 4. 1. Simulink model of standalone solar water pumping system

4.2. Simulation Result

The simulation result of standalone solar water pumping system is organized as follow:

1. The first category discussed the performance of a photovoltaic system at different sun irradiance and fixed temperature
2. The second category discussed the performance and efficiency of different dc to dc converters
3. The last category discussed the performance of PMDC at different load.

4.2.1. PV array

BYD_220- 250P module has been used for this thesis work and this module can produce a maximum power of 250W at STC. 5230W power is generated from the PV array by connecting 9 strings in parallel and two modules in series [appendix A]. The modules I-V and P-V characteristics curves at variable sun irradiance and temperature are shown in figure 4.2 and figure 4.3 respectively.

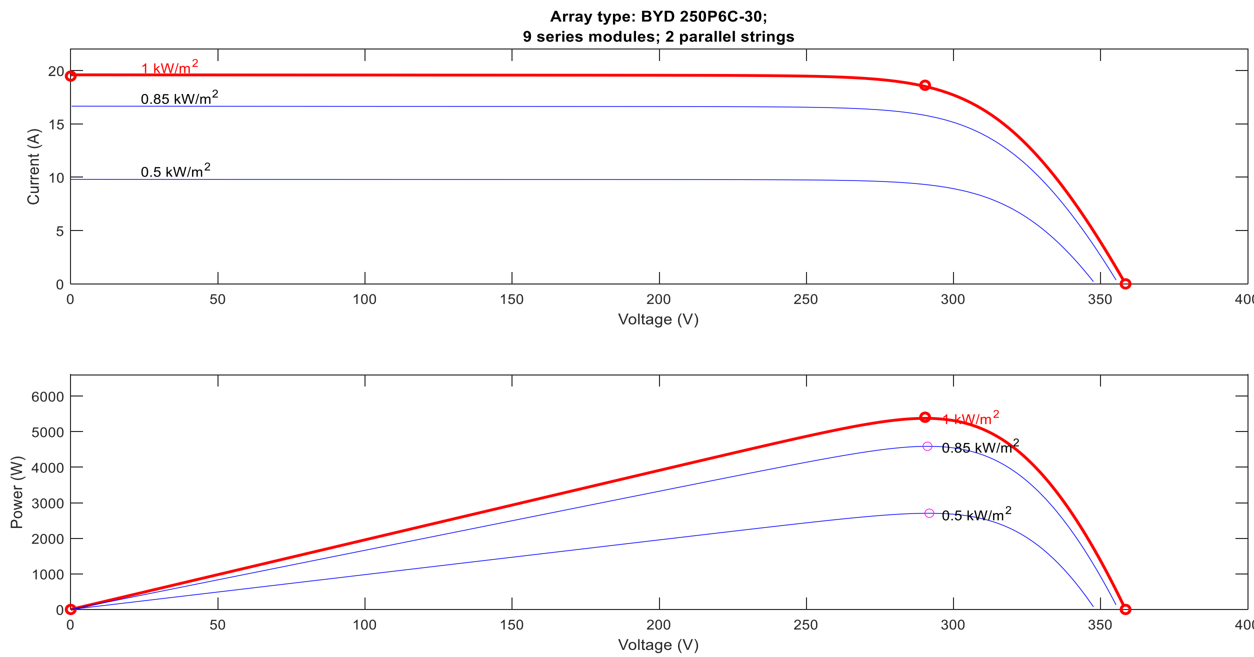

FIGURE 4. 2. PV module's P-V and I-V characteristics curve under fixed temperature and variable sun irradiance

As shown in figure 4.2 the PV array maximum voltage and power at $100W/m^2$ irradiance and 25℃ temperatures are 290.34V and 4506.13W respectively. As the irradiance decrease to $850W/m^2$ array maximum current drops down to 4588.21W however the maximum voltage rise to 291.137V. Similarly, as shown in figure 4.3 when the temperature increases to 45℃, the array voltage and power decreases as well.

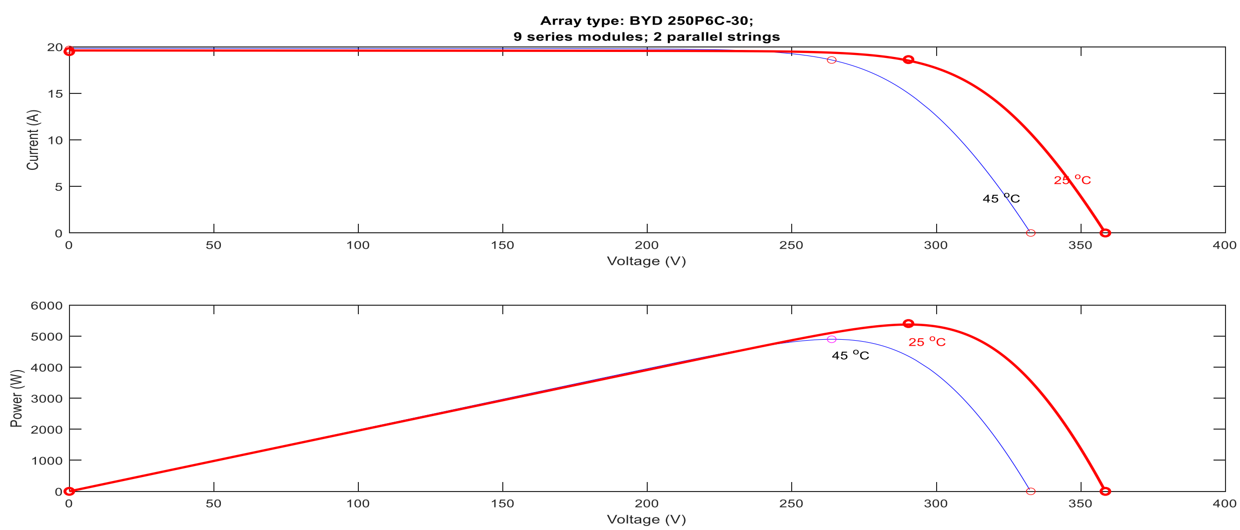

FIGURE 4. 3. PV module's P-V and I-V characteristics curve under fixed irradiance and variable temperature

Temperature and sun irradiance affect, the PV array voltage and current respectively, as the temperature increases the PV array voltage decreases which is less than the PV array maximum voltage, while decrease in temperature result in increase in the volage above the maximum voltage that PV array has to operate. Similarly increase in the sun irradiance also increases the current produced by the PV array which rises the power generated by the PV array and also decrease in sun irradiance result in decrease in current generated by the PV array. Thus, the designed PV array must operate at the maximum power point curve showed in figure 4.2 and 4.3,

To test the standalone solar water pumping system 5 second is taken. Time varying irradiance and fixed temperature are the PV array's input signal. The temperature kept constant at 25℃ is due to the selected location for this thesis work is around 24 ℃, while the sun irradiance varies daily and monthly. The input irradiance signal is start from $1000W/m^2$ then decrease slowly to $850W/m^2$ while keeping the input temperature signal to 25℃. Figure 4.4 shows the input irradiance and temperature signal.

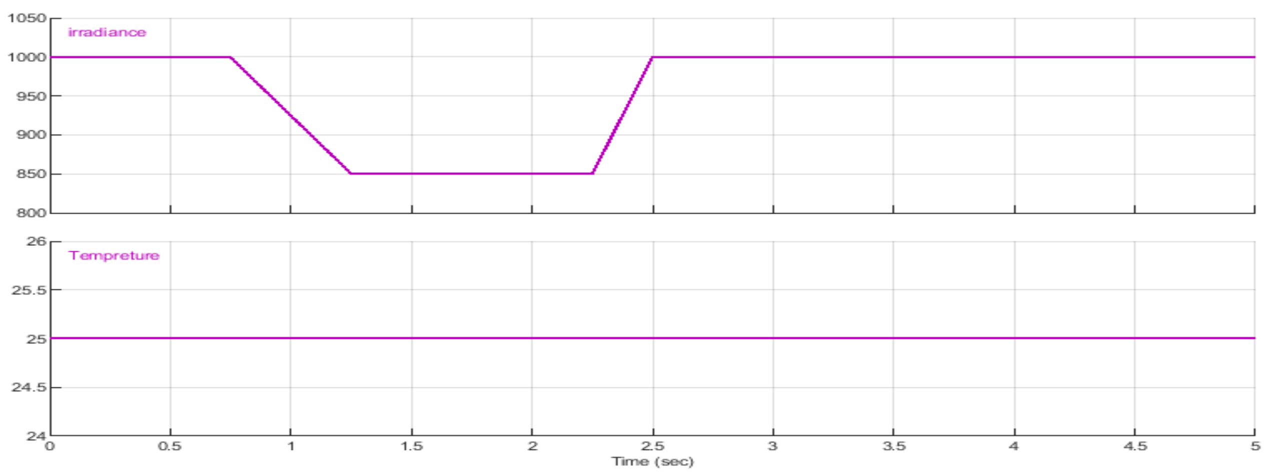

FIGURE 4. 4. Variable sun irradiance and fixed temperature input signal

4.2.2. DC to DC Converter

This section discusses the performance of dc-to-dc converter at different sun irradiance and fixed temperature. Five converters (buck, buck boost, Cuk, SEPIC and Zeta) with perturb and observe maximum power point tracking controller are designed and their performance based on their efficiency are studied.

1. **Buck converter**

Buck converter is a type of step-down dc converter, which decreases the PV voltage to 260V. Figure 4.5 shows the Simulink model of buck converter with perturb and observe maximum power point tracking.

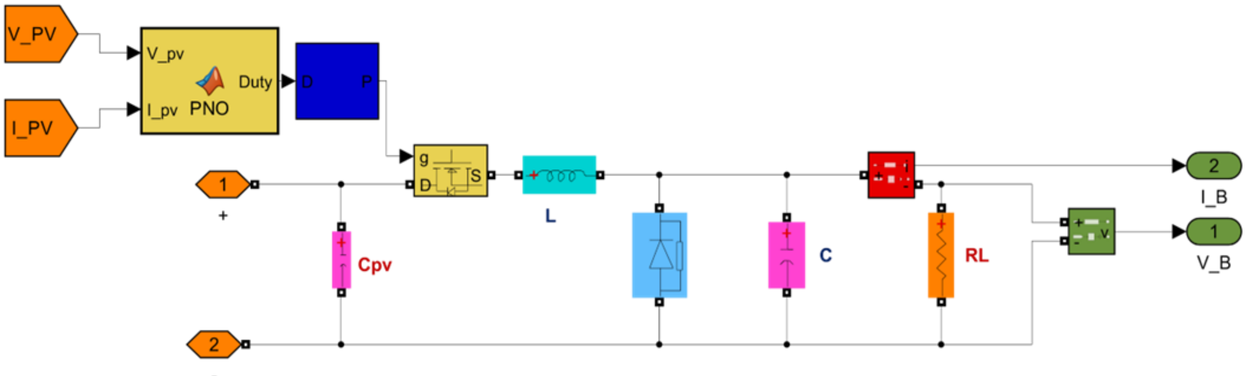

FIGURE 4. 5. Simulink model of buck converter with PO MPPT

Figure 4.6 shows the results of the simulation for the buck DC-DC converter controlled through perturb and observe MPPT controller.

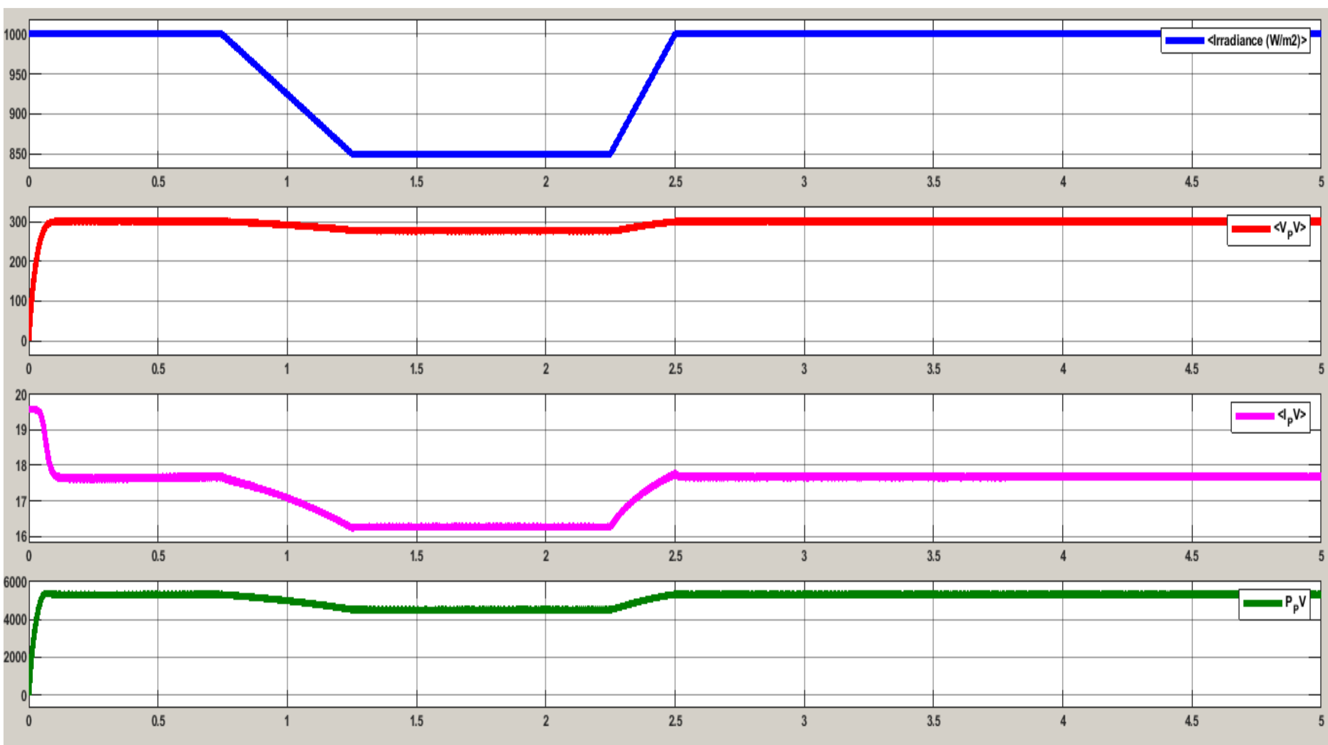

FIGURE 4. 6. Simulation results for buck converter controlled through P&O MPPT controller

As shown in figure 4.6, the X-axis represent time and the Y-axis represents the sun irradiance, PV array voltage, current and power respectively. Figure 4.7 shows the voltage, current, power and efficiency simulation results for buck dc-dc converter controlled through perturb and observe MPPT controller under variable irradiance and fixed temperature.

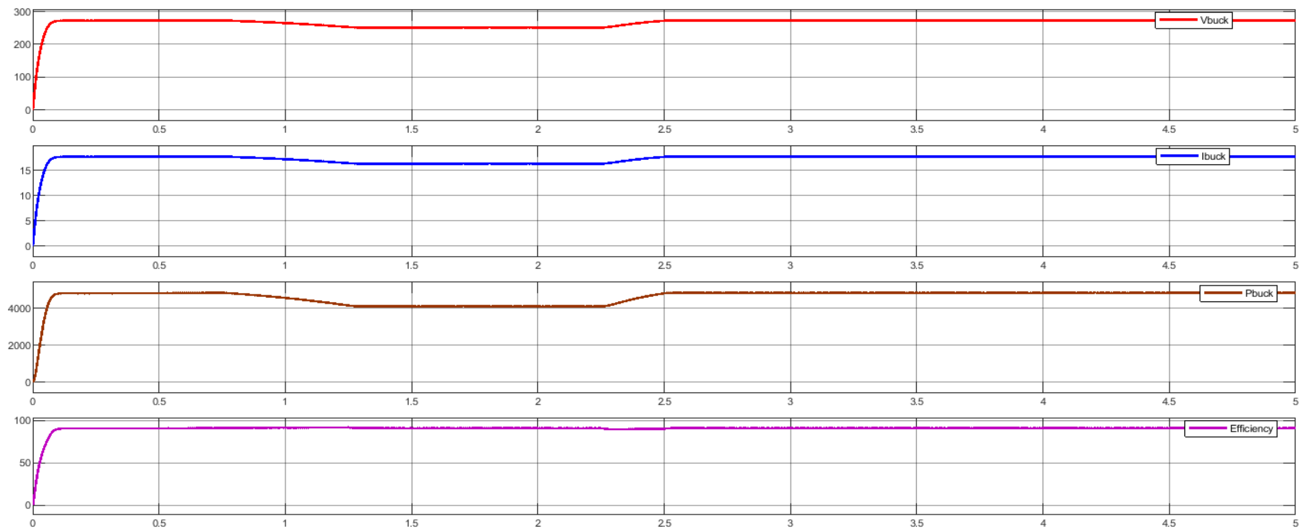

FIGURE 4. 7. waveforms of buck converter

2. **Buck boost Converter**

Figure 4.8 shows the Simulink model of buck boost converter with perturb and observe maximum power point tracking.

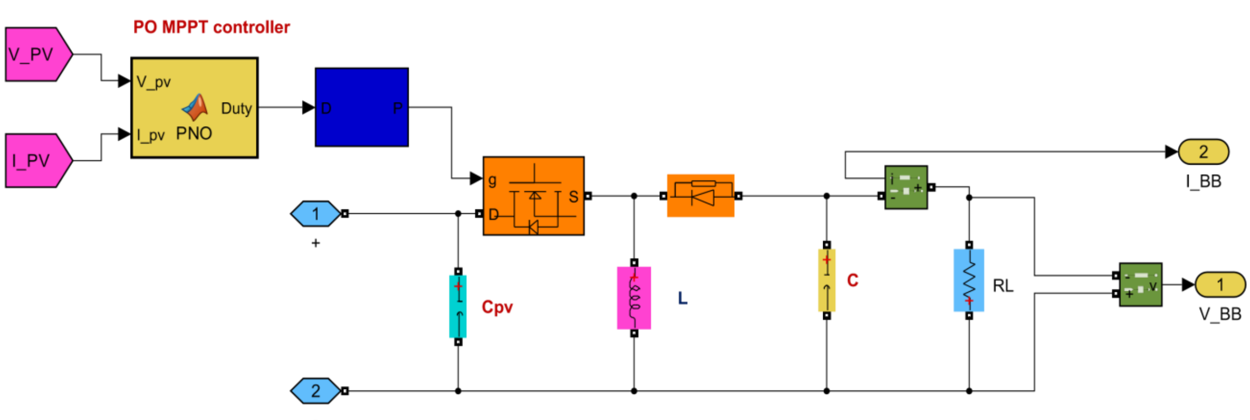

FIGURE 4. 8. Figure 4.8. Simulink model of buck boost converter with PO MPPT

Figure 4.9 shows the simulation results for buck boost dc-dc converter controlled through perturb and observe MPPT controller under variable irradiance and fixed temperature.

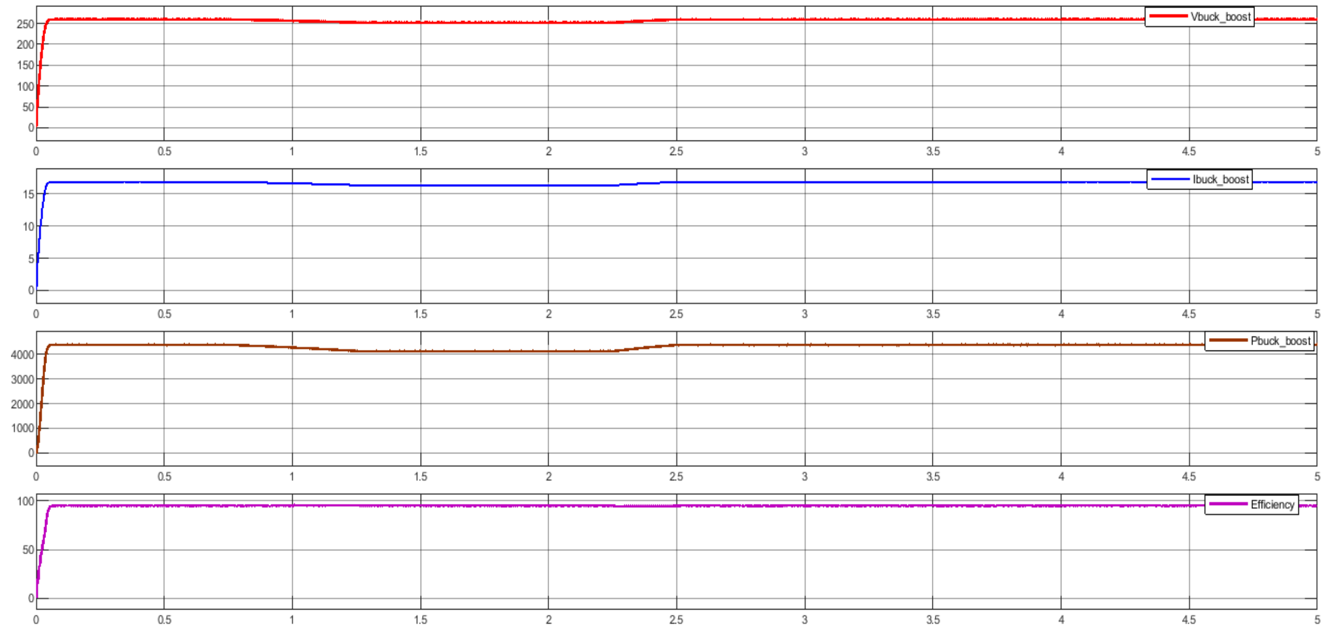

FIGURE 4. 9. Buck boost waveforms

3. Cuk Converter

Figure 4.10 shows the Simulink model of Cuk converter with perturb and observe maximum power point tracking.

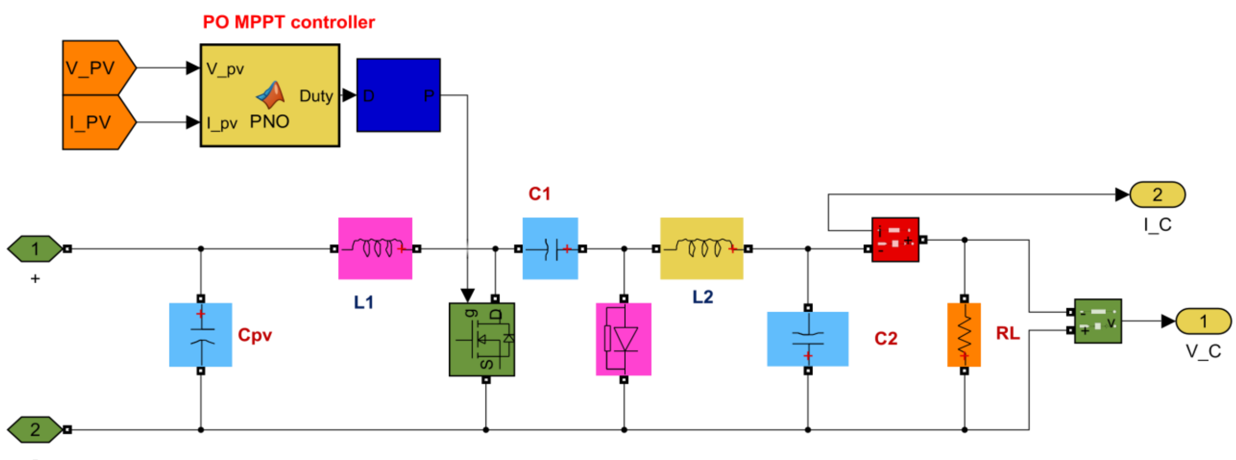

FIGURE 4. 10. Simulink model of Cuk converter with PO MPPT

Figure 4.11 shows the simulation results for Cuk dc-dc converter controlled through perturb and observe MPPT controller under variable irradiance and fixed temperature.

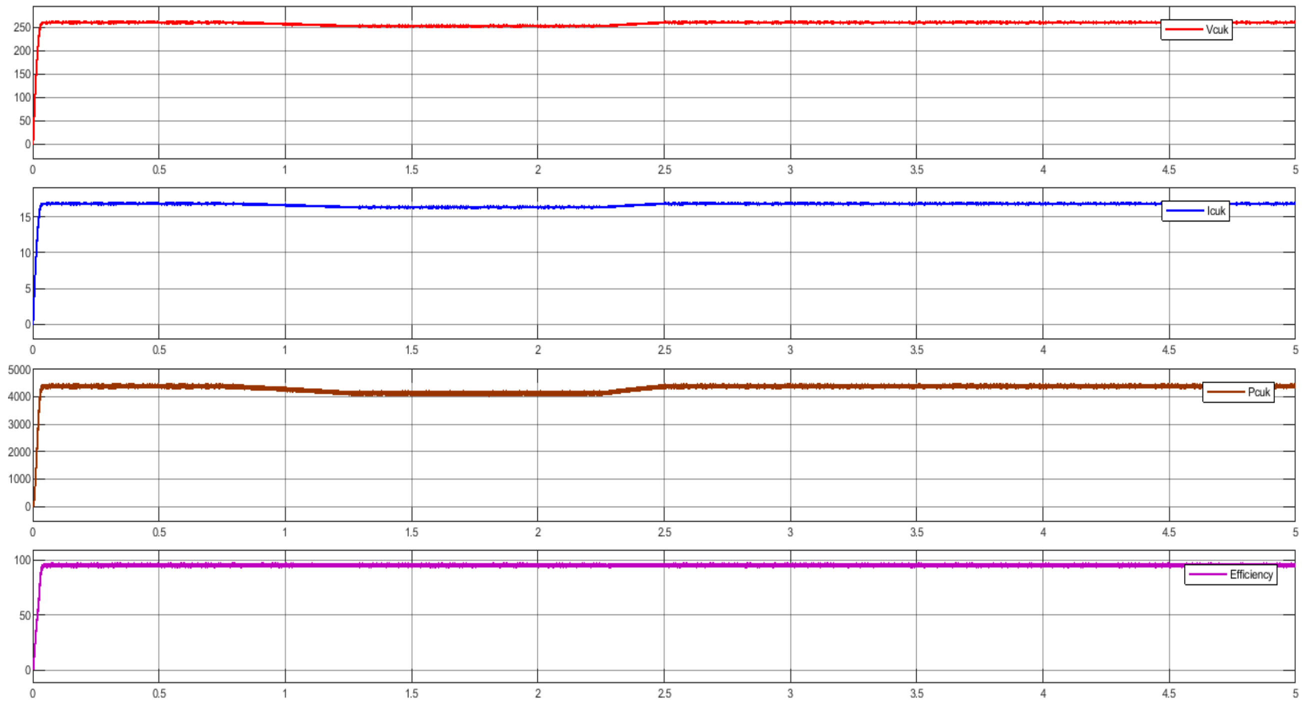

FIGURE 4. 11. Cuk converter waveforms

4. SEPIC Converter

Figure 4.12 shows the Simulink model of SEPIC converter with perturb and observe maximum power point tracking.

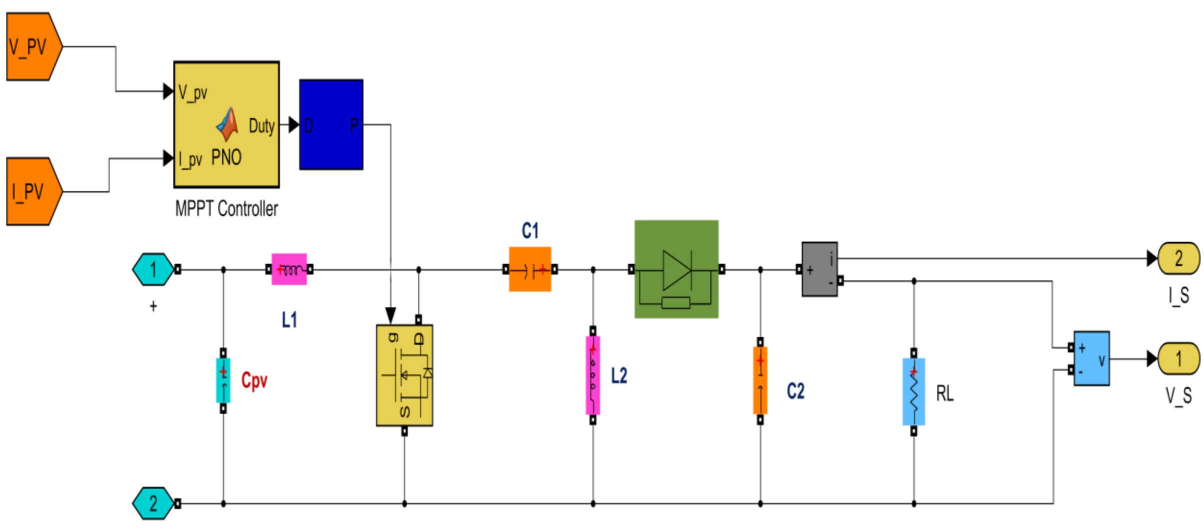

FIGURE 4. 12. Simulink model of SEPIC converter with PO MPPT

Figure 4.13 shows the simulation results for SEPIC dc-dc converter controlled through perturb and observe MPPT controller under variable irradiance and fixed temperature.

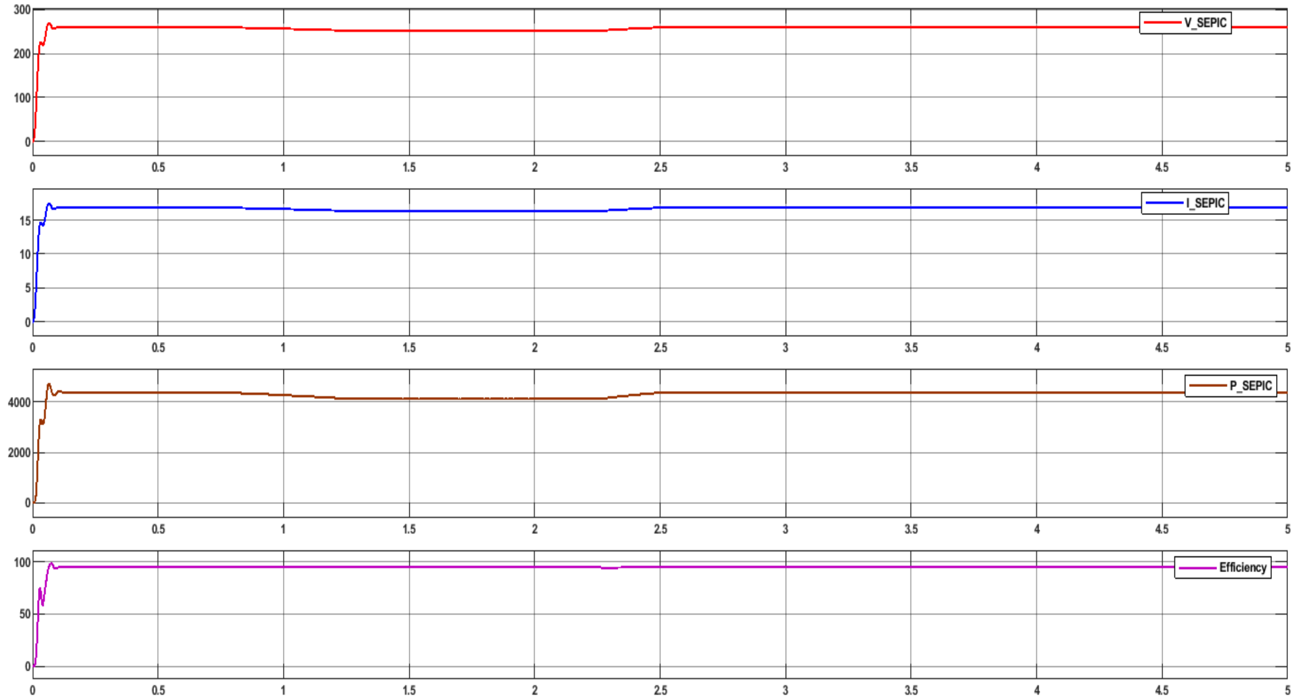

FIGURE 4. 13. SEPIC converter waveforms

5. Zeta Converter

Figure 4.14 shows the Simulink model of Zeta converter with perturb and observe maximum power point tracking.

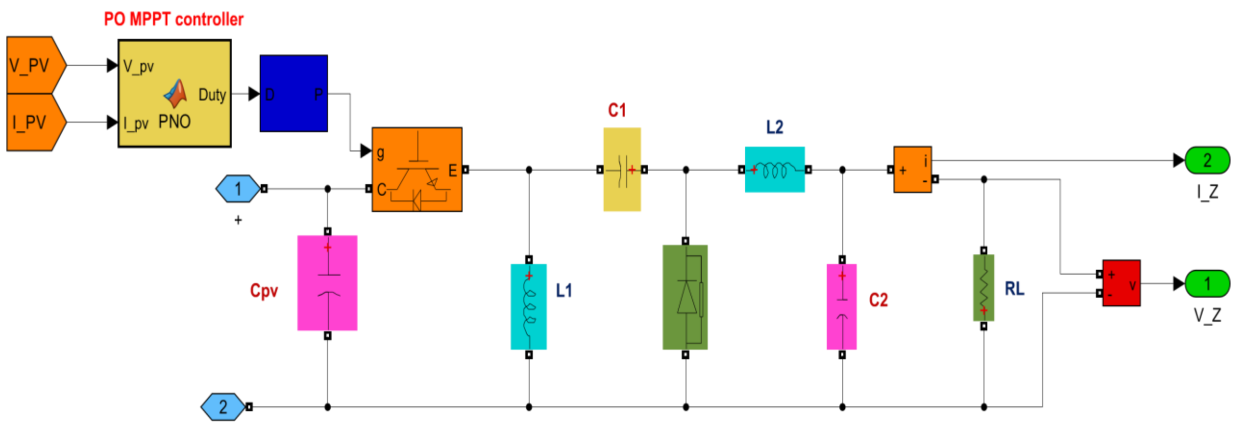

FIGURE 4. 14. Simulink model of Zeta converter with PO MPPT

Figure 4.15 shows the simulation results for Zeta dc-dc converter controlled through perturb and observe MPPT controller under variable irradiance and fixed temperature.

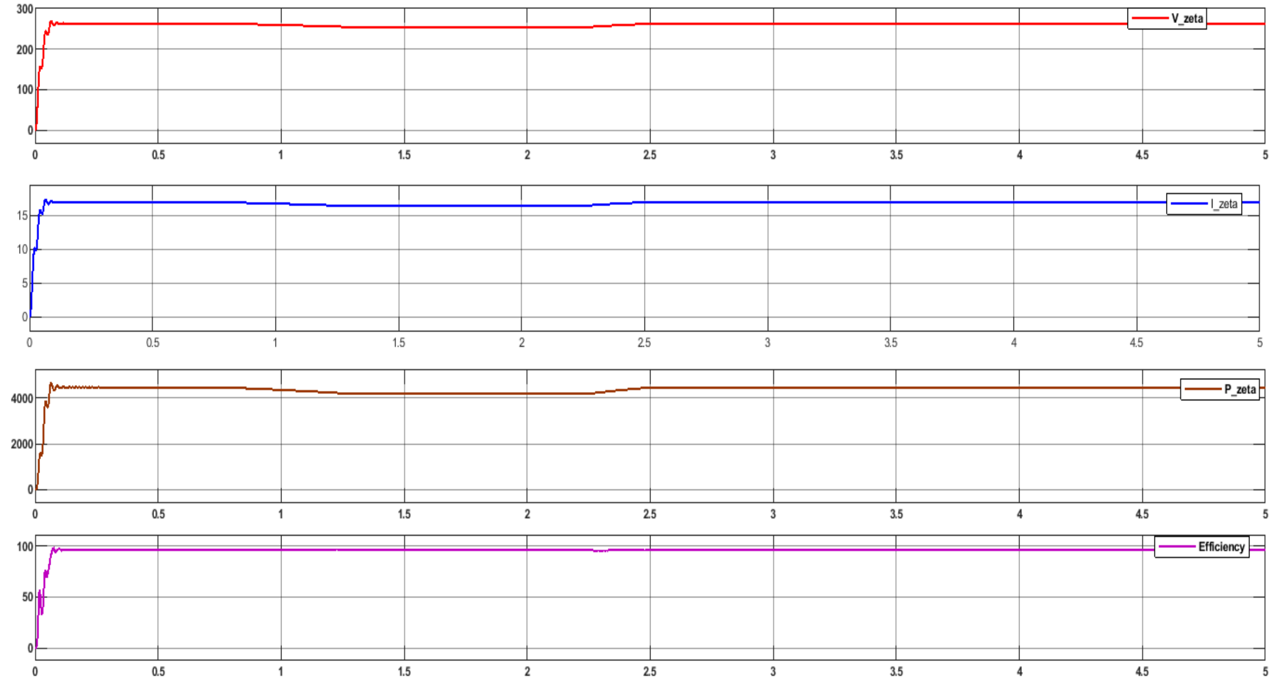

FIGURE 4. 15.Zeta converter waveforms

4.2.3. Discussion

The simulation results of step-down dc to dc converters for standalone solar water pumping system are presented above. Five dc to dc converters are simulated for studying the appropriate and efficient converter for water pumping system. The criteria taken to select the performance of these converters are efficiency. Table 4.1 shows the efficiency of those converters.

TABLE 4. 1. Converters efficiency

Parameter	Buck	Buck boost	Cuk	SEPIC	Zeta
Efficiency (%)	90.9%	95%	94%	95.2%	96.3%

From the above table, Zeta converter has higher efficiency from others with 96.3%, SEPIC and buck boost follows with the efficiency of 95.2% and 95%. Thus, for this thesis Zeta converter is recommended for such types of application.

4.2.4. Permanent magnet dc (PMDC) motor

PMDC motor is used in this research work, armature current controller and speed controller is used to control the motor. The Simulink model of PMDC motor with armature current and speed controller is illustrated in figure 4.15 and figure 4.16.

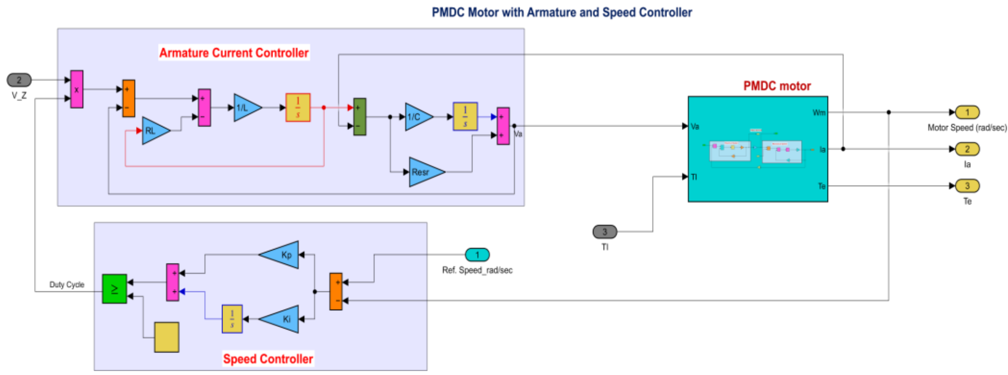

FIGURE 4. 16. Simulink model of PMDC motor with armature current and speed controller

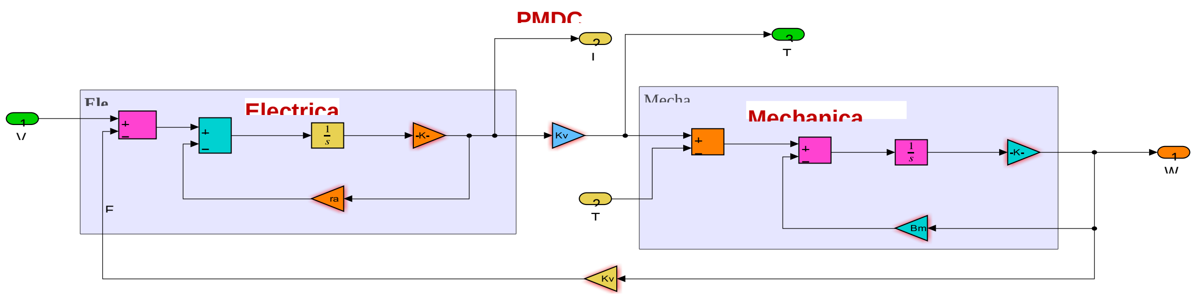

FIGURE 4. 17. Internal block diagram of PMDC motor

In order to study the performance of PMDC motor, variable load torque is provided. The electromagnetic torque is directly proportional to the armature current. Moreover, the load torque is square of the motor torque. Figure 4.17 shows the relationship of load torque and motor speed. As shown in the figure below, the motor speed increases rapidly as the load torque rises from 5 to 22.

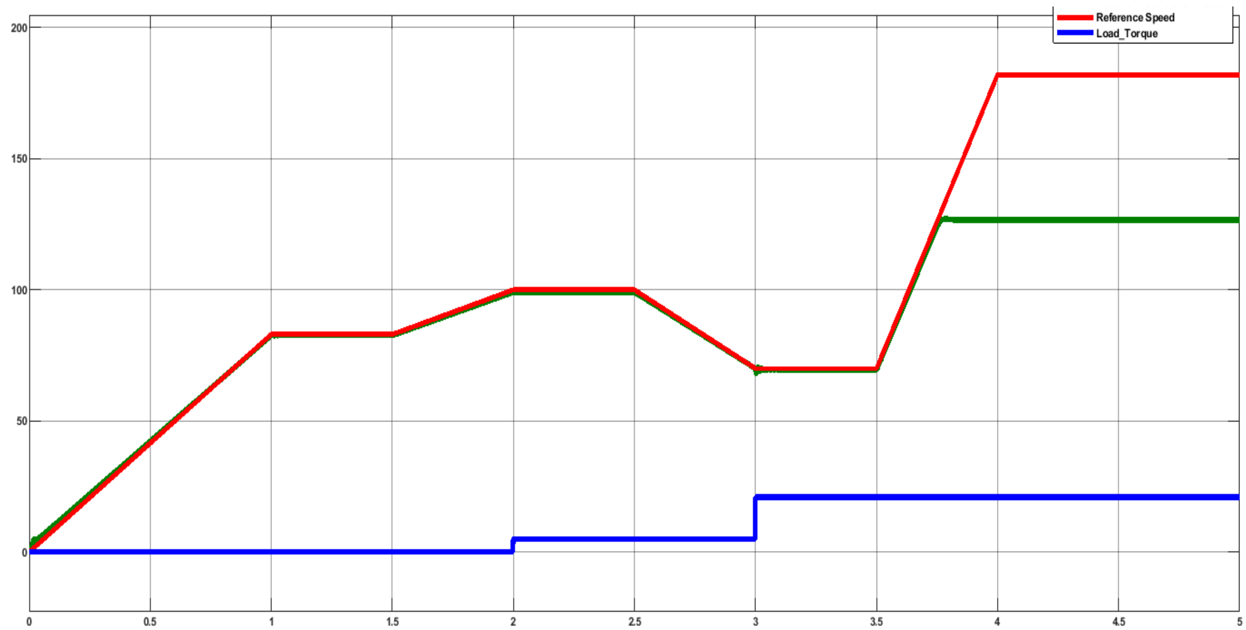

FIGURE 4. 18. simulation results of PMDC motor rotational speed, reference speed and load torque

As shown in figure 4.18, the X-axis represents the time and the Y-axis represent the motor speed, reference speed and load torque. If as the speed decreases, the electromagnet torque becomes greater than the load torque, and the motor can maintain the required torque to drive the load. However, if the load torque becomes too high, the motor may not be able to provide enough electromagnet torque to overcome the load, and the motor will stall or slow down significantly.

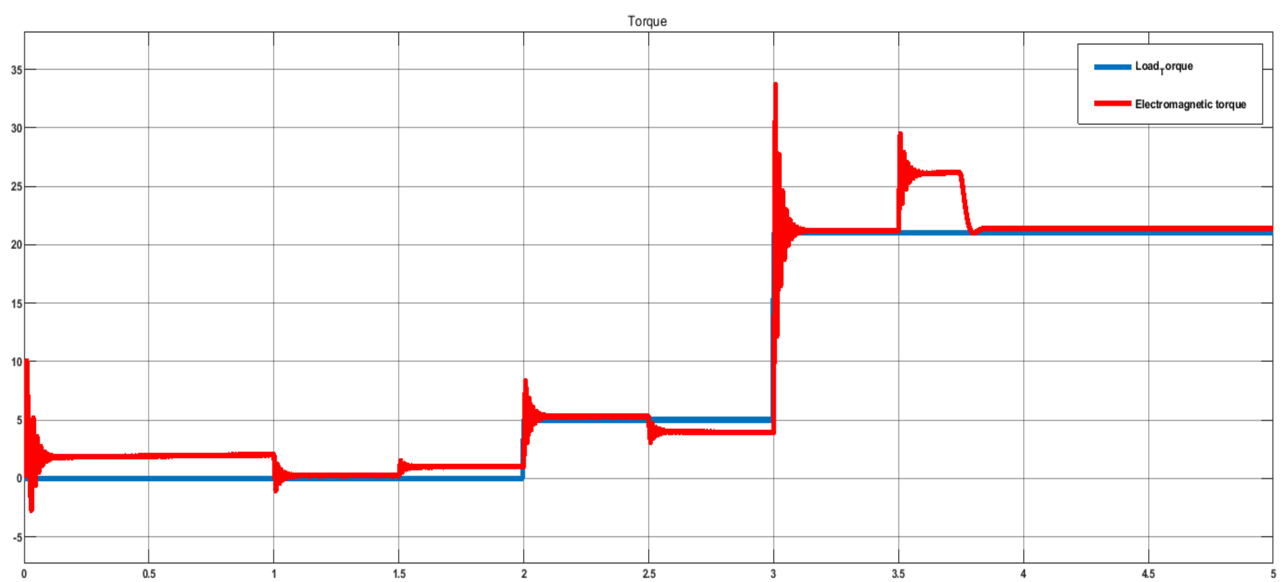

FIGURE 4. 19. PMDC motor electromagnetic torque and load torque relationship

Armature control is used to control the electromagnetic torque. The armature current is directly proportional to the electromagnetic torque. Figure 4.19 shows the relationship between armature current, motor speed and electromagnetic torque.

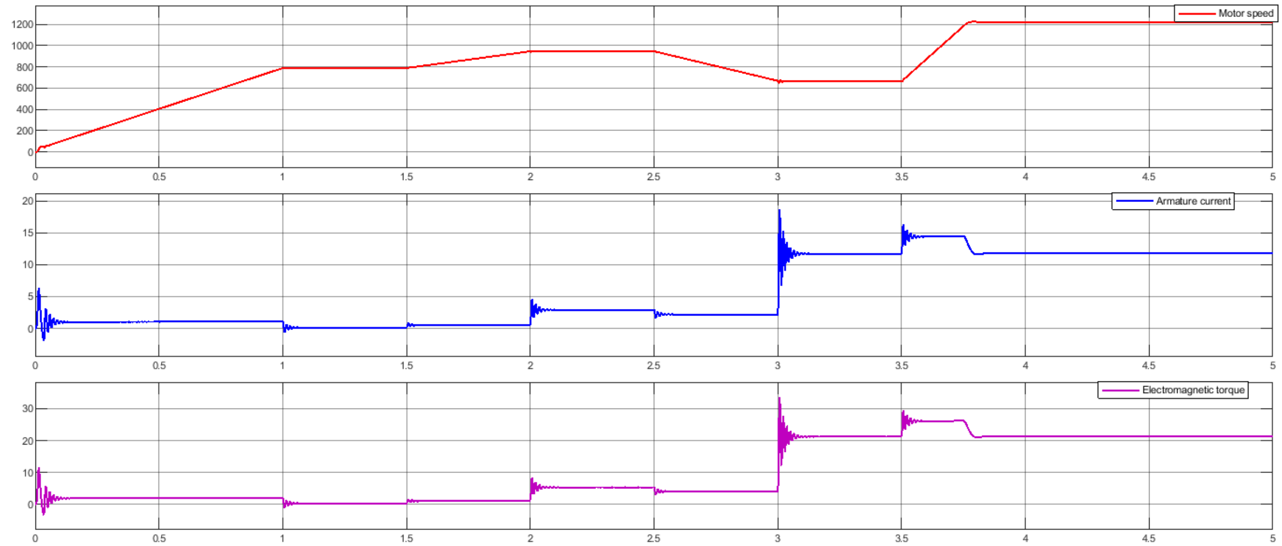

FIGURE 4. 20. PMDC motor rotational speed, armature current and electromagnetic torque simulation results

CHAPTER FIVE

5. CONCLUSION, RECOMMENDATION AND FUTURE WORK

5.1. Conclusion

A comparative study of dc-to-dc converters for a standalone water pumping system has been successfully completed. The system comprises PV generator, step down dc-dc converters and dc motors. Chorora town in west Hararge region is taken as a case study, the town has water and solar resources however the community didn't get clean water and sufficient electricity. Thus, first suitable location has been selected, then the required power capacity has been identified. Based on those results, standalone dc solar water pumping system has been designed and simulated by using MATLAB/Simulink software. The system has been tested by changing sun irradiance from $1000W/m^2$ to $850W/m^2$ by keeping the temperature at 25℃.

Five stepdown dc-dc converters such as buck, buck boost, Cuk, SEPIC and Zeta are compared based on their efficiency. The simulation result showed that zeta converter has maximum efficiency than the others with 96.2% efficiency, then SEPIC took the second with 95.6% and buck boost the third with 95% efficiency and buck took the less efficient dc-dc converter with 90% efficiency.

Moreover, PMDC motor with speed and armature current controller has been used and the simulation result has been tested by supplying variable load torque. The armature current has directly proportional to the motor torque, if the load torque exceeds the motor torque, thus the motor is decelerating. The result showed that controller regulates effectively.

\Finally, I conclude that standalone dc solar water pumping system is operate well, and important for Chorora town in west Hararge region, Ethiopia, dc zeta converter is the most efficient dc-dc converter for such type of application and PMDC motor is recommended for such system.

5.2. Recommendation

The following recommendation are provided:

- Choose the most efficient DC-DC converter topology based on the comparative analysis in the study, ensuring it aligns with the specific power requirements and environmental conditions of the solar water pumping system.

- Implement control strategies that optimize both the speed and torque of the PMDC motor, allowing for adaptive performance based on varying load conditions and solar irradiance.
- Utilize high-quality components in the construction of the solar water pumping system to enhance reliability and efficiency, particularly in the selection of the PMDC motor and the DC-DC converter.
- Conduct field tests in representative rural settings to validate the performance of the solar water pumping system, allowing for real-world data collection and adjustments based on actual operational conditions.

5.3. Future Work

For the future the following parts are added to this thesis

- Investigate additional DC-DC converter topologies beyond those studied, such as resonant converters and advanced control techniques, to further enhance efficiency and performance in solar applications.
- Explore the integration of smart technologies, such as IoT and remote monitoring systems, to optimize the operation and maintenance of solar water pumping systems in real-time.
- Research hybrid systems that combine solar energy with other renewable sources, such as wind or biomass, to improve energy reliability and availability in rural areas.
- Develop and test advanced control algorithms (e.g., fuzzy logic, PID, or model predictive control) for better performance under dynamic load conditions and varying solar irradiance.
- Perform comprehensive economic feasibility studies to evaluate the long-term financial benefits of solar water pumping systems compared to traditional water supply methods.

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Appendix

Appendix A: PV panel Specification

0 10 20 30 40
Voltage(V)

BYD P6C-30 Series Electrical Specification

STC

Item \ Module	BYD 245P6C-30	BYD 250P6C-30	BYD 255P6C-30	BYD 260P6C-30
Open Circuit Voltage (Voc)	37.45 V	37.76V	38.07 V	38.38 V
Maximum Operating Voltage (Vmp)	29.85 V	30.13 V	30.40 V	30.67V
Short Circuit Current (Isc)	8.73 A	8.81A	8.89 A	8.97 A
Maximum Operating Current (Imp)	8.21 A	8.30 A	8.39 A	8.48 A
Maximum Power in STC (Pmax)	245 Wp	250 Wp	255 Wp	260 Wp
Module Efficiency	15.06%	15.37%	15.67%	15.98%
Operating Temperature	-40℃~85℃			
Max. Fuse Current Rating	15A			
Maximum System Voltage	1000 VDC(IEC) / 600 VDC (UL)			
Power Tolerance	0~5W			
Application Classes	Class A			

STC: IRRADIANCE 1000W/m², Module Temperature 25℃, AM=1.5   Ave. efficiency reduction of 4.5% at 200W/m²

NOCT

Item \ Module	BYD 245P6C-30	BYD 250P6C-30	BYD 255P6C-30	BYD 260P6C-30
Open Circuit Voltage (Voc)	34.45 V	34.74 V	34.99 V	35.00 V
Maximum Operating Voltage (Vmp)	27.27 V	27.57 V	27.86 V	28.30 V
Short Circuit Current (Isc)	7.07 A	7.12 A	7.17 A	7.26 A
Maximum Operating Current (Imp)	6.53 A	6.58 A	6.62 A	6.65 A
Maximum Power in NOCT (Pmax)	178.1 Wp	181.4 Wp	184.4 Wp	188.5 Wp

NOCT: open-circuit module operation temperature at 800W/m2 irradiance, 20° C ambient temperature, 1m/s wind speed.

Appendix B: Converters designed values

Converter type: Buck	
Parameter	Value
Decoupling capacitor C_b (μF)	1000
Inductance L_b (mH)	0.008
Capacitance C_b (μF)	1000
Input voltage V_s (V)	291.8
Output voltage V_o (V)	250
Duty cycle D	0.452-0.9
Load resistance R_L (Ω)	15.44
Switching frequency (kHz)	20
Converter type: Buck boost	
Parameter	Value
Inductance L_{bb} (mH)	0.8

Capacitance C_{bb} (μF)	550
Converter type: Cuk	
Parameter	Value
Inductance L_1 (mH)	17.08
Inductance L_2 (mH)	14.07
Capacitance C_1 (μF)	9.59
Capacitance C_2 (μF)	0.405
Converter type: SEPIC	
Parameter	Value
Inductance L_1 (mH)	35.351
Inductance L_2 (mH)	29.1733
Capacitance C_1 (μF)	21.234
Capacitance C_2 (μF)	1059
Converter type: Zeta	
Parameter	Value
Inductance L_1 (mH)	11.75
Inductance L_2 (mH)	11.78
Capacitance C_1 (μF)	226
Capacitance C_2 (μF)	1059

Appendix C: Permanent magnet dc motor parameter

Parameter	Value
Rated power P_a (W)	3700
Rated voltage V_a (V)	240
Rated current I_a (A)	15.416
Angular speed ω_m $(rad)/_{sec}$	132.5
Rated electromagnetic torque T_{em} $(N.m)$	27.9245
Armature resistance r_a (Ω)	2.581
Armature inductance L_a (H)	0.028

Moments of inertia L_a (kgm^2)	0.02215
Viscous friction constant B_m $(kg\,m^2/s)$	0.002953

Appendix D: Perturb and Observe MPPT MATLAB code

```
function Duty = PO_MPPT(V_pv, I_pv)
D = 120e-6;
D_init = 0.452;
D_min=0;
D_max=0.9;
persistent Vold Pold d_old;
if isempty(Vold)
    Vold=0;
    Pold=0;
    d_old=D_init;
end
P= V_pv*I_pv;
dV= V_pv - Vold;
dP= P - Pold;
if dP ~= 0
    if dP > 0
        if dV > 0
            D = d_old - D;
        else
            D = d_old + D;
        end
         else
        if dV > 0
            D = d_old + D;
        else
            D = d_old - D;
        end
    end
else
```

```
    D = d_old;
end
if D >= D_max || D <= D_min
    D = d_old;
end
d_old=D;
Vold=V_pv;
Pold=P;
```