TITLE: *"DC converter design for a DC direct use. Case study: Solar powered Irrigation system at Kabuga, Rwanda "*

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Month and Year of submission: October 2020

DECLARATION

I, the undersigned, declare that this project proposal is my original work, and has not been presented for a degree in University of Rwanda or any other universities. All sources of materials that will be used for the thesis work will have been fully acknowledged.

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This thesis proposal has been submitted for examination with my approval as a university advisor.

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ABSTRACT

A DC-DC booster converter for PV DC direct use was designed within research. A desired voltage of 48V as output from the converter is needed to drive a 0.5hp,10 A Dc water pump for irrigation. The converter input supply is from the PV system, which was designed and calculated dependent on the Rwandan atmosphere and sun oriented conditions. The chose site for the contextual analysis is found at Kabuga, Gasabo, Kigali where a minimum solar insolation at this site is 4.54kwh/m^2.

Selection of component used in this design by looking at the type of the materials was taken into the consideration as a way of ensuring that the converter is providing the maximum efficiency. Polypropylene film capacitor was used at the output to increase the lifetime of the converter due to its good properties like self-healing, diode selection was based on the reverse recovery time in the spirit of avoiding and reducing the reverse conduction losses. The type of switch used is IGBT because of its lower state voltage drop, easy control and the range of frequency the converter is switching on which is 30KHZ in this work.

Voltage control was applied to adjust the voltage output from the DC to DC converter, where PID was the technique employed. Simulation and analysis proved that the output voltage was following the controlled reference given to it despite the fluctuation of the input voltage due to the solar insolation level hence providing a required output voltage to the load.

Key word: DC-DC converter, PV system, PID control, DC direct use.

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GLOSSARY OF TERMS AND ABBREVIAIONS

Terms	**Explanation/Meaning**
PV	Photovoltaics
DC	Direct Current
HVDC	High Voltage Direct Current
AC	Alternating Current
RE	Renewable Energy
DG	Distributed Generation
KVL	Kirchhoff's circuit laws
PWM	Pulse Width Modulation
Cin	Input capacitor
Cout	Output capacitor
ESR	Equivalent Series Resistance
EMI	Electromagnetic interference
MPPF Caps	Metallized Polypropylene Film Capacitors
DF	Dissipation Factor
IGBT	Insulated Gate Bipolar transistor

CHAPTER ONE: INTRODUCTION

1.1 Background

Global warming is now a danger to every human; carbon dioxide emissions [1] are some of global warming's major contributors. The burning of fossil fuels to generate energy from power plants is one cause of carbon dioxide. Gasoline combustion in cars and aircraft also leads to the release into the atmosphere of vast quantities of carbon dioxide. Global climate change is caused by major sources of ozone depleting substances, for example, carbon dioxide, nitrous oxide and methane [2].

The most important and promising solutions to global warming are various applications of renewable energy. This will help to confront this global challenge, without restricting economic and social growth and with an emphasis on protecting the environment for the near future. However, there is a need for more advancement in different kind of such energies to let them be more commercialized, indeed within the household commercial center, by diminishing the costs of the different innovations.

Electrical power is produced, transmitted and distributed in AC form almost exclusively. DC supply, however, is completely essential for some applications. These include variable-speed machinery integrating DC motors, critical sectors where reserves of batteries for storage are needed. Several additional spot bring the ideas about the distribution of dc power; including a development in power electronics, which have made it possible to efficiently convert DC voltage levels and conversion between AC and DC. Sun oriented and wind energy distribution production is developing quickly and both of these sources are naturally DC[3]. A few addition point to take into account are problems such as phase balancing, skin effect; that are not the case in DC systems. In general, a significant amount of equipment in office or household need low voltage DC supply; these appliances are supplied with AC supply and then converted to lower voltage and converted into DC by a built-in circuitry, resulting in additional losses in converting. Furthermore, to the specified variables, the DC might be easily stored as a backup in batteries and fuel cells and after that effortlessly utilized within the occasion of failure of supply [4].

Lately, an increase in numbers of appliances, which operate of DC current such as personal computers and household electronic equipment, has been growing [5]. As power provided from the utility lines is AC instead of DC, the process of converting power the power in supplying DC load gives addition losses thus a decrease in the efficiency [6]. The typical electricity format that comes from outlets is alternating current (AC) power in the most realistic applications. However, as the idea of sustainability by integrating Distributed generation (DG) is gaining popularity, it is understandable that getting power from such renewable sources (RE) fast truck for building plant for power. DG is made up of nearby generator of small capacity and storing devices that produce DC from the supply side, like the PV and fuel cells platforms. Grid connected inverters are used when such systems need to be linked with the main AC power grid [5]. Because DC power is so compatible with the supplied voltage, this form of power is needed by most electronics. This is the reason many electronics are built with a DC power supply source like battery or made up of rectifiers for to change the AC energy taken of the outlet into DC. To increase or lower a voltage to a required level, sometimes the rectifiers are embedded with small transformers in the power suppliers. This work is mainly concentrating to the DC-DC converter design to apply in Photovoltaics DC power direct application.

1.2 Problem statement

The method of energy transfer from traditional energy sources is ruining the environment, leading to extreme and adverse climate instability. The two key issues of providing the needed demand of electricity and by generating minimal harm to the atmosphere are mutually opposed. Energy generation with Distributed renewable sources in one key in addressing such situation [7] [8]. Therefore, there is a significant tendency among various energy-conscious designers to be able of generating electrical power from healthy and replenishing type of energy sources such as wind or solar[9][10].

An increase in the appliances that internally run on DC, can give the capability of DC direct use from renewable energies supplies, thus eliminating some losses associated with the conversion of electricity AC and then back in direct current to supply the loads. The direct application of DC can provide benefits together with versatility. At a higher power quality, it can offer greater efficiency and reliability. As it needs few steps of converting power, reduced amount of copper, and less floor space, it can also provide reduced installation costs. In reality, many devices, including computers, run at a lower voltage than the one supplied, and they usually need Universal Power Supply within their housing and this requires a transformer for stepping down which result in addition design cost.

An efficient, controlled and cost effective DC-DC converter can help in addressing some of those challenges stated above within the context of supplying DC load with direct current at the first hand. However, most of the designed converter do not consider much on correctly selecting the components to use based on materials properties. The characteristics of matters which makes capacitors, inductors, switching devices and diodes contributes a lot on the overall converter performance and power losses. By taking into account all, those mentioned points; it is obvious that by establishing a powerful DC-DC converter for dc direct use can save a lot in terms of power loss and systems' cost.

1.3 Objectives

1.3.1 Major objectives

An overall goal of this thesis to design an efficient DC-DC booster converter, to show how the PV system can be directly used for irrigation. The system will be cost effective by excluding the storage batteries and inverter. This will also help to minimize the greenhouse gas emission, since the system will be solar based and therefore, renewable and sustainable.

1.3.2 Specific objectives

Here are the definite scheme to be addressed within this study:

- Analysis of various conventional DC-DC converter topologies
- Comparing AC and DC distribution structure
- Designing a controllable circuit that allows modulating the converter output voltage in the required ranges by adjusting the duty cycle
- Model and simulate the designed system
- Take out suitable conclusion and recommendation from the analysis of the study

1.4 Hypothesis

PV systems DC direct use by eliminating inverters and batteries storage can help to increase efficiency and effectiveness of the system.

1.5 Scope of the study

The emphasis of this work is primarily on the modelling and simulations of a DC to DC converter that is reliable and cost-effective. The study analysis are conducted toward DC direct use in PV powered water pumping irrigation structure. The Rwandan climate and solar radiation conditions are the basis for this research analysis; the site chosen as a case study is located in Kabuga, Kigali. With MATLAB SIMULINK, the completed built model and its analysis are simulated.

1.6 Expected outcomes and significance of the study

1.6.1 Expected outcome of the study

The study anticipate showing that PV DC direct utilization can effective in comparison with battery or inverter coupled systems. It is predicted that the cost of such systems will be much lower and that the performance, efficiency, controllability and lifespan of the DC-DC converter built for such a Photovoltaic system much higher.

1.6.2 Significance of the study

High performance, diminished stresses applied on semiconductors, reduced price, Simplicity and solidity of topology incorporated are often correlated with the most important factor in dc to dc conversion. Due to its broad applicability, boost dc-dc converters has become very common in the last few years, in particular, keeping in mind that dc-ac converters usually requires a high DC voltage supply. For this reason, the most common topology is a traditional non-isolated boost converter, even though the effectiveness of conversation is restricted at certain value of duty ratio. To manage dealing with this constraint, there have been different derived topologies. Besides this, more research have been put into the control system technologies depending on desired application of the converter. In this regard, this study will emphasize more on the selection of components to be used in the converter design; choosing semiconductor by taking into account the characteristics like coil type on inductors, dielectric material for capacitor can contribute in making a great DC-DC converter.

There are different technics of controlling PV systems with the purpose of extracting maximum power, but this work will focus more of the converter controllability as another approach of providing the required output power in an effective way. In this study, a bigger focus is made on voltage controlling where PID control is the chosen approach. All these have a clear intention of looking at PV dc direct viability, which can minimize the number of conversation stages when supplying DC loads, and by minimizing unwanted power losses and stress on the converter.

1.6.3 Related works

Power conversion transforms electrical energy from one form to another. This involves changing from AC to DC or vice versa [11]. Past works classify a DC to DC converter as an electronic circuit which is able of adjusting a DC voltage given to it from one level to another [11][12]. Several isolated dc-dc converter topologies have been suggested in the past, some of them were based on providing high-voltage gain by increasing a high-frequency transformer's turn ratio.

Z.Chen, S.Lium and L.Shi[13] suggested and addressed a full-bridge converter for phase-shift zero voltage switching (ZVS) pulse width modulation (PWM). Where by utilizing a high-leakage inductance of the transformer, zero-voltage switching over a large load range can be achieved. There are important drawbacks, however, such as high-circulating current; the voltage stress around the output diode becomes considerably greater than the output voltage. The additional downside is that converter efficiency is diminished in applications where the output voltage is high. Moreover, in some applications, the pulsating input current is restricted such in area of PV application; due to the fact, it might degrade the lifespan of the arrays. [14].

X.Hu and C.Gong in [15] proposed a high voltage gain dc-dc converter combining coupled-inductor with extended voltage doubler and coupled-capacitor methods. With the required duty cycle and reduction of voltage stress on the power devices, the proposed converter achieves an incredibly high voltage conversion proportion. Moreover, the energy contained in the coupled inductor leakage inductance is efficiently delivered to the output, and the double voltage cell acts as a regenerative clamping circuit, alleviating the issue of potential resonance between the leakage inductance and the output diode junction capacitor.

These characteristics allow a compact circuit to be designed for industry applications with high static gain and high performance. Furthermore, the unexpected high-pulsed input current in the inductor-coupled converter is minimized. One of the research they listed in their work is that non-isolated dc-dc converters can be used to achieve voltage step-up or step-down in situations where galvanic insulation is not mandatory, with resulting decrease in size, weight and volume related with efficiency improvement because of the absence of a high-frequency transformer. In this regard, it is obvious that it is important to consider many aspects in order to decide which topology is the foremost reasonable for a given application that includes the utilization of electronic power converters. Cost, control strategies, effectiveness, useful perspectives, and power density are taken as fundamental issues [16].

J.paulo and Fernando L.Tofoli[17] proposed a comparative analysis of non-isolated dc-dc converters by applying the principle of commutation power .It has been demonstrated that the proposed approach comprises of a basic and fast standard that permits the most appropriate topology to be characterized for a given working circumstance, considering the efficiency perspective.

It has been indicated that the buck or boost converter normally implies upgraded output contrasted with buck-boost equivalents for applications including dc voltage step down or voltage step up. This can be clarified since the latter topologies have higher commutative power outcomes. The exact measurement of switching and conduction losses using the SPICE simulation program also proved that the switching power is straightforwardly linked to the converters' loss mechanism. There are also substantial losses and consequently reduced efficiency in systems with high commutative strength. The study established has also shown that correct element specification is a concerning issue that influences the efficiency of the converter. The term adopted is intended to be used for qualitative purposes, far from being a definitive criterion for an exhaustive comparison of converter topologies, since only the intrinsic characteristics of a given structure are taken under consideration. It is evident from the work that studies that are more detailed are required in this case, taking into account the cost of power circuit elements and drive circuitry component. Magnetic and heat sink size and capacity, as well as many other related features.

In such manner, clearly it is imperative to consider numerous viewpoints to choose which topology is the most reasonable for a given application that includes the utilization of electronic power DC-DC converters.

1.7 Thesis outline

This study is structured as follows: Chapter 2 compares DC and AC; Chapter 3 and 4 respectively examine traditional DC converter topologies and the construction of a DC converter for direct DC use. Chapter 5 describes the simulation and discussion of the outcomes for the designed system.

CHAPTER TWO: Dc and AC comparison

2.1 Background

Everything started in the last part of the 1880s, where two types of currents were made by the two innovators and specialists, Nicola Tesla and Thomas Edison. The occurrences encompassing these two sorts of currents are referred to today as "War of currents." Direct current (DC) [18] was created by Thomas Edison, where the current runs consistently a one way, as in case of batteries. One significant issue Edison had was that it was hard to change over DC among higher and lower voltages back then, since the innovation was not yet made for that.

Then again, Nicola Tesla had created (AC) alternating current, which around then ended up being the arrangement that was appropriate. The clarification for this is that, utilizing a transformer, AC can be effectively changed from lower and higher voltage or vice versa. Thus, for several years, the events of the "War of Currents" influenced electrical development in a direction dominated by AC. However, there has been an uprising of research and new application possibilities for the use of DC.

For a long time, the supply of electricity was based on AC power grid, as transformers can easily change the AC voltage [19]. In the past, the DC voltage was hard to change. The development in the electronic power field, however, has made the transformation of DC voltage a lot simpler and more successful. Furthermore, in recent years, the application of DC supplied loads and sources of Dc power (for example photovoltaic, battery-operated) has expanded significantly [20]. As a result, more focus is now drawn to the DC distribution network than ever. The following advantages are included in the DC distribution systems. [21] First, in the DC systems, the stages of DC to AC or AC to DC transformation steps that come back in AC systems can be skipped and this will improve the system's operating efficiency and power quality. In general, various renewable energy sources (RESs) such as photovoltaics and wind typically generate DC power directly, and then it is converted to AC. In addition, there are major new DC loads emerging such as electric vehicles and electronic devices, so connecting them directly to DC systems will be more advantageous. It is also worth noting that DC systems [22] can remove the drawbacks of AC systems, such as frequency control, reactive power flow, synchronization and harmonics. The utilization of DC power for business and in households is not a completely new phenomenon; hence, several studies have been performed in this area of DC use and are still ongoing.

2.2 High voltage DC transmission lines

Transmission lines of DC higher voltage ratings (HVDC) are among foremost effective means to transfer large quantities of power over long distances in today's electrical grid. In the case of overhead, underground and subsea lines such type of lines are efficient. In economic and environmental terms, the utilization of HVDC in transmission lines ends up being significantly more effective contrasted with HVAC transmission lines [23].

The fact that it is asynchronous is among significant attractive reasons of integrating HVDC. It does not have frequency, in other words; an advantage of not having a frequency is that, without synchronization, it is still possible to transfer power within two energy grids. Addition advantage of using HVDC transmission line is that the cost of materials and construction costs are much lower. It is achievable to transmit HVDC by one single lime and the ground; recognized as unipolar connection. On the other hand, power may be conducted with a bipolar connection approach, where two conductors can be used instead of three. On the other side, due to the way AC operates, HVAC uses three conductors.

Power losses are proportional with the length of the transmission line. Transmitting with HVDC removes some losses regardless of the distance in comparison with HVAC due to some parameters found in AC and not in DC. Those include skin effect losses, and reactive loosed, while on the other hand DC only deals mostly with resistive losses.

Evaluation of losses in HVDC compared with HVAC transmission was performed by authors in [23] [24]. The results of the assessment and calculations in [23] indicate that the loss difference between HVAC and HVDC is marginal on short transmission lines (50 km range). As indicated in table 1 below, when the transmission line length increases at 100 km or 150 km, there is also a significant losses increment within HVAC. Instead, for HVDC transmission line side has small changes in the total losses, nevertheless in the line extent.

Table 1: Losses depending on lengths in HVAC and HVDC transmission lines[23]

Length [Km]	HVDC losses [%]	HVAC losses [%]
50	4.26	5.3
100	4.73	8.04
150	4.77	19

Concerning development and economy in utilizing HVDC transmission lines, there are also drawbacks. The production of equipment such as high power converters is not that much developed because of the AC supremacy in the power networks for a long time. The impact of this is that the converter innovation utilized in HVDC lines is expensive. These converters likewise have an issue of generating harmonics, thus there is a need of addition filters for them.

Despite the fact that HVDC transmission lines have the two points of interest and disservices, they are all around demonstrated as a suitable remedy. By reliability, stability and overall performance, integration of DC in distribution assembly demonstrate having a positive impact on the future energy sector. The knowledge derived from the structure and study of HVDC may lead to the evolution of the distribution grid for DC [25].

2.3 DC in Distribution grid and its advantages

A highly efficient power supply is of great significance in our modern society. The explanation for this is that the most important appliances, such as hospitals, data centers and communication networks, rely on a continuous and reliable flow of electricity. With current solutions, power electronic converters are used widely, proving to be extremely effective and quick to monitor. With these power converters, however, there are also some performance concerns, considering that there are multiple steps of converting interchange. This outcome lower than desired overall system efficiency. DC power distribution systems ended up as a topic of research, which has attracted interest because of this. First, the motivation for DC development was because in long-distance power transmission DC was more effective when is used[23]. Reason being that only active without reactive power is transmitted without reactive as in case of AC, thus a reduction in losses [25].

Replenishing energy type such as wind and photovoltaics PV) [26] are becoming greatly significant in recent times. For being possible to inject this power into the grid, as they produce DC, that implies an AC to DC conversation step; it is also important to synchronize first. A DC distribution grid is a fascinating proposal with these kinds of power sources that could be important to the micro or nano grids, which are consolidated [27]. While interesting in what to come, this study will not cover a deeper insight into microgrid and nanogrid, yet it worth noting that they might be huge.

The introduction of DC can result in decreasing the number of stages of converting power that can have impact on the total energy lost in grid [22]. Several variables need to be addressed to introduce a DC distribution grid. This include how power will be transmitted and how the grid's interconnections should be designed. This suggests that it is imperative to see at practical alternatives for where DC can be utilized within the network, and how it can branch out to clients as far as possible. How to deal with the existing structure, looking if some of it can be reused. The AC system and the cables in use that are already installed might be saved and utilized in coming DC. There should be a system of standard voltage magnitudes for the distribution system must be developed and set up; several different suggestions for this voltage need to be discussed, and how they can be resolved.

Since one of DC's talking points in power delivery is that it is more efficient[23]. A lot issues need more study in regards with of DC 's efficiency, how and what makes it more effective. These include comparing conversation and conduction losses found in AC with those in DC.

2.4 AC grid distribution

As stated earlier, AC has long been the only type used since Westinghouse and Tesla won "the War of Currents". Reason being that it has been very simple to transform it to a certain needed voltage magnitude in an adaptive manner.

Transformers are effective approach to change and in voltage monitoring. The control of voltage level is accomplished by using tap changers, which are around at either side of the transformer by controlling the number of turns. Tap changers are in two categories; on-load and off-load ones [29]. On-load tap-changers can vary the number of turns, which goes with the voltage level even when they are connected; these are mostly found at the generation plant or in substation with power transformers. Only when it is not linked to any load [29] can the Of-load tap changer vary its turns.

The ability to control voltage easily is what made AC the preferred option in the distribution grid for long time.

The AC innovation has been around for such a long time; therefore, the infrastructure is focused on it in societies. In other words, the electric grid is largely based on AC around the world, which facilitated AC based invention development and standard establishment. Thus, influencing the cost of direct current equipment for power system, which are much costly relative to the counterpart of AC. these are like protective circuit breakers, and the stated case depend on the characteristics of AC vs DC as well as a clear big development in todays used AC appliance [30].

While AC has its advantages in general, it has drawbacks as well. One of the main AC flaws, for example, is that many electrical appliance are supplied by DC for smother functionality; which indicate why a rectifier that converts AC to DC [31] is required for any system of this type. Besides that, the output from renewable sources such as PV is direct current; a number of losses is generated while converting the generated energy into AC form. Mostly, this energy has to be converted back into DC again at the stage of supplying the load. AC has addition challenge like Corona and skin effect which affect the cable conductivity [25] resulting into more losses and HVAC lower transport capability [32]. Frequency synchronization when linking different grids is also an issue in regards to the failures and controllability behind it.

CHAPTER 3. CONVENTIONAL DC CONVERTER TOPOLOGIES

3.1 Converters

Converters of some type are in use in the transmission system, distribution system and households. There are many kinds of converters, with various usage areas. For instance, DC is a productive method of transporting energy on long distance transmission lines. The converter is in use at both ends of a DC transmission line [33]. The four power converting methods are:

- AC -DC (rectifier)
- DC -AC (inverter)
- DC - DC (converter)
- AC- AC converter

Since the present work intends at showing how the DC converter can be in DC direct use, the following section reviews different types of DC-DC converters.

3.2 AC to DC converters

When considering the method of providing power to the household, the line current from a transmission system are predominantly AC. Even if most of home apparatus are plugged into the socket, a current they need to work is DC. The aim of the AC to DC converter given in Fig.1 is to convert the input alternating current into an output direct current [34]; Rectification is term used for such process. These rectifiers might be utilized for some reasons; they are generally utilized in the DC power supply or even in applications of high voltage DC transmission [33].

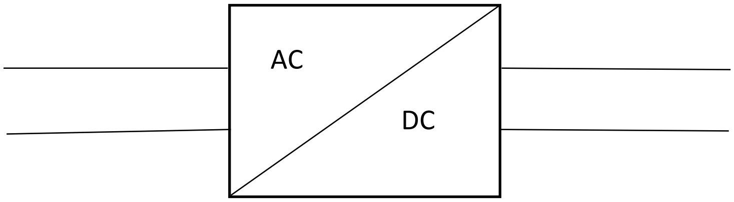


Figure 1: AC to DC converter symbol

3.3 DC to DC converters

To alter a level of DC voltage source from one to the other, DC to DC converters are used. These control converters are utilized in a number of applications, such as individual computer control supplies, office gear; desktop computers, broadcast communications hardware, and dc engine drives [35]. However, dc-dc converters are used in PV systems these days, as they are useful for the implementation of current and voltage controls. An unregulated dc voltage Vs is the input to a dc-dc converter. A converter generates a balanced output voltage Vo and it has a magnitude (and possibly polarity) that contrasts from input Vs.

The DC to DC converter may be planned in diminishing, raising the voltage level, or both, basing to the relationship between output and input. The change proportion D is the proportion between the output voltage and the input voltage. The converter is referred as a buck converter when this proportion is less than 1; a boost converter when the proportion is greater than 1; and the converter is named a buck-boost converter when the same ratio can be greater or less than 1[36].

With regard to the inductor current, converters can work in two distinct modes: the continuous conduction mode (CCM) and the discontinuous conduction mode (DCM). It is in CCM because the inductor current is always larger than zero. If, because of the high-load resistance or low-switching frequency, the average inductor current is too low, the converter is in DCM. For high performance and effective use of semiconductor switches and passive components, the CCM is preferable. Because the dynamic order of the converter is reduced, the DCM needs special control. Thus, it is required to figure out the minimum value of the inductor to maintain the CCM [37].

3.3.1 DC-DC converter circuit topologies

A large number of dc-dc converter circuits are known; the magnitude of the dc voltage can be increased, decreased or its polarity inverted. Figure 2 shows ratios for some dc-dc converter conversion that are widely used. The switch is realized using a power MOSFET and diode in each example, but other semiconductor switches such as IGBTs, BJTs, or thyristors can be in use if desired [38].

The buck converter is the first converter, which decreases the voltage of dc and has a conversion ratio of M(D) = D. The positions of the switch and inductor are interchanged in a similar topology known as the boost converter. This converter generates a Vo, output voltage that is greater than the VS input voltage in magnitude. The conversion ratio is M(D) = 1/(1-D)[39].

The switch connects the inductor alternately via the input and output voltages of the power in the buck-boost converter. This converter inverts the voltage polarity, and can either increase the voltage magnitude or decrease it. M(D) =-D/(1 – D) is the conversion ratio.

The Cuk converter comprises inductors in series with the input and output ports of the converter. A capacitor is alternately connected to the input and output inductors by the switch network. The conversion ratio M(D) is similar to that of the converter for buck-boost. Hence, the voltage polarity is also reversed by this converter, while either increasing or decreasing the voltage magnitude [39]. The voltage magnitude may also be either increased or decreased by the single-ended primary inductance converter (SEPIC). It does not, however, invert polarity. The ratio for conversion is M(D) = D/(1- D).

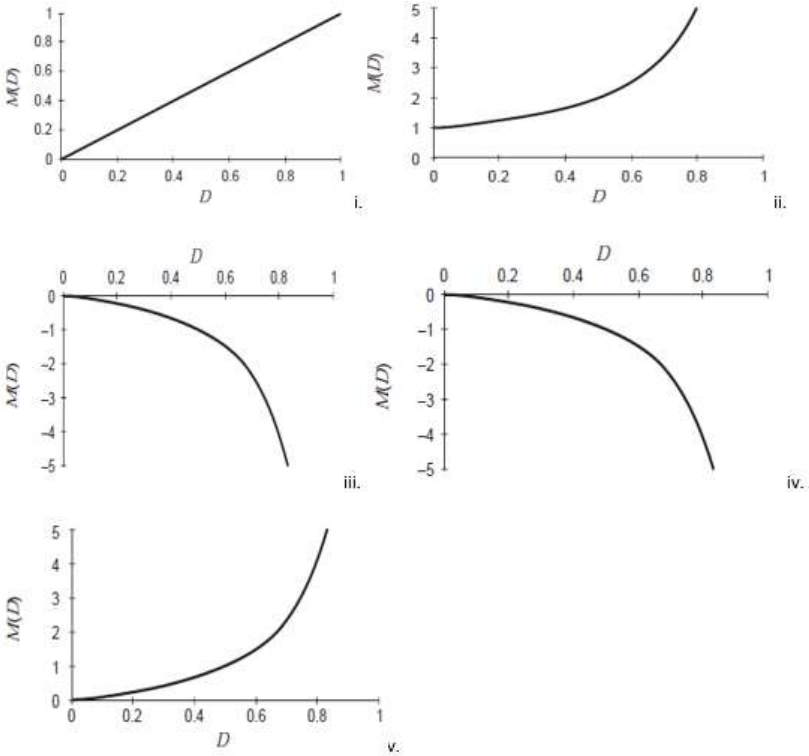


Figure 2: DC to DC rations: i. buck, ii. Boost, iii. Buck-boost, iv. Cuk , v. SEPIC[39]

3.3.2 Classical converter analysis

To have a good design of a converter, a classical analysis is necessary. This classical analysis presents a converter under steady state. The voltage and current waveforms of a dc-dc converter can be discovered under steady-state conditions by using two fundamental concepts of circuit analysis. The inductor volt-second balance principle states that the average value of the voltage applied over an ideal inductor winding, or dc part, must be zero. For each winding of a transformer or other multiple winding magnetic devices, this concept also applies. Its dual, amp-second balance applies to capacitors, by stating that the average current flowing through an ideal capacitor must be zero [40]. Therefore, one averages the inductor current and capacitor voltage waveforms over one switching cycle to assess the voltages and currents of dc-dc converters operating in a periodic steady state, and equates the results to zero.

3.3.2.1 Buck converters

A buck converter is a step-down converter from DC to DC. This converter is found as a DC link in PV systems that can be used to control voltage and current. The standard buck converter, consisting of two switches (a transistor and a diode), an inductor, and a capacitor, is shown in Fig 3. The buck converter consists of two switches, i.e., a DC supply or a rectified AC output. D (diode) and S (power electronics switches can be semi-controlled or fully controlled), two-pole low-pass filters (L and C) and a load. Assume that (i.e. no resistive component) the inductor and capacitor are pure. However, what we call a small-ripple approximation [40] still exists. The output voltage ripple in an effective converter is small. It is presumed that the load is resistive and there are no ripples in the DC portion of the output voltage, or simply that the DC output has a fixed value to facilitate the analysis.

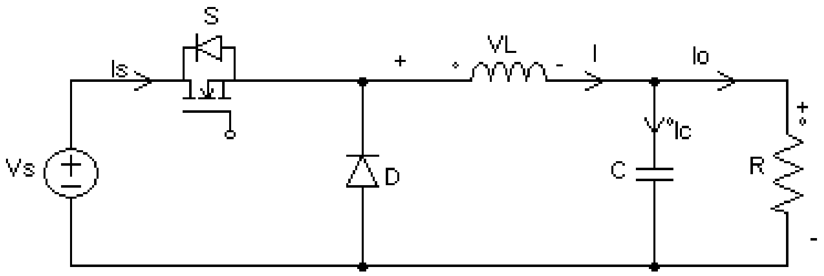


Figure 3: The conventional topology of Buck converter.

The diode D is reverse-biased when the switch S is commanded to the on condition. The diode conducts to support an uninterrupted current in the inductor when the switch S is off. The duty cycle or conversion ratio for switch S of the converter is measured or calculated as in indicated in Eq.3.1 below:

$$\mathrm{D} = \frac{\mathrm{Ton}}{\mathrm{T}} \qquad (Eq.3.1)$$

$$\mathrm{Where, T} = \mathrm{Ton} + \mathrm{Toff} \qquad (Eq.3.2)$$

With two different modes, this circuit can be analyzed. The first one is when the S switch is on, while when the switch S is off in the second mode. The diagrams of the circuit when the switch is on and off are shown in Fig.5 and Fig. 6 respectively.

$$\mathrm{Voltage\ across\ the\ Inductor} = \mathrm{VL} = \mathrm{L}\frac{\mathrm{di}}{\mathrm{dt}} \qquad (Eq.3.3)$$

Where $\mathrm{I} = \mathrm{Ic} + \mathrm{Io}$ and

$$\mathrm{Load\ current} = \mathrm{Io} = \frac{\mathrm{Vo}}{\mathrm{R}}$$

When the switch S is on and the voltage rule (KVL) of the Kirchhoff is applied, we can get,

$$\mathrm{Vs} = \mathrm{VL} + \mathrm{Vo}$$

$$\Rightarrow \mathrm{Vs} = \mathrm{L}\frac{\mathrm{di}}{\mathrm{dt}} + \mathrm{Vo\ and\ Vo} = \mathrm{Vc} \qquad (\mathrm{Eq.}3.4)$$

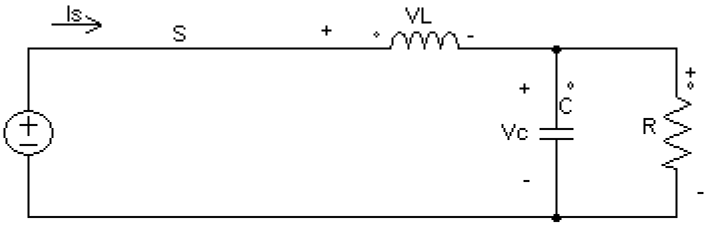


Figure 4: When switch is on for buck converter

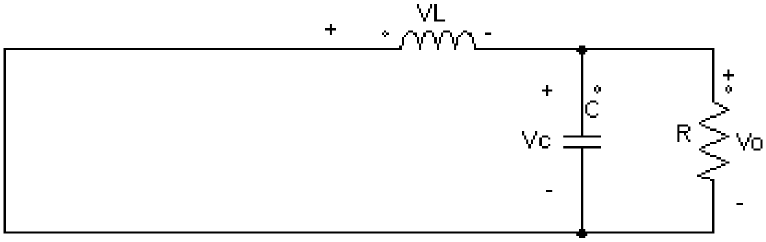


Figure 5: When switch S is off for buck converter

The KVL is applied the same circuit when the switch S is off; the output voltage is given by:

$$\mathrm{VL} + \mathrm{Vo} = 0 \qquad (\mathrm{Eq.}\,3.5)$$

$$\text{From Eq. 3.3}, \quad \mathrm{Vo} = -\,\mathrm{L}\frac{\mathrm{di}}{\mathrm{dt}} \qquad (\mathrm{Eq.}\,3.6)$$

The output voltage, by the small-ripple approximation theory is assumed constant,

$$\mathrm{L}\frac{\mathrm{di}}{\mathrm{dt}} = \text{Constant}$$

$$\mathrm{L}\frac{\mathrm{di}}{\mathrm{dt}} = \text{Constant, Hence the slope of the inductor current is contant}$$

Under the assumption that the inductive current is always positive, the waveforms in the buck convertor are shown in Fig.6 below:

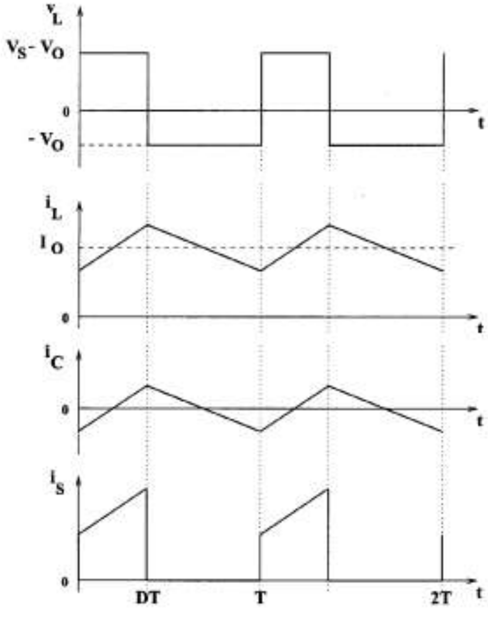


Figure 6: Waveforms for a buck converter [41]

By applying the volt-sec inductor balance for the one voltage period with respect to time under steady-state condition, the region under the voltage and time of the inductor is zero. This means that an inductor's average voltage in a complete loop is zero:

$$\text{Average voltage across the inductor} = \frac{\text{Area of curve}}{\text{Length of base(T)}} \qquad (\text{Eq. 3.7})$$

$$\Rightarrow \text{Average voltage across the inductor} = \frac{(\text{VLon} \times \text{Ton}) + (\text{VLoff} \times \text{Toff})}{\text{T}} = 0$$

$$\Rightarrow (\text{Vs} - \text{V0})\text{DT} - \text{Vo}(1 - \text{DT}) = 0$$

$$\text{Finally } \mathbf{Vo} = \mathbf{DVs} \qquad (Eq. 3.8)$$

3.3.2.2 Boost converter

A boost converter is found as a DC-link in the PV system as the buck converter, can be used to control the voltage and current. In Fig.7, the boost converter is shown; it is a switching converter that works by opening and closing an electronic switch periodically. As the output voltage is greater than the input, it is called a boost converter.

A. Relationships between voltage and current

The study makes the following assumptions:

1. Steady-state situations exist.

2. The period of switching is T, and the switch is closed for DT time and open for (1-D) T.

3. The current of the inductors is continuous (always positive).

4. The capacitor is very big, and the output voltage Vo is continuously maintained constant.

5. The used components are ideal.

The work continues by analyzing the voltage and current of the inductor for the The switch closed condition and the switch opened again.

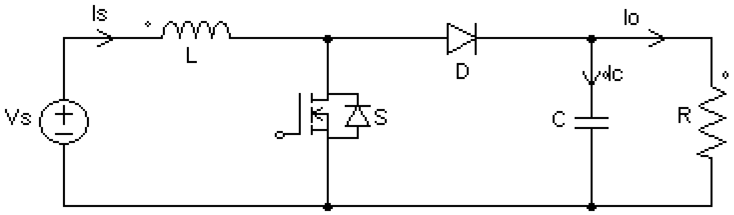


Figure 7: Conventional topology of a boost converter

B. Analysis when the switch is closed

The diode is reverse biased when the switch is closed. The voltage law of Kirchhoff around the path containing the source, inductor, and closed switch is:

$$\mathrm{VL} = \mathrm{Vs} = \mathrm{L}\frac{\mathrm{diL}}{\mathrm{dt}} \; or \; \frac{\mathrm{diL}}{\mathrm{dt}} = \frac{\mathrm{Vs}}{\mathrm{L}} \qquad (Eq.3.9)$$

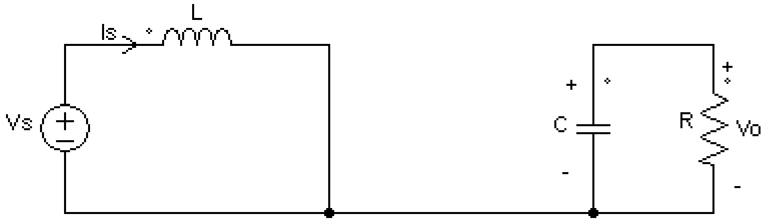


Figure 8: Booster converter circuit when the switch closed

The rate of current change is constant, as seen in Fig.9, the current increases linearly when the switch is closed. The difference in the current of the inductor is determined as follows:

$$\frac{\Delta \mathrm{iL}}{\Delta \mathrm{t}} = \frac{\Delta \mathrm{iL}}{\mathrm{Dt}} = \frac{\mathrm{Vs}}{\mathrm{L}} \qquad (Eq.3.10)$$

By solving for ΔiL from Eq.3.10 as the switch is closed, it is found as shown below:

$$(\Delta \mathrm{iL})\ \mathrm{closed} = \frac{\mathrm{VsDT}}{\mathrm{L}} \qquad (Eq.3.11)$$

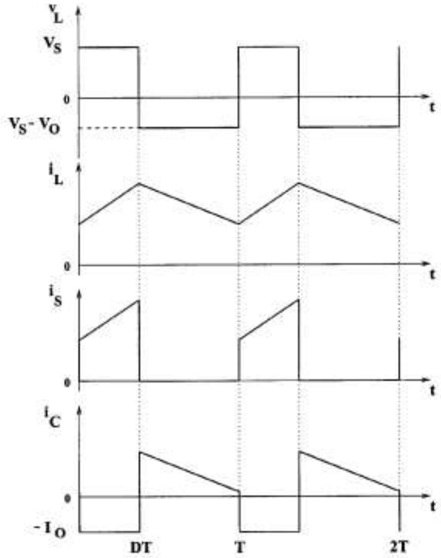


Figure 9: Waveforms for a booster converter.

C. Analysis when then switch is open

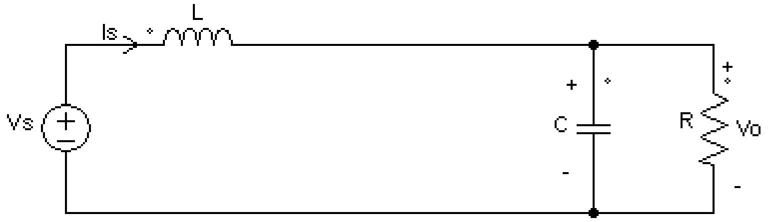


Figure 10: Booster circuit t circuit for an open switch[42].

The inductor current does not change instantaneously when the switch is opened; the diode becomes forward biased to provide an inductor current flow path. The voltage across the inductor VL by assuming that the output voltage Vo is a constant is:

$$\mathrm{VL} = \mathrm{Vs} - \mathrm{Vo} = \mathrm{L}\frac{\mathrm{diL}}{\mathrm{dt}}$$

$$\frac{\mathrm{diL}}{\mathrm{dt}} = \frac{\mathrm{Vs} - \mathrm{Vo}}{\mathrm{L}} \qquad (Eq. 3.12)$$

The rate of change of the inductor current is constant, so when the switch is open, the current must change linearly. While the switch is open, the change in inductor current is:

$$\frac{\Delta \mathrm{iL}}{\Delta \mathrm{t}} = \frac{\Delta \mathrm{iL}}{(1 - \mathrm{D})\mathrm{T}} = \frac{\mathrm{Vs} - \mathrm{Vo}}{\mathrm{L}} \qquad (Eq. 3.13)$$

When the switch is open, by solving for ΔiL; it will be:

$$(\Delta \mathrm{iL})\mathrm{open} = \frac{(\mathrm{Vs} - \mathrm{Vo})(1 - \mathrm{D})\mathrm{T}}{\mathrm{L}} \qquad (Eq. 3.14)$$

The net change in inductive current must be zero for steady-state condition. Hence,

$$(\Delta \mathrm{iL})\ \mathrm{closed} + (\Delta \mathrm{iL})\mathrm{open} = \frac{\mathrm{VsDT}}{\mathrm{L}} + \frac{(\mathrm{Vs} - \mathrm{Vo})(1 - \mathrm{D})\mathrm{T}}{\mathrm{L}} = 0 \qquad (Eq. 3.15)$$

Then, the output voltage Vo, is solved from there as:

$$\mathrm{Vs}(\mathrm{D} + 1 - \mathrm{D}) - \mathrm{Vo}(1 - \mathrm{D}) = 0 \qquad (Eq. 3.16)$$

Finally,

$$\mathbf{Vo} = \frac{\mathbf{Vs}}{\mathbf{1-D}} \qquad (Eq. 3.17)$$

3.3.2.3 Buck boost converters

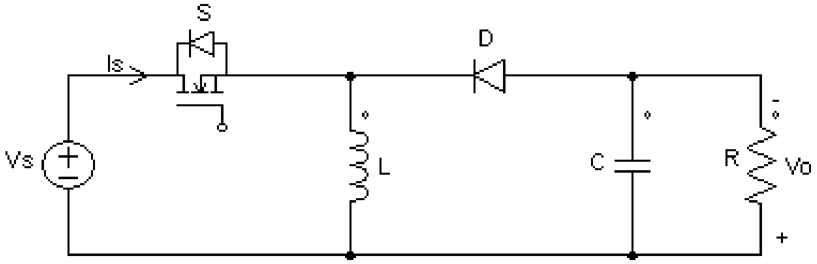


Figure 11: Conventional Buck booster topology

A step-up and step-down converter can be needed at the same time in a PV system, as well as in other industrial applications. Researchers have therefore considered the buck-boost converter to be useful [43]. The buck-boost converter is capable of providing an output voltage that is either greater or smaller in magnitude than the input voltage. This converter is a DC-DC inverting converter, i.e. the output voltage polarity is inverted compared to the input supply. The buck-boost converter structure is as shown in Fig.11 above.

The input voltage is applied through the inductor when the switch S is on, and the current in inductor L increases linearly. The capacitor C provides the load current at this moment, and it is partly discharged. The voltage around the inductor is reversed in polarity during the second interval when the transistor is off, and the diode conducts. The energy stored in the inductor provides power to the load during this period and, in addition, recharges the capacitor.

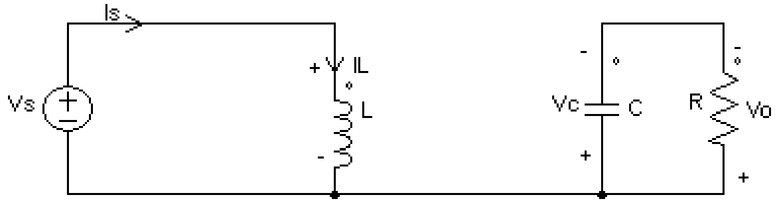


Figure 12: Equivalent buck-boost converter when the switch is on

It is assumed that the capacitor was fully charged up before switching on the switch S for the analysis of this converter behavior and functionality. When the S switch is shut down, as shown in Fig. 12. 12. In the first loop and with Kirchhoff's voltage law, it will be:

$$-\mathrm{Vs} + \mathrm{VL} = 0 \qquad (Eq. 3.18)$$

$$\Rightarrow \mathrm{Vs} = \mathrm{VL} = \mathrm{L}\frac{\mathrm{di}}{\mathrm{dt}} \qquad (Eq. 3.19)$$

By applying KVL the second loop it will become:

$$-\mathrm{Vc} + \mathrm{Vo} = 0 \qquad (Eq. 3.20)$$

$$\Rightarrow Vo = Vc \qquad (Eq. 3.21)$$

Now, the converter circuit as shown in Fig.13, it is analyzed as follows when switch S is opened.

$$\mathrm{VL} + \mathrm{Vc} = 0 \qquad (Eq. 3.21)$$

$$\Rightarrow \mathrm{L}\frac{\mathrm{di}}{\mathrm{dt}} + Vc = 0$$

$$\Rightarrow \mathrm{L}\frac{\mathrm{di}}{\mathrm{dt}} = -\frac{\mathrm{Vc}}{\mathrm{L}} \qquad (Eq. 3.22)$$

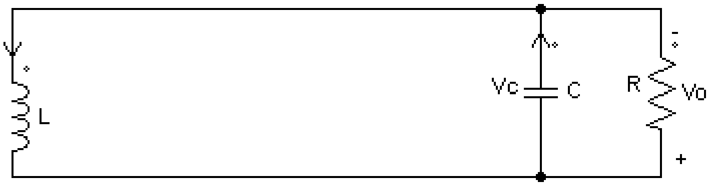


Figure 13: Equivalent of Buck-boost converter if the switch is off

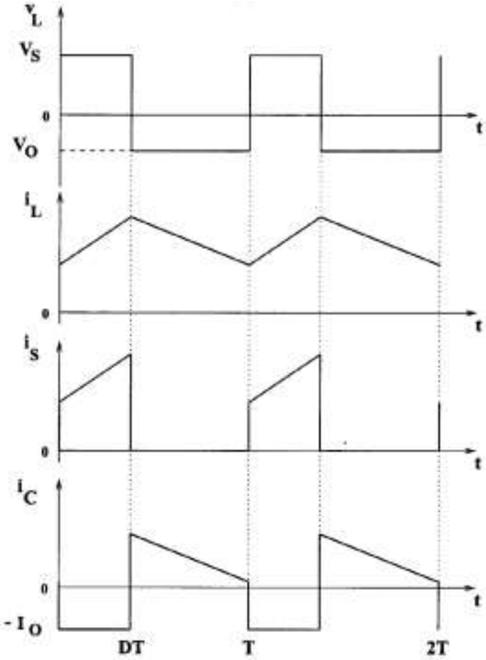


Figure 14: Waveforms of a buck boost [44]

Referring to the waveforms shown in Fig.14 and then applying the Inductor Volt-sec:

$$\text{Average voltage across the inductor} = \frac{\text{Area of curve}}{\text{Length of base(T)}} \qquad (Eq. 3.22)$$

$$\text{Average voltage across the inductor} = \frac{(\text{VLon} \times \text{Ton}) + (\text{VLoff} \times \text{Toff})}{\mathrm{T}} = 0 \qquad (Eq. 3.23)$$

$$\Rightarrow \frac{\mathrm{VsDT} - \mathrm{Vo}(1 - \mathrm{DT}\,)}{\mathrm{T}} = 0$$

$$\Rightarrow \mathrm{DVs} - \mathrm{Vo} + \mathrm{VoD} = 0$$

$$\Rightarrow \mathrm{DVs} = \mathrm{Vo}(1 - \mathrm{D})$$

The output voltage of the buck boost converter is eventually given by the following relationship:

$$\boldsymbol{Vo} = \frac{\mathbf{VsD}}{\mathbf{1-D}} \qquad (Eq.3.24)$$

This converter’s functionality depends on the duty cycle range. When 0 < D<0.5 the converter acts as a Buck converter, when 0.5 < D<1 the converter acts as a Boost converter and the input and output voltages are the same when D=0.5.

3.3.2.4 Cuk converters

Cuk converters are derived from the cascading of converters with buck and boost. This converter is based on capacitive energy transfer, and it’s analysis is based on the capacitor's current balance.

The capacitor is connected to the input through L when the diode is on, and the energy source is stored in the capacitor. In this loop, the current in C is Is. If the switch S is on, the stored energy the capacitor is transferred to the load through the second inductor, in this cycle the current is C is Io. To obtain a steady state solution, the capacitive charge balance principle is used. Like the basic buck-boost converter, the cuk converter also has a negative-output polarity. With the application of the Volt-sec balance, the output voltage for a Cuk converter is as shown in Eq.3.25 below:

$$\boldsymbol{Vo} = \frac{\mathbf{VsD}}{\mathbf{1-D}} \qquad (Eq.3.25)$$

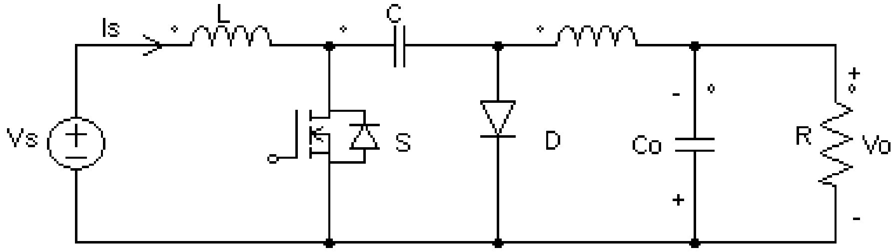


Figure 15: Cuk converter conventional topology

CHAPTER 4. DESIGN OF A DC CONVERTER FOR A DC DIRECT USE

A design of a DC converter for a DC direct use is based on a DC-DC converter. However, to optimize the efficiency and cost effectiveness of the converter, some controls and battery storage system are excluded. In addition, to increase its lifetime, electrolytic capacitors in the power stage of the circuit output are avoided and they are replaced by film capacitors. In fact, among specification requirements for DC/DC converter circuits, the following are considered critical:

1. Stable operation (Not to be broken down by operation failure such as abnormal switching, burnout or over-voltage)
2. High efficiency
3. Small output ripple
4. Good load-transient response

These properties can be improved to some extent by selecting wisely DC/DC converter components. Weightings of these four properties vary with individual applications. In the following, each component of power stage is analyzed before its selection to improve these properties. The selection of the components are based on the Fig 16 below. The features of the figure are almost similar to the conventional topology; however, the use of film capacitor at output is employed whereas at the input there is an electrolytic capacitor. The film capacitor is employed to increase the lifetime of the converter; the lifetime[45] of a capacitor is the time to failure, where failure is defined as the lack of ability of a component to fulfil its specified function. Film commonly offer superb electrical properties, they have the one of a kind capacity to heal themselves after electrical breakdown, and are viable with the most recent assembly methods [45]. The electrolytic capacitor is used at the input to protect the converter from over voltage due to its electric property of withstanding high voltage level and providing a much higher level of capacitance for a given volume than most ceramic capacitors[46].

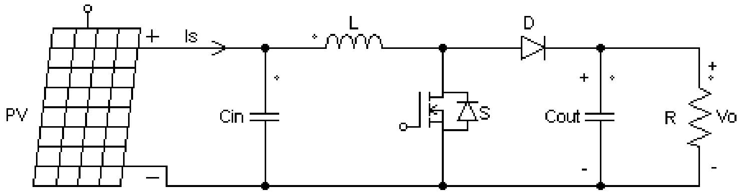


Figure 16: Proposed converter topology

4.1 Inductor selection

Inductor is among key components of power stage of a boost converter. Its acts as an energy storage component which charges when the switch is off and discharges when the switch is on. The energy is stored in its core material in the form of magnetic energy[47].

The size of the inductor is given by the equation:

$$L = \frac{V_s \times (V_O - V_s)}{\Delta I_L \times f_s \times V_O} \qquad (Eq. 4.1)$$

Where

V_s	Input Voltage
V_O	Output Voltage
ΔI_L	Ripple current
f_s	Switching frequency

If a higher switching frequency is used, then a smaller inductance is required to operate the converter.

The ripple current is given by:

$$\Delta I_L = \frac{V_{s(min)} \times D}{f_s \times L} \qquad (Eq. 4.2)$$

Where

$V_{s(min)}$	Minimum input voltage
D	Duty ratio

The ripple current cannot be calculated as the inductance is still unknown. However, it can be estimated to be between 20% to 40% of the output current. Eq.4.3 is used to calculate the estimated ripple current.

$$\Delta I_{Le} = (0.2\ to\ 0.4) \times I_{OUT(max)} \times \frac{V_O}{V_s} \qquad (Eq. 4.3)$$

Where

ΔI_{Le} Estimated ripple current

$I_{O(max)}$ Maximum output current

Table 2: Some values of inductor referring to level of switching frequency

Item	**Condition**	**Recommended Values**		
L value	Switching frequency	When light-load time weighted	Standard value	When heavy-load time weighted
	30kHz, 50kHz	330µH	220µH	100µH
	100kHz	220µH	100µH	47µH
	180kHz	100µH	47µH	22µH
	300kHz	47µH	22µH	10µH
	500kHz	33µH	15µH	6.8µH
	600kHz	22µH	10µH	4.7µH
	900kHz	10µH	4.7µH	3.3µH
	1.2MHz	6.8µH	3.3µH	2.2µH
	2MHz	3.3µH	2.2µH	1.5µH
	3MHz	2.2µH	1.5µH	1.0µH

Rated current	Step-up circuit	Approx. 2 to 3 times of Max. input current
	Step-down circuit	Approx. 1.5 to 2 times of Max. output current

4.2 Input capacitor selection

In spite of the fact that its impact on output steadiness is not as noteworthy as Cout, CIN moreover contains a huge capacity and the littler the Equivalent Series Resistance (ESR) is, the more the output is stabilized consequently the littler the ripple voltage gets to be. Expanding CIN to a few degree will have an impact on the level of ripple voltage. In arrange to avoid Electromagnetic interference (EMI) on the input side, the CIN value ought to begin with around half that of the Cout level. With CIN, indeed in the event that ESR is as well little, the output will not sway. In this manner, utilizing capacitors with ESR as little as conceivable is prescribed.

4.3 Switching device selection

One other main component of a boost converter is the switching device. The switch is described as the device that works in Off and ON states and their main function in the converter is to control when the other components either store or release energy. The Boost converter uses two types of switches, namely, a non-controlled switch (such as a diode) and a controlled switch. In this section, the appropriate controlled switch of the converter is selected[48].

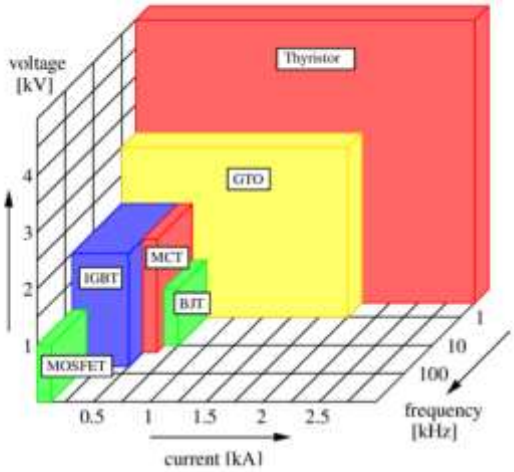


Figure 17: Voltage, current and switching frequency domains of power electronics switches.

Source: Wikipedia

Proficient DC/DC converter circuits may be planned by selecting the absolute maximum ratings of the voltage and the current that are t1.5 to 2 times of the working voltage and current to decrease the failures rates against impulse and spike noises at the switching time . Therefore, adequate selection of switching devices are necessary.

There are a number of semiconductor devices that can be used as a controlled switching device for the converter . Some of these are MOSFET, IGBT, GTO and ordinary thyristors. Fig.17 shows the operating conditions of these devices in terms of current voltage and frequency.

When selecting the appropriate switch for the converter, it is important to consider how much current and voltage the converter will be subjected to under its operations. The type of switch can limit the power rating of the converter.

It is also important to consider the switching frequency at which the switching device will be operated because it has an effect on the switching losses that occur during operation. Eq.4.4 shows the relationship between the switching losses and the switching frequency

$$P_{sw} = (t_1 + t_2) \times \frac{V_s \times I_o}{2} \times f_s \qquad (Eq\ 4.4)$$

Where

P_{sw}	Switching power losses
V_s	input voltage
I_o	Output voltage
f_s	Switching frequency

From the equation it can clearly be seen that the switching losses is directly proportional to the switching frequency as explained in [49]. So selecting a switch that operates at high switching frequencies will result in high switching losses.

[49] also explains how the switching frequency also has an effect on the ripple voltage as it can be seen in Eq.4.4.

$$\varDelta V_o = \frac{D \times I_o}{f_s \times C_{out}} \qquad (Eq\ 4.4)$$

Where

D	Duty ratio
I_o	Output current
f_s	Switching frequency
C_{out}	Output Capacitor

From Eq.4.4, it can be seen that as the switching frequency is increasing, the size of the ripple voltage will be reducing, thereby increasing the quality of our output voltage.

By considering the voltage, current and the switching frequency, the appropriate switch has to be selected. Because higher frequencies cause an increase in switching losses, and lower operating frequencies cause an increase in ripple voltage, then a compromise has to be reached where a switching device that operated in the middle frequencies is used. From Fig.17, it can be seen that the Thyristor operate at lower frequencies whereas the MOSFET operates at higher frequencies. However, the IGBT operates across a frequency range that is between 1kHz and 100kHz. From this range, an operating frequency which gives an allowable ripple voltage and while at the same time keeping the switching losses low enough can be chosen. Fig.17 also shows that the IGBT can handle current of up to 500A and a voltage of up to 2kV. This gives it a power rating of up to 1 MW.

The IGBT is also a better choice for the convert application when compared to BJT and MCT as it has lower on-state voltage drop and its current density in the on state is also more superior. For this reason, smaller chips of IGBTs can be manufactured and this reduces their cost as explained in [50]. When it comes to high current and high voltage appliactions, the IGBT can be more easily controlled compared to BJT and thyristors.[50].

This converter is designed to work at a frequency of 30KHZ; as the operating frequency of the IGBT is between 1kHz to 100kHz. Thus the IGBT is selected in this work.

Table 3: Tips for selecting the Switching devices

Items		**Tips**
Electric properties	R_{DS}, C_{ISS}	Minimize C_{ISS} to increase efficiency at the light-load time. Minimize R_{DS} to increase efficiency at the heavy-load time.
Absolute Maximum Ratings	V_{DS}	Select approx. twice the output voltage for a step-up circuit. Select approx. twice the input voltage for a step-down circuit.
	V_{GS}	Select approx. twice the supply voltage for a step-up circuit. Select approx. twice the input voltage for a step-down circuit.
	I_D	Select approx. twice the input current for a step-up circuit. Select approx. twice the output current for a step-down circuit.

4.4 Output capacitor selection

The output capacitor is used to minimize the ripple voltage that appears at the output voltage. A higher capacitance reduces the ripple that is present in the output voltage whereas a lower capacitance will be cheaper and smaller in size, which is ideal for the converter’s design. So when selecting a capacitor, it is important to select a size that is small enough not to compromise the operation of the converter. If a larger C_{out} value is selected, the output ripple becomes smaller. However, an unnecessarily large C_{out} value increases the dimensions of the capacitor, increasing the cost. The minimum capacitor value is given by:

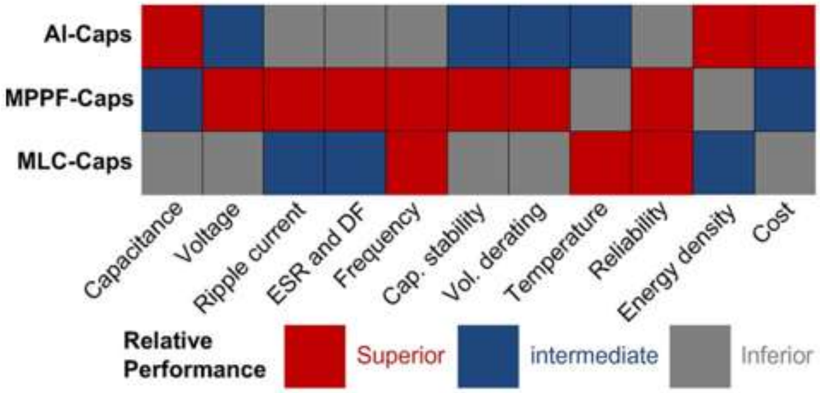
$$C_{OUT(\min)} = \frac{I_{O(max)} \times D}{f_s \times \Delta V_O} \qquad (Eq\ 4.5)$$

Where

$C_{OUT(min)}$	Minimum output capacitance
$I_{O(max)}$	Maximum output current
D	Duty ratio
ΔV_O	Desired output ripple voltage

It can be seen from the equation that a higher switching frequency would result in the lower capacitor value being required to operate the converter.

The desired output ripple voltage should be between 1% to 5% of the output voltage.



	Capacitance	Voltage	Ripple current	ESR and DF	Frequency	Cap. stability	Vol. derating	Temperature	Reliability	Energy density	Cost
Al-Caps	🟥	🟦	▨	▨	▨	🟦	🟦	🟦	▨	🟥	🟥
MPPF-Caps	🟦	🟥	🟥	🟥	🟥	🟥	🟥	▨	🟥	▨	🟦
MLC-Caps	▨	▨	🟦	🟦	🟥	▨	▨	🟥	🟥	🟦	▨

Relative Performance 🟥 Superior 🟦 intermediate ▨ Inferior

Figure 18: Performance comparison of different capacitors[51]

The selected output capacitor is Film type to increase the lifetime of the converter as it was mentioned early. Capacitor with polypropylene dielectric is selected because of its good properties as indicated in Fig.18 above; it has low dissipation factor (DF) that permits high currents with low self heating, it performs well over the temperature ranges and frequency[51]. Such dielectric material is also cheap compared to the others like polycarbonate and Polyphenylene Sulfide (PPS), which are scarce and exotic materials[52]. Metallized polypropylene capacitors offer highest energy density of all the available film construction. Such capacitor self heal. A fault in the dielectric system vaporizes the metal deposit in the area of the faulty; this process is called clearing[53]. The result of "clearing" is a tiny amount of capacitance loss while allowing the capacitor to keep operating with no any adverse effects. There might be multiple clearings due to some effect like overvoltage, or dielectric aging, the capacitor will continue to self heal until it loses capacitance.

Moreover, film capacitors have specific advantages in comparison with electrolytic for converter applications. Film capacitors are two times the voltage capabilities that eliminates the series capacitors and voltage balancing resistors. These capacitors are three times the ripple current capability as indicated in Fig.19 that frees you from needing excess capacitors to handle the ripple. They are also dry constructed which removes the explosive failures with liquid electrolyte[52]. In addition to all these, film capacitor are solid encapsulate that delivers higher shock and vibration withstanding; non-polar dielectric of these capacitors offers reverse proof mounting and AC withstanding[52].

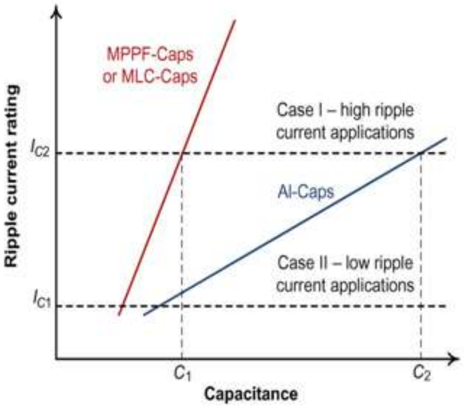


Figure 19: Capacitance requirement of low and high ripple current applications[51]

4.5 Power diode selection

In the design of DC converters, the reverse recovery time of the diode is one of the characteristics to be considered when selecting diode types to be used in the system. This is due to how RRT affects the system switching speed as well as the overall system losses. Reverse recovery depends on the silicon doping level and its geometry [54]. The RRT is influenced very much by the junction temperature, the rate at which the forward current falls and the value of the forward current before the reverse bias is applied [55].

At the point the diode in forward bias state, its depletion area is reduced to nearly nothing. This is because the component's ability to utilize the external supply voltage applied and overcome the barrier potential that is placed on it due to the existence in its depletion region of immobile charge carriers [54].

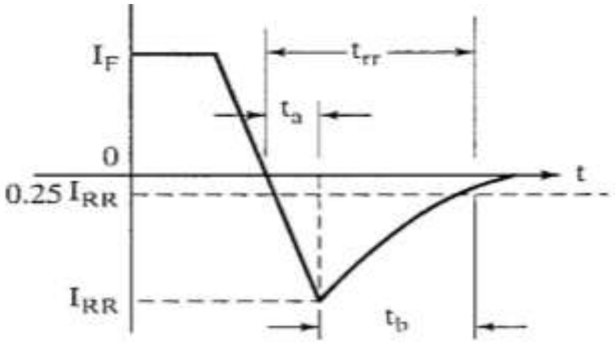


Figure 20: Reverse recovery characteristics of a diode[55]

Where

Ta	Time taken by the current to decay
Tb	Time taken by the current to reach to 25% of the negative peak.
Trr	Reverse recovery time.

If the diode is reverse biased by altering the polarities associated to the terminals, in perfect word the act of doing so ought to bring the diode from its ON condition to OFF condition instantly. Which means that it is anticipated that the diode, that conducts current in its forward direction, will halt conducting instantly. This is not feasible in fact, however, as the movement of majority charge carriers through the diode does not stop immediately at the time of turning around the bias [54]. In reality, before stopping, they will take a certain amount of time and this time is known as the diode reverse recovery time. As indicated in Fig.20, this is the time when the reverse current start flowing through the diode up to its peak value and then decaying again to 25% of its peak value[55].

Commonly, diodes with lesser reverse recovery time are favored, particularly when high switching velocity is required. Furthermore, there will be a large amount of current flow back to the supply during such interval, which provides the diode with electricity. This makes the diode's reverse recovery time an important aspect to consider when designing a converter for DC-DC application.

4.6 Voltage and current control

Generally, there are different algorithm of MPTT which are currently on the market and in this work will not go much in into them. This part mainly emphasize on the voltage control looking forward to stabilizing the DC-DC converter. PID control is employed in this case.

CHAPTER 5. SIMULATION AND DISCUSSION BASED ON IRRIGATION SYSTEM

In this proposed system, the major components are the solar panel, controller, DC-DC booster converter and the DC water pump. Two solar panels of 250 W each are used to drive a 0.5Hp, 10A, 48V pump. A boost converter and the duty ratio controller technology is being incorporated such that the efficiency of the overall system is improved. Each component is properly designed and selected. The PV design criteria is based on the Rwanda climate and solar condition at Kabuga sector, Gasabo district in Rwanda. The steady state stability is finally simulated and analyzed with MATLAB.

5.1 Solar PV system sizing

As mentioned early, this system design is based on the solar condition of the selected site; daily solar radiation indicated in Fig.1 are for Kabuga sector. Referring to the global solar Atlas and in the Rwandan solar Irradiation map, Rwanda has a daily solar radiation of 5Kwh/m^2 on the average. This design is made referring to the month of November as the worst-case scenario; where the solar provide 4.54Kwh/m^2 as daily insolation.

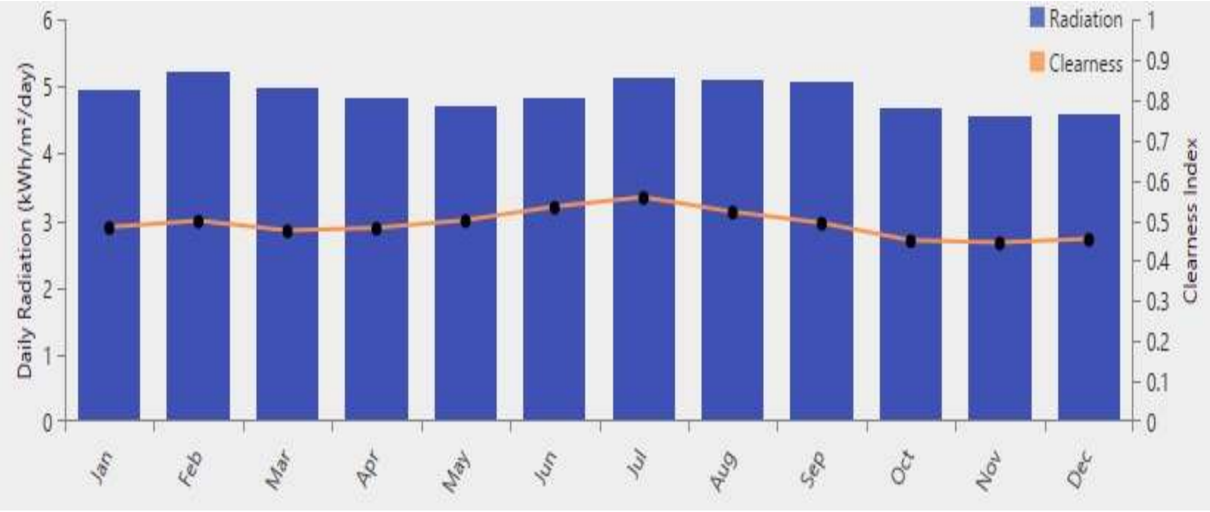


Figure 21: Kabuga Daily Solar Radiation

5.1.1 Determining the power consumption demand

The primary step in the design of a solar PV system is to calculate the total power and energy usage of all the loads that the solar PV system requires to supply, as follows:

A. Calculating the total Watt-hours (Energy) per day for each appliance

To get the total Watt-hours per day that needs to be supplied to the appliances, include the Watt-hours requires for all appliances together.

Table 4: Daily Watt-hour consumption calculation

Item	Rating (Watts)	Quantity	Usage (hours)	Consumption per day(Watt-Hours)
No.1	X	A	N	$X \times A \times N$
No.2	Y	B	M	$Y \times B \times M$
No.3	Z	C	K	$Z \times C \times K$
Total consumption per day				*Total Wh/day*

From table 4; the daily watthours consumption is given by:

$$\text{Daily Watt} - \text{hours consumption} = \sum_{1}^{n} (\text{power } \times operating\ hours\ ) \qquad (Eq. 5.1)$$

Where n is the number of loads

B. Calculating the total Watt-hours needed per day needed from the PV modules

To get the total Watt-hours per day that must be provided by the panels, multiply the total equipment Watt-hours per day by 1.3 (the energy lost in the system).

$$\text{Total watt} - \text{hours from PV per day} = \text{Total daily watt} - \text{hours} \times 1.3 \qquad (Eq. 5.2)$$

Where 1.3 is a loss factor.

C. Size the PV modules

Various sizes of PV modules can generate various amounts of power. The total peak watt produced is required to find out the size of the PV module. The maximum watt (Wp) generated depends on the size of the PV module and the location of the site environment. We have to consider the "panel generation factor" that is distinct from each position of the site. Calculate as follows to assess the scale of the PV modules:

i. Calculating the total Watt-peak rating needed for PV modules

Divide the total Watt-hours per day required by the location panel generation factor from the PV modules (from item 1.2) to get the total Watt-peak rating needed for the appliances to be powered by the PV panels.

$$\textbf{Total what} - \textbf{Peak rating} = \frac{\textbf{Total what} - \textbf{hours from PV per day}}{\boldsymbol{Panel\ generating\ factor}} \qquad (Eq. 5.3)$$

ii. Calculating the required number of PV panels for the system.

Divide the response obtained in item 2.1 by the Watt-peak rating performance of the PV modules available to you. Increase any fractional part of the outcome to the next highest complete number and that will be the necessary number of PV modules.

5.1.2 PV sizing for the load used in our designed system.

These calculations are conducted in Rwanda, Kigali, Kabuga for a DC pump. This means that the factors used in the calculations depend on that site location. Pump specifications are **0.5Hp (367.749 W), 10A and 48V.** Based on this load and making it operate 5hours a day; the sizing of the PV system will be as follows:

By substituting in Eq.5.1, the daily Watt-hours consumption is:

$$\text{Daily Watt} - \text{hours consumption} = 367.749 \times 5 = 1838.745\ Wh$$

To calculate the daily Watt-hours needed from the PV modules, we will use the daily Watt-hours consumption of our load and multiply it by a loss factor of 1.3 as indicated in Eq.5.2. This factor is used to ensure that any losses that may occur within our PV modules are accounted for.

By substituting in Eq.5.2

$$\text{Daily Watt} - \text{hours needed from the PV modules} = 1838.745\text{Wh} \times 1.3 = 2390.4Wh$$

To calculate the Total watt peak Rating: we multiply the total Watt-hour per day from the PV module by the insolation factor also called panel generation factor. 4.54kw/m^2 is applied as an insulation factor, as heighted in section 5.1 of this design part.

By substituting in Eq.5.3

$$\text{Total whatt} - \text{Peak rating } = \frac{2390.4\text{Wp}}{4.54} = 526.52Wp$$

To calculating the number of PV modules, the total watt peak rating is divided by the power rating of our PV module. The selected PV module (TSM-250PC/PA05A) has the following tabulated specifications at standard test conditions:

Table 5: Selected PV parameters

Electrical Data at Standard Test Condition	TSM-250PC/PA05A
Peak Power Watts (Pmax)	250 Wp
Power Output Tolerance (Pmax)	0/+3 %
Maximum Power Voltage (Vmp)	30.5 V
Maximum Power Current (Impp)	8.20 A
Open Circuit Voltage (Voc)	37.8 V
Short Circuit Current (Isc)	8.90 A
Module Efficency (ηm)	15.3 %

$$\text{Number of PV modules } = \frac{\text{Total Whatt} - \text{peak rating}}{\text{Power rating of the PV module}} \qquad (Eq. 5.4)$$

$$\text{Number of PV modules } = \frac{526.52\text{Wp}}{250} = 2.1$$

By increasing the fraction Part to the next highest full number, the designed system will require **three (3) modules**

To achieve the voltage and current requirements (24V DC, 12.3A) of the pump the two modules will be series parallel connected; hence providing:

The maximum power voltage of 30.5V and the maximum power current of $8.2\text{A} \times 3 = 24.6A$

5.2 Sizing components for the DC-DC boost converter

This part is focusing on sizing and selecting the components for the DC-DC booster converter; those are inductors, switching device, diode and capacitors. The selection criteria are based on the analysis, which was demonstrated in chapter 4 of this work. The type and size of materials used are all intended to make the system efficient, stable and cost effective. Moreover this section refers to solar panel output value calculated in section 5.2.1 as well as the load input requirement as highlighted in Table 5.

Table 6: Converter parameters used for sizing

Parameters	**Values**
Vs	30.5 V
Is	24.6 A
Vo	48 V
Io	10 A

5.2.1 Inductor

The size of the inductor is calculated from the Eq.4.1 below

$$L = \frac{V_s \times (V_O - V_s)}{\Delta I_L \times f_s \times V_O}$$

This shows that the value of L depends on the ripple current; where the estimated ripple current is calculated from Eq.4.3 below

$$\varDelta I_{Le} = (0.2\ to\ 0.4) \times I_{O(max)} \times \frac{V_O}{V_s}$$

By substituting in this equation and designing to the worst-case scenario, the estimated ripple current is given by:

$$\varDelta I_{Le} = (0.4) \times I_{O(max)} \times \frac{V_O}{V_s} = (0.4) \times 10 \times \frac{48}{30.5} = 6.295\ A$$

Now, by switching to the frequency of 30KHZ as indicated in section 4.3; and then substituting in Eq.4.1 the minimum required inductor value is:

$$L = \frac{30.5 \times (48 - 30.5)}{6.295 \times 30000 \times 48} = 58.8\mu H$$

The selected standard inductor value is 62µH.

In selecting the inductor to use, the type of coil used should also be put into consideration. The coil type influences more on the inductor heating, functionality and efficiency. Amorphous coil allow small, lighter and more energy efficient converter design than the copper coil type inductors. Amorphous metal has high permeability due to the crystalline magnetic anisotropy; this allows their magnetic cores to have superior magnetic characteristics, such as lower core loss by comparing to conventional crystalline magnetic and copper materials[56]. Thus, in this work the inductor with amorphous coil is chosen.

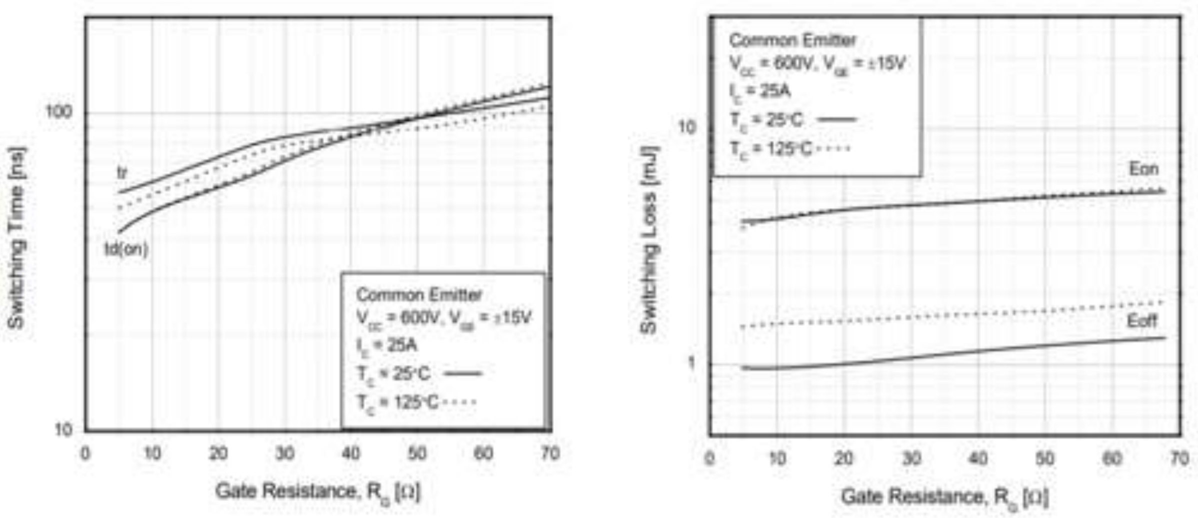
5.2.2 Input capacitor

In this design, it was important to consider other characteristics beyond the capacitance and voltages values. When selecting capacitors to use; the Equivalent Series Resistance (ESR) is taken into consideration. This due to the fact that ESR influences the DC-DC converter power usage and efficiency. A higher ESR value degrades the converter performance due to I^2R losses, noise, and higher voltage drop. An electrolytic capacitor of 100µf with low ESR is selected for the system protection and efficiency

5.2.3 Switching device

As indicated in section 4.3 the type of switch may limit the converter power rating. Thus, when selecting the device, the operating switching frequency should be considered due to the reason that the switching losses depend much on the frequency as Eq.4.4 indicates.

The operating frequency of the IGBT is between 1kHz to 100kHz as described in Fig17. Thus, for this design which operates at 30KHZ, such the IGBT was the best choice another to achieve more efficiency. FGA25N120ANTD was chosen based on its performance characteristics. For Fig.22.a it shows that the switching time is very short whereas Fig.22.b shows that the switching losses (On and OFF) are less, regardless the value of Gate Resistance values.



a)Gate resistance Vs switching time

b)Gate resistance Vs switching loss

Figure 22: Selected Switching device performance

5.2.4 Output capacitor selection

Selecting appropriate capacitor is important, this is for ensuring that the output ripple voltage is reduced as well as avoiding unnecessary cost and dimension of the capacitor. This minimum required capacitor value is calculated based on the Eq.4.5 below:

$$C_{OUT(\min)} = \frac{I_{O(max)} \times D}{f_s \times \Delta V_O}$$

From Eq.3.17 of the boost converter, the duty cycle is derived as follows:

$$\mathrm{Vo} = \frac{\mathrm{Vs}}{1 - \mathrm{D}}$$

$$\Rightarrow \mathrm{D} = 1 - \frac{\mathrm{Vs}}{\mathrm{Vo}} = 1 - \frac{30.5}{48} = 0.365$$

The acceptable output ripple voltage range is from 0 to 5% of the output voltage. Considering the worst case scenario this converter is designed for 5% thus the $\varDelta V_O$ becomes:

$$\varDelta V_O = 0.05 \times 48 = 2.4V$$

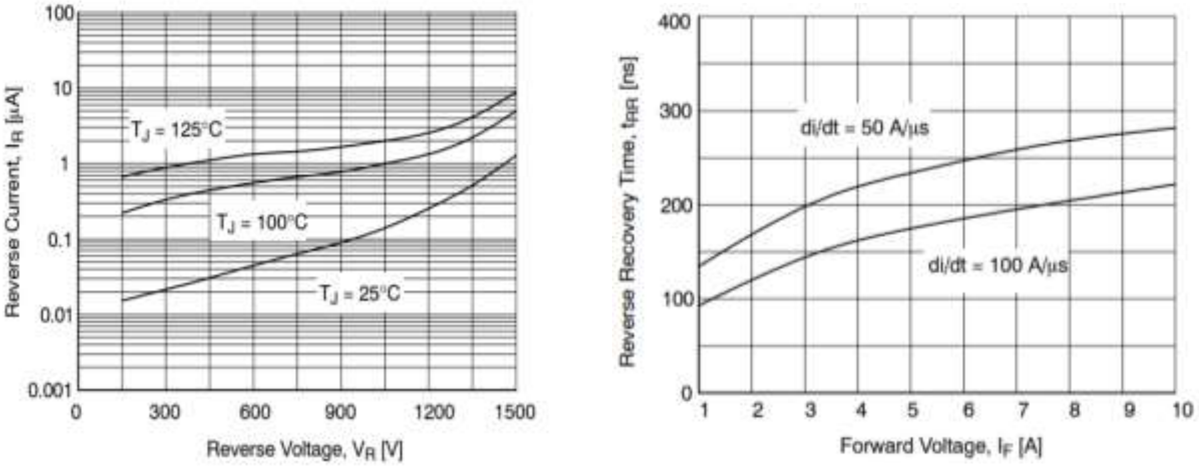
Hence by substituting in Eq.4.5 the required minimum output capacitor is:

$$C_{OUT(\mathrm{min})} = \frac{I_{O(max)} \times D}{f_s \times \varDelta V_O} = \frac{10 \times 0.365}{30000 \times 2.4} = 50.69\mu F$$

The selected standard value is 68µF.

5.2.5 Diode

The diode is selected based on reverse recovery time as described in section 4.5. The chosen diode is FFPF10F150S because of it’s good property of having low RRT hence the system is limited to more addition losses due to diode reverse conductivity. Fig.23 shows the performance of the chosen diode where this diode would allow up to 1500V in reverse direction when operating at temperature of 125 Celsius degrees and this would result into losses; But due the fact that this diode recovery time is less than 300 nanoseconds, such losses will be avoided.



a) Reverse voltage Vs Reverse current

b)Forward voltage Vs Reverse recovery time

Figure 23: Selected Diode performance

5.3 Simulation and Analysis of the results

5.3.1 Open loop model analysis

MATLAB SIMULINK is used to simulate and analyze the result of the designed system. The components values used in this part are the ones calculated in section 5 to 5.2.4 of this research. The model indicated in Fig.24 is used to simulate how the output voltage of the booster converter changes depending on the output voltage (Vs) from the PV and the switching frequency of the converter. Basically, the input to the model are the voltage from PV system (Vs) and the switching frequency of the booster (fs). The output are the boosted voltage (Vo) and the output current of the booster (Io). Inputs are manipulated in order to understand the behavior of the system before designing a closed loop control system.

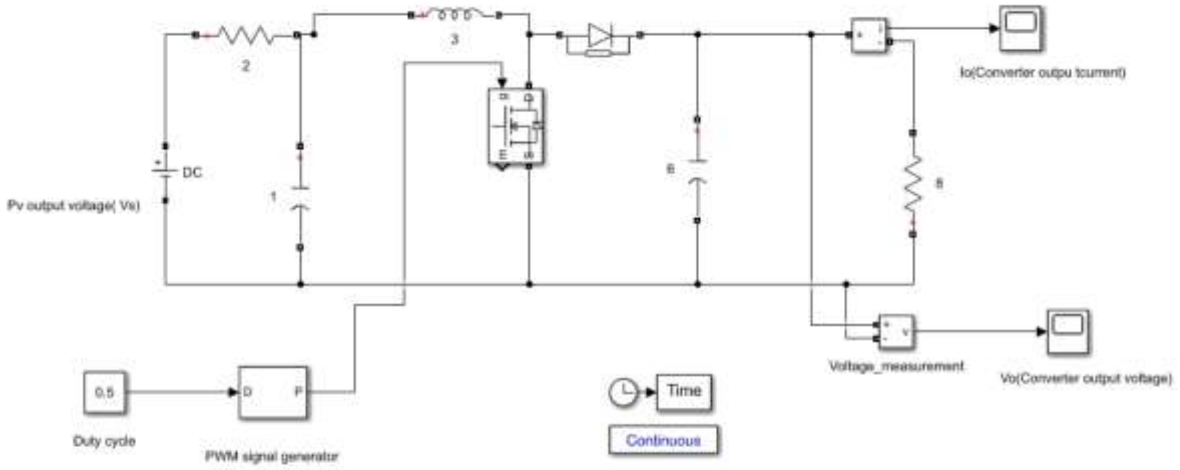


Figure 24: Booster Open loop simulation model

5.3.1.1 The PV output voltage, duty cycle and the Booster output voltage Relationship

Keeping the duty cycle of the converter constant, the PV voltage output (Vs) was varied to analyze its effect on the output voltage of the booster. Results are shown in fig.25 below.

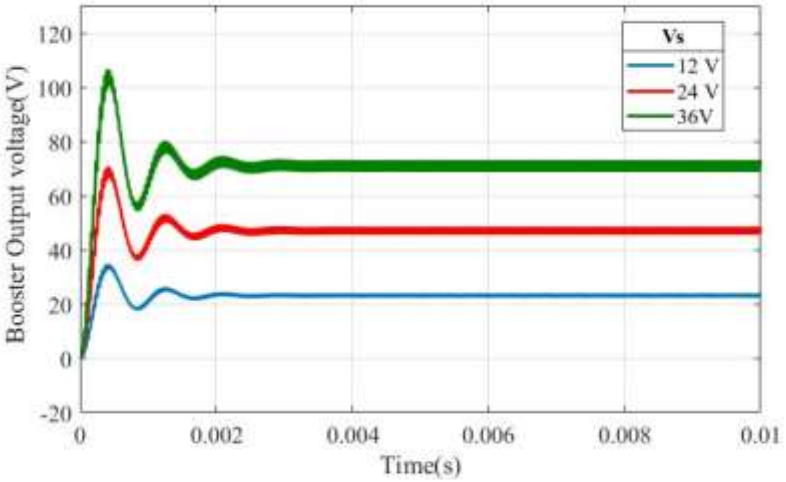


Figure 25: Converter output voltage at a varying solar voltage and a constant duty cycle

As shown in fig.25, the output voltage of the booster converter is proportional to the input voltage from PV. This indicates that fluctuation in the output voltage of the PV can affect the required voltage output from the booster; the converter output voltage of 48V needs to remain constant. Given that the output voltage of the PV changes with the sun radiation, this indicate that the converter input voltage (Vs) cannot be controlled directly, thus another control method will be required.

Another analysis was conducted to understand the effect of the booster's duty cycle to the output voltage. This is done so that the duty cycle can be used as the control parameter if it is realized that there is relationship between the two. The output voltage of the PV was held constant and duty cycle varied. Results of that analysis are shown in fig.26.

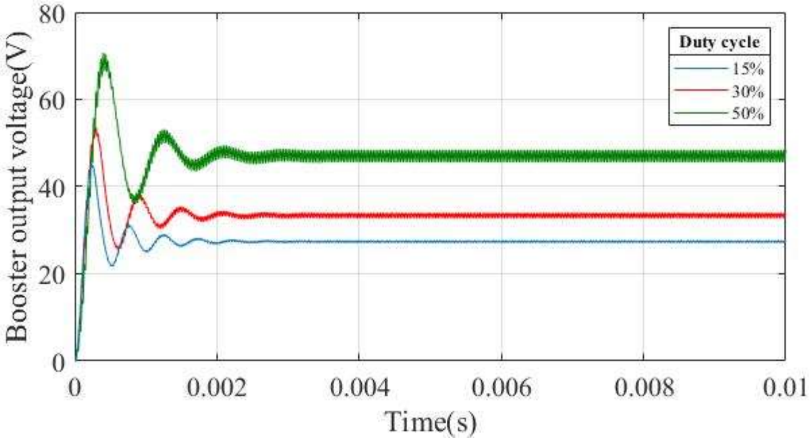


Figure 26: Converter output voltage at a varying duty cycle and a constant voltage from PV

As shown in fig.26, by varying the duty cycle of the designed booster converter, the output voltage of the booster can be controlled. The output voltage of the booster increases with the increase of its duty cycle. Based on this analysis, a closed loop system is designed in a way that the controller adjusts the duty cycle of the booster depending on the error between the set voltage and the actual one.

5.3.1.2 Inductor ripple current and output voltage ripple analysis

Ripple currents in the inductor were also analyzed. Fig.27 shows ripple current for a duty cycle of 50% and PV voltage of 24 V.

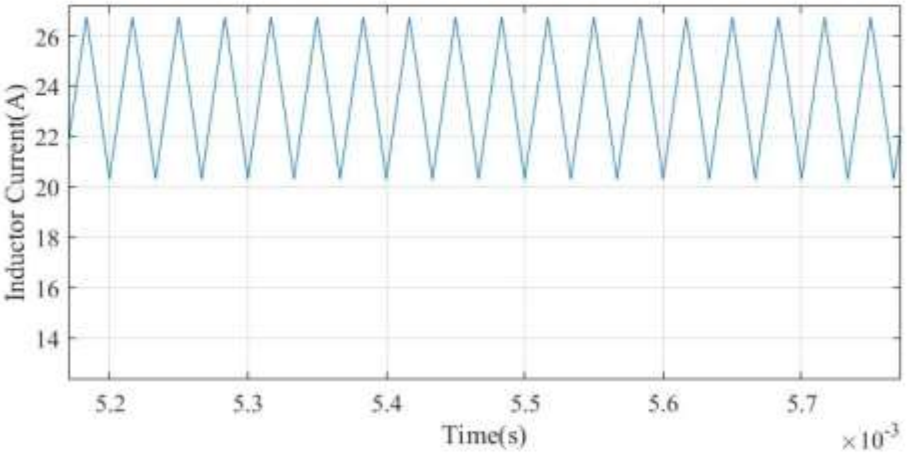


Figure 27: Inductor ripple current

From the values found in fig.27; the ripple percentages is calculated by:

$$\Delta I_L = \frac{I_{Lmax} - I_{lmin}}{I_{LRMS}} \times 100 \qquad (Eq\ 5.5)$$

By substituting in Eq.5.5 the ripple, value is:

$$\Delta I_L = \frac{26.74 - 20.29}{23.65} \times 100 = 27.27\ \%$$

As indicated in Eq. 4.3 the estimated ripple current should not exceed 40%, this means that this calculated ripple current value of 27.27% is within the allowable range.

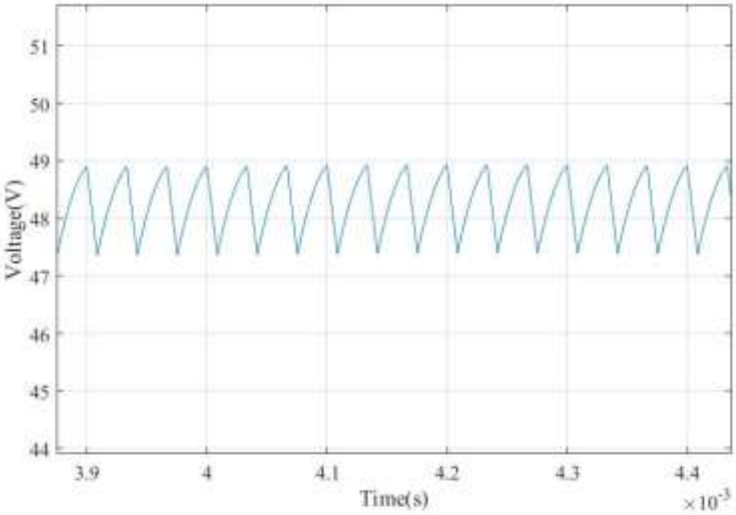


Figure 28: Output ripple voltage

The out ripple voltage in the output capacitor is analyzed. Fig.28 below shows the simulated value. From the values found in Fig.28 the ripple percentages is calculated by:

$$\Delta V_o = \frac{Vo_{max} - Vo_{min}}{Vo_{RMS}} \times 100 \qquad (Eq\ 5.6)$$

$$\Delta V_o = \frac{48.92 - 47.38}{48.27} \times 100 = 3\%$$

As it was seen in section 5.2.4, the desired output ripple voltage should not exceed 5%; hence, 3% from the calculated value is in acceptable range.

From this analysis, it is also clear that the booster converter components are well sized and selected, as the inductor current ripple and the output voltage ripple are with the acceptable ranges.

5.3.2 Closed loop control model analysis

After analyzing and understanding the relationship between the duty cycle and the booster converter output voltage, a closed loop control system was designed. The aim of this closed loop control system is to make sure that the booster can still output the same predetermined voltage even when there is change in the output voltage of the PV due to the solar insolation changes.

The model of the closed loop control system is shown in fig.29.

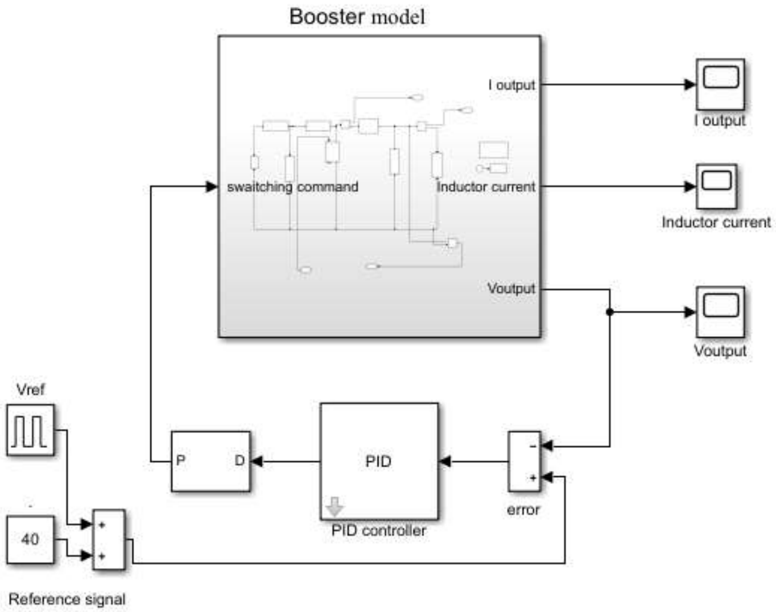


Figure 29: Closed loop control system model

Detailed model of the booster is shown in fig.30.

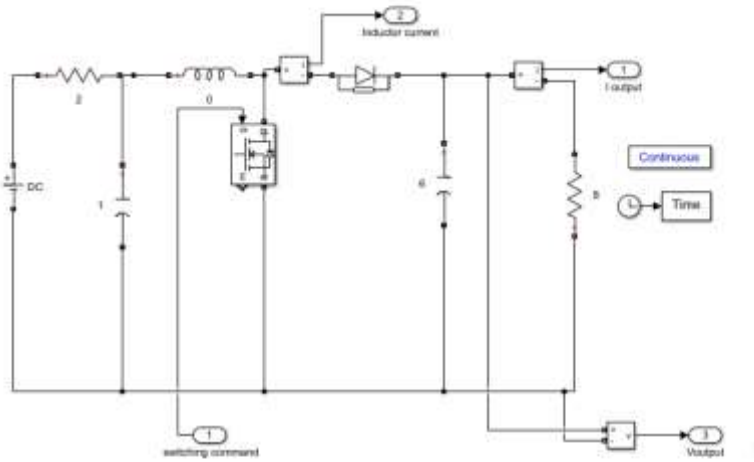


Figure 30: Booster detailed model

5.3.2.1 Closed loop control simulation results

PID control

A square reference signal was used to evaluate the performance of the designed controller. One of the most widely recognized controlling techniques in the market is the PID controller. Thus, it was used in this study. Utilization of the PID includes picking the KP, KI and KD that give adequate closed loop performance [57].Choosing these parameters is a requirement so that the features like settling time, rise time and proper overshoot rate are within acceptable ranges. The numerical portray of the PID controller is shown in Eq.5.7 and the effects of the error signal e are evaluated and computed to form the control signal applied to the plant model [58].

$$\boldsymbol{u = k_p e + k_i \int_0^t e dt + k_d \frac{de}{dt}} \qquad (\boldsymbol{Eq. 5.7})$$

Where u denotes the control signal. Kp, Ki and Kd denote the coefficients for the proportional, integral, and derivative terms, respectively.

Tuning is the process of calculating the aforementioned coefficients to accomplish optimum functionality from the system [58]. There are variety of approaches to tuning which can boost efficiency. One of the methods commonly used is the manual tuning. Tuning a PID regulator includes the control of four factors:

Rise time: the amount of time necessary for the system's initial output to rise past 90% of its desired value

Overshoot : the amount by which the initial response exceeds the set-point value

Settling time: the amount of time required by the system to converge to the set-point value.

Steady-state error: the measured difference between the system output and the set-point value

The PID controller's manual tuning relies on the basic method of trial and error. Using Table 7 as a reference, the integral and derivative values were set to zero, and then the proportional gain was increased to reach the point where the output of the control loop oscillates around the set point.

Then, the integral value was changed to reduce the steady state error. After setting the proportional and integral values to achieve a minimal steady state error. No overshoot was observed. Thus, the derivative value remained on zero.

Table 7: Effect of PID on closed loop system[57]

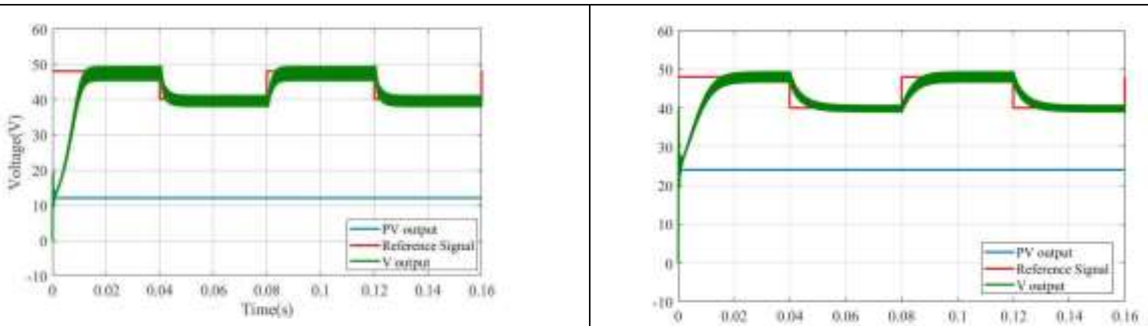
	Rise time	Overshoot	Settling time	Steady state error
Proportional	Decrease	Increase	Small change	Decrease
Integral	Decrease	Increase	Increase	Eliminate
Derivative	Small change	Decrease	Decrease	Small change

Values of Kp, Ki and Kp obtained after tuning the controller are summarized in the table below:

Table 8: PID constant

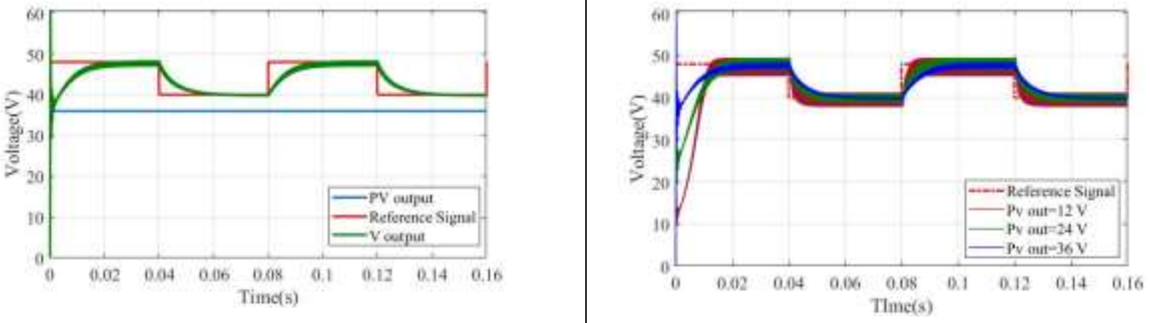
Constant	Value
Kp	0.00025
Ki	3
Kd	0

Figure 31(a) up to (c) show how the booster is able to follow the reference signal despite the output voltage of the PV. In Figure 31(a), 31(b) and 31(c), the output voltage of the PV was set to 12V, 24V and 36V, respectively. It can be shown that the voltage output of the booster converter has a short rise time, no overshoot and negligible steady state error. Figure 31(d) shows the comparison of Vout from the converter for different PV voltages. It can be seen that the Vout remains the same, irrespective of the PV voltage output. This leads to conclude that the designed booster converter can still output the preset voltage even when PV voltage fluctuates.



a) Control for 12V from PV

b) Control for 24V from PV



c) Control for 36V from PV

d) Control for 12V,24V and 36V from PV

Figure 31: Controlled booster output voltage

CHAPTTER 6. CONCLUSION AND FUTURE WORKS

6.1 Conclusion

The designed DC-DC converter for DC direct use has the inductor ripple current and output ripple voltage of 27.27% and 3% respectively. These parameters are all in required ripple maximum allowable ranges of 40% for ripple current and 50% of the ripple voltage; which makes the designed converter effective.

PID controller and a square wave signal were used to control the output voltage. Through the analysis made, it was well proved that the output voltage was able to follow the control logic given to the converter and provide the required output voltage; despite the change in the Voltage from PV, due to the solar irradiance changes.

The components used in the design were selected according to the materials and performance of them with the purpose of making the system more reliable. Polypropylene film capacitor is used at the input to increase the converter lifetime; this is due to it's good characteristics of low dissipation factor and self-healing; where such capacitors clears the faulty part and continue to work. Electrolytic capacitor with low equivalent series resistance is used in this to protect the system from over voltages. The type of inductor used is amorphous coil type because of its magnetic characteristics, which makes it dissipate lower losses compared to copper coil inductor.

This system is efficient and cost effective as the compared to the Battery storage Dc system which would requires more incentives to buy and service the battery. The use of PV make this design renewable and environmental friendly which gives a positive impact to the climate.

6.2 Future works

1. The performance characteristics of the designed DC-DC converter indicated in this work were only the simulation values. Therefore, more analysis and result from the prototype would be required before the final implementation of the work.

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