Optimisation of wind turbine electrical power conversion

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"Vertrou op die Here! Wees sterk en hou goeie moed! Ja, vertrou op die Here!"

Psalm 27:14

ABSTRACT

With South Africa being one of the major contributors of greenhouse gases in the world due the large number of coal burning power stations, and Eskom the local electrical power utility enforcing "load-shedding" to cope with the current demand in electrical energy, it is apparent that there is a need to do research on an off-grid home powered by a renewable energy source. The renewable energy source selected for this dissertation is wind energy. The main goal is to determine if it is viable for an off-grid home to be powered by only using wind energy. Wind energy is a well established source of renewable energy in countries like Denmark and Germany.

An energy usage analysis is done on a home with no energy efficient strategy. The energy wasting appliances are identified and replaced with energy efficient appliances to reduce the energy usage of the home. This indirectly reduces the size and cost of the wind generator system (WGS) required to supply the house with electrical energy.

The various components of an off-grid WGS are identified and researched in terms of available technologies, efficiency and maintenance requirements. The WGS is pulled apart to view each component separately. This helps to identify the areas where the WGS can be optimised in terms of energy conversion efficiency.

A WGS is assembled according to a theoretical specification (based on real life parameters) of an off-grid home with no energy efficiency strategy in place. The home is made energy efficient by identifying and replacing the energy wasting appliances with energy efficient appliances. The components of the off-grid WGS are sized and selected based on their performance characteristics. The cost of the WGS is calculated for a period of 20 years. The cost of the WGS is compared to the cost of supplying the home with electrical energy from a fuel generator for the same period. The cost is also compared to supplying the home with electrical energy from the utility for the same period.

Keywords: *Wind generator system, off-grid, energy efficient, permanent magnet generator, switch mode power supply, battery charger*

OPSOMMING

Suid Afrika is een van die groot bydraers van groenhuisgasse in die wêreld as gevolg van die groot hoeveelhede steenkoolkragstasies wat in die land voorkom. Die plaaslike elektriese diensverskaffer, Eskom, pas beurtkrag toe om die huidige vraag na elektrisisteit te hanteer. As gevolg van die bogenoemde probleme is dit duidelik dat daar 'n behoefte is aan navorsing oor hernubare energiebronne vir 'n huis wat onafhanklik is van die plaaslike energie verskaffer. Die hoof doel is om te bepaal of dit lewensvatbaar is om 'n huis met elektriese energie te voorsien deur slegs van wind energie gebruik te maak. Wind energie is 'n goed gevestigde bron van hernubare energie in lande soos Denemarke en Duitsland.

'n Energie-verbruik-analise word gedoen op 'n huis sonder enige doeltreffende energie-verbruik-strategie. Die elektriese toestelle wat energie vermors word vervang deur energie-doeltreffende-toestelle om die energie verbruik van die huis te verminder. Dit verminder indirek die grootte en koste van die wind generator stelsel wat benodig word om die huis van elektriese energie te voorsien. Die verskillende komponente waaruit die elektries-diensverskaffer-onafhanklike wind turbine stelsel bestaan word geidentifiseer en nagevors in terme van beskikbare tegnologie, doeltreffendheid en onderhoud. Die wind generator stelsel word dan onderverdeel in die verskillende komponente om hulle elk afsonderlik te beskou. Die onderverdeling help om die areas te identifiseer waar die wind generator stelsel se uitset energie meer doeltreffend gemaak kan word in terme van energie omskakelings-doeltreffenheid.

'n Wind generator stelsel word saamgestel volgens 'n teoretiese spesifikasie (die parameters is gebaseer op werklike data) vir 'n elektries-diensverskaffer-onafhanklike huis sonder enige doeltreffende energie-verbruik-strategie. Die huis word energie-doeltreffend gemaak deur toestelle wat energie vermors te identifiseer en dan te vervang met toestelle wat meer energie-doeltreffend is. Die grootte van die komponente van die elektries-diensverskaffer-onafhanklike wind generator stelsel word eerstens bepaal.

Daarna bepaal die prestasie eienskappe van die komponente wat beskikbaar is in die mark, watter spesifieke komponent vir die elektries-diensverskaffer-onafhanklike wind generator stelsel gebruik sal word. Die koste van die wind generator stelsel word bereken vir 'n periode van 20 jaar en word dan vergelyk met die koste van 'n brandstof generator wat energie verskaf aan dieselfde elektries-diensverskaffer-onafhanklike huis. So ook word die koste van die wind generator stelsel vergelyk met die koste van die plaaslike energie verskaffer vir die selfde periode en huis.

Sleutelwoorde: Wind generator stelsel, elektries-diensverskaffer-onafhanklik, energie-doeltreffendheid, permanente magneet generator, skakel-mode kragbron, battery laaier

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LIST OF ABBREVIATIONS

AC	Alternating Current
CCM	Continuous Conduction Mode
CR	Current Ripple
CSI	Current Source Inverter
DC	Direct Current
DCM	Discontinuous Conduction Mode
DOD	Depth of Discharge
ESR	Equivalent Series Resistance
ESL	Equivalent Series Inductance
GHG	Green House Gasses
GTO	Gate Turn Off Thyristor
HAWT	Horizontal-Axis Wind Turbines
MCT	MOSFET Controller Thyristor
MOSFET	Metal-oxide-semiconductor field-effect transistor
PMG	Permanent Magnet Generator
PWM	Pulse Width Modulation
RFI	Radio Frequency Interference
RMS	Root Mean Square
SCR	Silicon Controlled Rectifier
SMPS	Switch Mode Power Supply
SOC	State of Discharge
SW	Power Switch
TF	Transformer
VAWT	Vertical-Axis Wind Turbines
VMOS	Vertical metal-oxide-semiconductor
VSI	Voltage Source Inverter
WGS	Wind Generator System
WT	Wind Turbine
WTG	Wind Turbine Generator

LIST OF SYMBOLS

α	Firing angle
C	Capacitor, Capacitance
D	Diameter in meter, Diode, Duty cycle
Δ	Increment
E_m	Peak value of input voltage
f	Frequency in Hz
h	hours
Hz	Hertz, unit of frequency
I	rms / dc value of current
i	Instantaneous current
I_m	Peak current
km/h	Kilometres per hour
L	Inductance
m	Base unit of length
n_1, N_1, N_2	Winding count of a transformer (1 – Primary, 2 – Secondary)
P	Electrical power
Q	Transistor
π	Constant, $\pi \approx 3.14159265$
R	ZAR, the ISO-4217 currency code for the South African rand, which on November 2010 traded at R6.96 to the USD.
R_L	Load resistance
t	time in seconds
V	rms / dc value of voltage
V_m	Peak voltage
W	Electrical energy
ω	Natural frequency, related to f, $\omega = 2\pi f$

1 Introduction

This chapter provides introductory information on renewable energy sources and wind turbines in general. The main objective is given, followed by the methodology. The chapter is closed off with an overview of the document.

1.1 Background

In 2008, South Africa saw first-hand the effect of neglecting energy usage and efficiency of energy usage when ESKOM, the local utility, had to start implementing "load shedding" on the national electricity grid. The first occurrence of load shedding was in 2006, when the Koeberg nuclear power station automatically disconnected from the national power grid due to a damaged rotor. This incident left a large part of the Western Cape without power.

The economic growth, the lack of building more power stations and inefficient use of energy due to its low cost, were the main contributors to this problem.

The Department of Minerals and Energy released an Energy Efficiency Strategy [1] for South Africa in 2005. According to the Energy Efficiency Strategy [1], the total renewable energy supply in the year 2000 was 6% of the total energy supply. The biggest conventional contributor, coal power stations, was at 79% for the same year.

South Africa is also a big contributor of carbon emissions and Green House Gasses (GHG) in the world. In 1999 [2], South Africa was ranked sixth largest contributor of carbon and GHG emissions in the world and is by far the largest contributor in Africa. This is due to the amount of coal fired power stations that are used as the primary power supply. Burning coal gives off sulphur dioxide, which has acid rain to effect, destroying plant life and property. The mining of coal also destroys large areas of land, rendering it useless for living or farming. Burning coal also releases a large amount of GHG.

The problem for a residential customer connected to the grid in load shedding times is obvious. It disrupts the lives of many and is a major discomfort. For the resident with a "green" conscience, it is also worrying to see how much of the environment is destroyed via energy supplied by coal burning power stations. In this dissertation we will consider the question "is an off-grid average sized house viable?" Living off-grid means that the power will have to be supplied solely by the resident, and that he will not get any power from the local utility. The resident will have to build his own power station so to say. For this dissertation, wind energy as renewable energy source is considered.

Other renewable sources are available, but none of them are as mature as wind energy. Sun energy could also be considered, but the South African public has not yet embraced the technology as an alternative.

The main objective is to determine if it is viable for a residential home to be off-grid and be supplied of electrical energy by a wind generator in South Africa. The technology, cost and efficiency is considered as applied to a home with an average energy use. A case study for taking a small house off-grid is done in Chapter 2. An energy usage analysis for a home where no effort is made to reduce energy usage will first be considered. Thereafter, all the energy wasting appliances is identified and replaced with an alternative energy efficient option. The remaining electrical energy usage of this house is supplied by a wind generator. The technology, cost and economic viability of this generator set is then considered and calculated.

The energy usage of the efficient house is used as an input specification to a wind generator. The generator is broken down into its underlying parts that are each discussed in terms of efficiency, cost and maintenance requirements. The goal will then be to theoretically assemble the wind generator system.

In Chapter 3 an overview is given of the various components that a wind turbine system consists out of. The various components are grouped in the following chapters:

- Chapter 4 – Location, Tower and Blades
- Chapter 5 - Generator
- Chapter 6 – AC-DC-AC Conversion
- Chapter 7 – Batteries and Battery Charger

In Chapter 8, a wind turbine is assembled from the components discussed in the previous chapters. The components that best fit the specifications defined are used and a long term running cost analysis is done. The cost per kWh is calculated for a 20-year period. The cost of the wind turbine generator will then be compared to running a carbon based fuel generator, or running from the utility for the same 20 years in Chapter 8. Chapter 8 is followed by the last chapter, Chapter 9 were a conclusion to the dissertation is drawn.

2 Energy Usage

In this chapter the importance of knowing one's energy usage and how to reduce it by identifying energy wasting appliances and also finding "phantom" loads is discussed. An energy usage analysis is done on a medium sized home. The energy hungry loads are identified and removed from the home. A comparison is then done to see what the difference in initial wind generation setup cost is between a non-energy efficient home and an energy efficient home.

2.1 Energy Usage in South Africa

In South Africa, electrical power was supplied cheaply and therefore end users had no motivation to use energy as efficient as possible. A vast amount of literature is found on energy usage in the UK, USA and Europe. Most of the literature from South Africa describes research that was done from either a government perspective, or from the energy supplier, Eskom's perspective, where there was looked at, the effect of cost increases on the economy, or the total amount of energy supplied by Eskom instead of concentrating on what amount of energy is used by each person or even a household.

Knowing the amount of energy used by each person or household will not only help in realising what is required to decrease energy usage, it will also help to show the average "Joe" how to quantify this energy, and will help him better manage his energy usage, or even efficiently manage his energy usage. The energy usage statistics have also changed a lot in recent times and the reason for this is that previously disadvantaged communities have now also been supplied with electricity and their knowledge of energy usage is limited. This means that they have no idea of how to use energy efficiently, as they have not been properly educated on efficient energy use.

Various references have been found on energy usage statistics. Bredekamp et al. [3] covers one of the most important factors in making a home's energy usage more efficient. This is that there are many electrical appliances that are used on a daily basis, that even when these devices are turned off, they are not really off, and still consume energy. This is also referred to as "Phantom" loads. These are devices like TV's, VHS-DVD players, Home Entertainment systems, personal computers etc. These appliances usually work by remote, and can't be totally switched off. The appliance will enter a "sleep" (low energy usage) mode, when in the apparent off state, but in this "sleep" mode some devices still use a considerable amount of energy, as was found by Bredekamp et al. [3] in their research.

In a study conducted by the Human Sciences Research Council [4], research was done on possible energy efficient solutions for business, industry and residential platforms. Not much information was given on how the table was obtained, but in Appendix D of the report [4], a table can be seen, that represents the energy using devices found in a residential home, the energy usage rating for each device is then used to calculate a daily energy usage value. An actual energy usage value is also determined. The study [4], recommends an energy efficient alternative, and shows the energy saving that is theoretically possible.

This will help to identify what devices should be looked at and what energy efficient solutions were available at that specific time, and can thus be compared to today's available energy efficient solutions.

Kallis et al. [5] monitored a few households for a time and determined that a 30 minute profile period is sufficient for energy profiling in residential areas and also estimated an average monthly energy use of 783 kWh. The Environmental Management Department [6] found in their research, that the average energy usage was 520 kWh per household per month.

2.2 Energy Usage Analysis

In the following sections, the energy usage of a small sized home is analysed. A theoretical calculation is done to determine the energy usage by taking the rated power rating of the device or appliance and multiplying it by the hours of use for a period of one month. Some of the appliances and devices are monitored by using single-phase electricity meters to determine the energy usage for these devices. This practical measurement is done to see how the theoretical calculations line up with the practical measurements and to verify if the theoretical calculations can be used rather than the practical measurements, which will take time to gather each time a variable changes.

A small sized house with no energy efficiency (Home A) strategy implemented will then be compared to one where all the appliances have been replaced with energy efficient appliances (Home B). The comparison is done in terms of what a wind generator system for each house would cost. This will also show the importance of first making one's home as energy efficient as possible before even considering living off-grid. A detailed energy usage table (Table A-1 and Table A-3) was set up for each home (Table A-1 Home A - not efficient and Table A-3 Home B - efficient) and can be seen in Appendix A.

In each table all the rooms with their respective appliances have been listed. The appliance rated power is given, and an estimated hours of use for a period of one month is also given.

The energy usage for each appliance is calculated for the month in terms of watt hours (Wh). The total electrical energy measured in kWh is calculated for the month. This total electrical energy is also the value one would see on one's utility bill at the end of each month. The theoretical calculations for this house's total kWh will also be compared to its real life monthly bill. This is easily done as the house's energy is managed by a credit system and a small in-house display shows the amount of kWh's used.

$$Wh = P \cdot h \qquad \textit{(Eq. 2.1)}$$

where, Wh is the energy used per hour, P is power rating of the device in question in W and h is the time the device is being powered for in hours. The above equation (Eq. 2.1) was used to determine the energy usage of Home A and Home B and can be seen in Appendix A.

2.2.1 Energy Usage Pilot Project

A project involving 20 pilot single-phase GSM (Global System for Mobile communication) remote meters have been launched in 2011 by Strike Technologies [7]. This is part of a new product launched by Strike Technologies [7] and is done as a field trail run for the single-phase energy meters. In two of the twenty houses the owners have solar geysers and it is used to compare to the energy usage of the owners that have electric geysers.

In one home, one single-phase meter was put on the main incomer, one single-phase meter was put on the stove and one single-phase meter was put on the geyser. This will help to show what energy usage savings are possible by removing these two power hungry appliances.

The energy usage profile for a house with an electric geyser can be seen below in Figure 2-1. The energy usage profile for a house with a solar geyser is shown in Figure 2-2 below. Both houses are matched in terms of number of adult occupants. The other loads of these houses do vary, but one can see that the solar geyser makes a huge difference in energy usage by just having a glance at these graphs.

The total energy usage for the house (residence 1) with the electric geyser was 1138 kWh and the geyser itself used 633 kWh for the same period, therefore one can see that the geyser make's up more than 55% of the total energy used in this case.

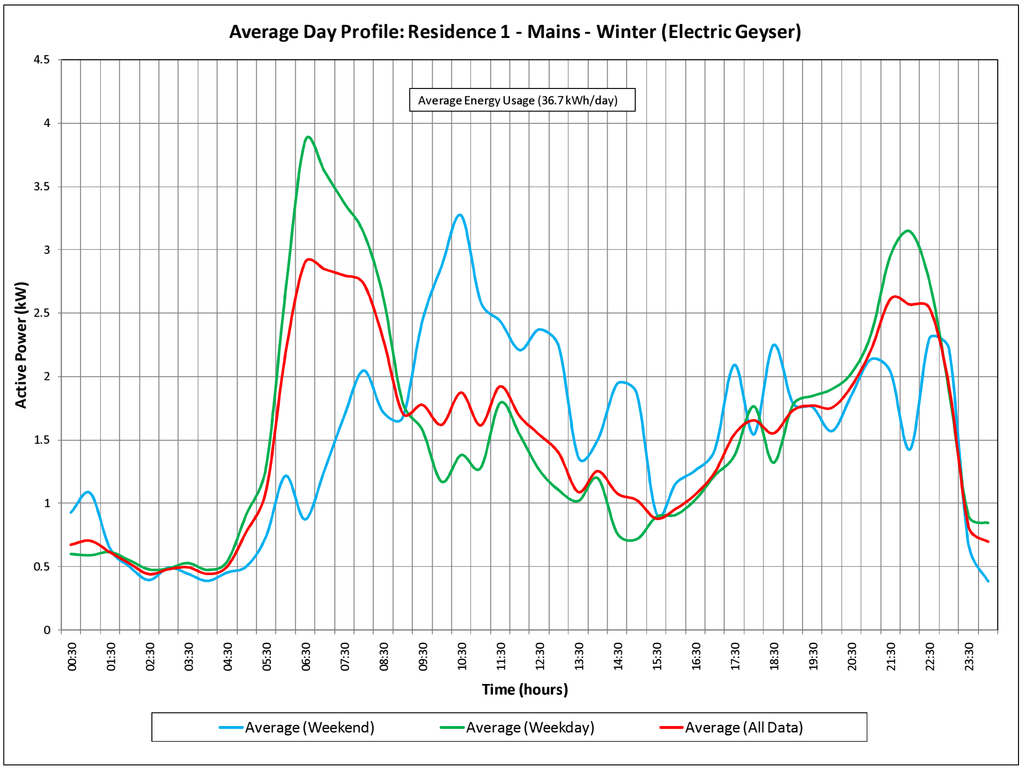


Figure 2-1 Energy Usage Profile Residence 1 – Mains – Winter (Electric Geyser)

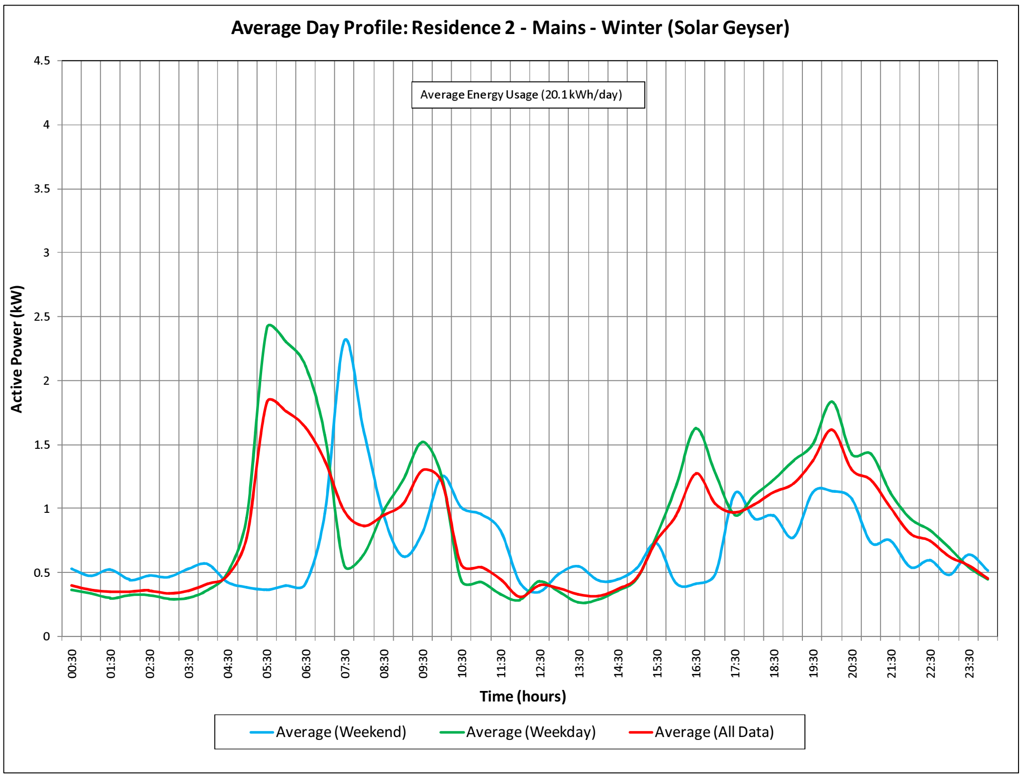


Figure 2-2 Energy Usage Profile Residence 2 – Mains – Winter (Solar Geyser)

The average daily energy used by residence 1 was calculated as 36.7 kWh per day for the winter months and this is a worst case scenario that is used as energy usage normally increases throughout the winter as was seen for all 20 houses. The average energy usage for residence 1 can be brought down to 15.2 kWh per day for the winter by just removing the geyser and stove and replacing them with alternatives like a gas stove and a solar geyser. This is a near 60% saving on the total energy usage for residence 1.

The average daily energy usage for residences containing 3-4 occupants (a total of 6 residences) during the winter months was calculated to be 37 kWh per day. With a 60% saving that can be made by replacing the geyser and stove, and implementing an efficient energy usage strategy by replacing incandescent light bulbs with LED light bulbs and unplugging un-used devices, the average daily energy usage could be brought down to less than 15 kWh per day.

2.2.2 Energy Usage Scenario

2.2.2.1 Energy usage of small sized home (Home A – No Efficiency)

In Home A, the energy usage is determined as is. Meaning there was no effort put into this home to try and make it as energy efficient as possible. The real life energy usage (Table A-2 in Appendix A) over a period of twelve months for this small-sized home was calculated as 790 kWh.

In this case the theoretical calculation is more than the practical values obtained. This is a good thing as the theoretical calculation gives an overhead of 150 kWh, a kind of worst case scenario. The energy usage of a few selected appliances was monitored together with their usage duration. It is showed that the estimated usage duration and rated power used in the theoretical calculation is close to the practical values measured.

2.2.2.2 Energy usage of small sized home (Home B - Efficient)

In Home B, all the energy wasting appliances of Home A were identified and replaced by an energy efficient appliance. The hours of use of some appliances was also shortened. “Phantom” load were identified, and this standby mode consumes a lot of energy on certain devices, as they might be old and were not designed for optimal energy usage. Thus, turning these devices completely off at the source is the best practice for serious energy savings.

To completely go off-grid is not an easy change. Serious considerations and changes on energy use habits will have to be made. One should also take future energy usage into account.

More efficient devices might become available, but also one's family might grow with time and as time goes on, humans become more dependable on electronic devices, which all consume energy.

From Table A-3, one can see that by just doing a basic energy usage assessment, replacing energy wasting devices with efficient ones and also reducing the run time of some appliances, one can already make a big energy usage saving. The theoretical energy usage of Home A was 150 kWh larger than the real life average determined in Table A-2. To get a worst case scenario for Home B, 150 kWh is added to the theoretical energy usage value (168 kWh) determined from Table A-3 to get to a total of 318 kWh for the efficient Home B. This is still a big energy usage saving of 61%.

2.3 Quick Wind Generator Cost Analysis

To determine the cost of the wind generator, there had to be looked at the energy usage first. But in an off-grid case, this problem could also be looked at from a different perspective. One can also first calculate the energy production capabilities of the geographical location, and then decide if it is possible to live within the energy production constraints, and if it is possible to finance a generator of the required size to produce this energy. The cost is determined on a wind generator placed on an ideal geographical location. Therefore, let's say that this home is placed in an area where the average wind speed is estimated to be around 4.5 m/s at 15 m above the ground.

2.3.1 Cost Analysis House A

The required diameter of the blades is 7 m. The generator required for house A should at least be able to generate 26 kWh of energy per day. The total cost for the generator with blades and 15 m tower for House A is about R185210. This amount is a really large amount and is hard to finance. One can get a loan from the bank, but another option is to consider making the home more energy efficient, and this option is considered in the next section.

2.3.2 Cost Analysis House B

The required diameter of the blades is 5 m. The generator required for house B should at least be able to generate 10 kWh of energy per day. The total cost for the generator with blades and 15 m tower for House B is about R52200. This amount might still be large, but it might be easier to obtain than the amount for House A. Also, by just doing a bit of work on reducing energy usage, a 72% saving was already made on wind generator, blades and tower cost. A saving of 61% per month can be made by just making the home energy efficient.

2.4 Summary

It was shown in this chapter that it is important to know ones energy usage. It was shown that one can make large saving on the WGS to be bought, by identifying ones energy usage, and applying an efficient energy usage strategy. By reducing ones energy usage, the size of the WGS required to supply the energy is reduced, not only in size but also in cost.

A pilot single-phase meter project was used to determine the average energy usage of a few residences in winter. It was also determined from one of the residences that a 60% saving on energy usage can be made by replacing the geyser and stove alone.

The energy usage of a small sized home with no energy efficiency strategy was recorded (Home A). Home A was analysed and all the energy wasting appliances was replaced with energy efficient appliances (Home B). A saving of 61% was made possible by applying an energy efficiency strategy. A WGS for each home was then assembled and priced. The cost of a WGS for each home was compared, and the initial energy efficiency strategy applied to Home A had a 72% cost saving on the required WGS to effect (Home B).

3 Wind Generator System

Chapter 3 contains literature that helps to identify what components an off-grid Wind Generator System (WGS), should consist of. An off-grid WGS is then proposed and all the various components are listed and described shortly.

3.1 Wind Generator System

Literature on WGS [8], [9], [10], [11], [12] all showed that the following basic components are needed for a WGS, i.e. - a tower, blades, generator, transmission wiring, inverter, power electronics and battery bank. One of the sources [9] explicitly defined an off-grid system that had the following components, i.e. - a tower, blades, generator, transmission wiring, inverter, battery charger and dump load, battery bank and backup generator. The backup generator is required when there is simply not enough wind to generate required power and to keep the battery bank from deep discharges that could damage the cells.

In [8], [10], [11], [12] gearboxes are also mentioned as a component to a WGS. But gearboxes are only found in larger WGS that generates more than 20 kW. For small turbine's meant for homes, direct driven generators are recommended as they have low maintenance requirements and costs. Gear driven generators will therefore not be mentioned further on. A typical off-grid WGS can be seen in Figure 3-1 and below is a list and short description of the major components of a WGS.

Wind Generator System Components:

- **Geographical Location** – The location is very important in terms of average wind speeds. An extensive wind analysis should be done to determine if the location is able to produce the required amount of energy from the available wind. The profile of the land should be preferably flat to not disturb the flow of the wind.
- **Tower** – The tower is one of the most overlooked components of the WGS. As the height increases so does the average wind speed; and as is seen in Section 4.2, the wind speed has a cube-three effect on the output power of the WGS. The tower also has a great effect on maintenance, as a tower that can easily be lowered will make maintenance a lot easier and cost effective.
- **Blades** – The blades make up the component that directly interfaces with the kinetic energy of the wind and converts it to mechanical energy to turn the generator. The blades are thus the

main energy collecting component of the WGS and not the generator as many people would think.

- **Generator** – The generator takes the mechanical energy from the blades and turns it into (Alternating Current) electrical energy. Various different options exist for the generator and these options are explored in detail.
- **AC-DC-AC Conversion** – This subsystem consists out of three underlying components listed below. It can usually be bought as one unit, but understanding the underlying components of these components is very important to choose the correct unit to be used on one WGS. This conversion is discussed in more detail and the different options available are discussed.
- **AC-DC conversion** – The AC voltage output from the wind generator needs to be converted to a DC voltage required for the charging of the batteries. Note that the AC voltage output from the turbine is not on the correct level or frequency to be used on electrical appliances. A transformer or star-delta connection can be used as a form of voltage control. The AC-DC conversion can be realised by using an uncontrolled rectifier or a controlled rectifier. The controlled rectifier will help to get the DC output voltage to the maximum battery voltage required for charging.
- **DC-DC Conversion** – If an uncontrolled rectifier is used in the AC-DC converter, the DC voltage output from the AC-DC converter will not be suitable for battery charging. The DC-DC will then need to convert the DC voltage to a suitable voltage for battery charging. A controlled AC-DC rectifier is recommended as the output voltage can be controlled and set to the battery voltage level. This will simplify the design of the DC-DC converter, which basically becomes a battery charger. A detailed discussion on DC-DC converters is given.
- **DC-AC Conversion** – The DC-AC converter, more generally known as the inverter, converts the low DC voltage from the batteries, back to a suitable AC voltage with a sine wave and frequency, for use in electrical appliances.
- **Battery Charger** – The battery charger manages the batteries to make sure that the batteries are not over charged and not under charged (which can also damage the batteries).
- **Batteries** – The batteries serve as a backup mechanism and this is where the generated energy is stored. They are very costly and require a lot of maintenance.

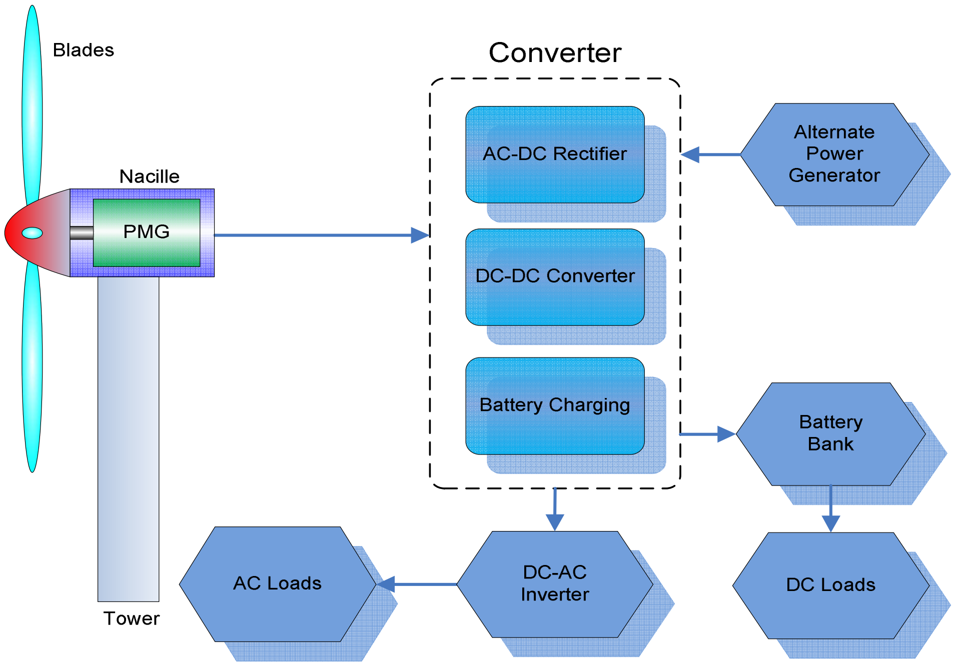


Figure 3-1 Typical Off-grid Wind Generator System (WGS)

3.2 Summary

In this chapter the various components of the typical off-grid WGS were identified. It was also determined that direct driven generators are less expensive and easier to maintain than gearbox driven wind generators. A list of all the major components of a typical off-grid WGS was made and each of the components were shortly described. Finally a diagram of a typical off-grid WGS was shown in Figure 3-1.

4 Location, Tower and Blades

Chapter 4 contains an overview of the location, tower types and blades of a wind turbine. The location is very important as a site with low average winds will be of no use. This section describes the two different types of wind turbines that exist, Horizontal-Axis Wind Turbines (HAWT) and Vertical-Axis Wind Turbines (VAWT). The structural differences, advantages and disadvantages are discussed. The number of blades also has an effect on a wind turbines performance and this will also be discussed.

4.1 Location

The location of the wind generator is very important. It is one of the most overlooked areas of a wind turbine system. To get the maximum usage out of a wind generator it must be placed at the position and height that will yield the most wind energy possible, thus the most consistent performance possible. This does not necessarily mean strong winds, but rather a continuous moderate wind.

From Ian Woofenden [9], having high wind speeds does not mean much for wind energy, but having a good average wind speed does mean a lot more and this is described in Wind Ian Woofenden [9], as the same way electrical engineers would understand watts and watt hours. Watts is an instantaneous power and does not give much historical info, just like instantaneous winds. Average winds give a lot more detail, just like watt hours does.

For commercial WT (Wind Turbine) sites a lot more is done in terms of site analysis. In Wind Energy Explained [11] a more elaborate process of determining the correct site is described; here use is made of atmospheric circulation patterns, wind roses (see Figure 4-1 below), wind variances and frequencies (how many times a certain wind speed occurs on a certain site).

Ian Woofenden [9] also mentions that the peak wind speed is important as it helps the WT engineer to understand the forces that is present on the tower and generator. Here the frequency of this peak wind speed is important. If the peak wind speed of 30 km/h only occurs once a year, compared to five times or more a year, a different tower and WT would be suggested.

According to Ian Woofenden [9], knowing the average wind speed for a site of a home wind turbine is enough information and an in depth analysis is not required, but having more information about the site is always a good thing and will help one with making better choices when assembling a WGS.

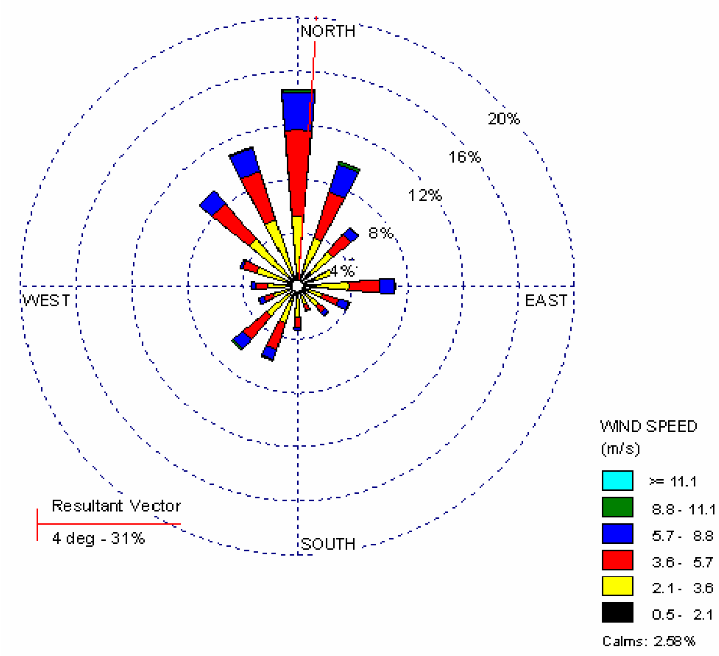
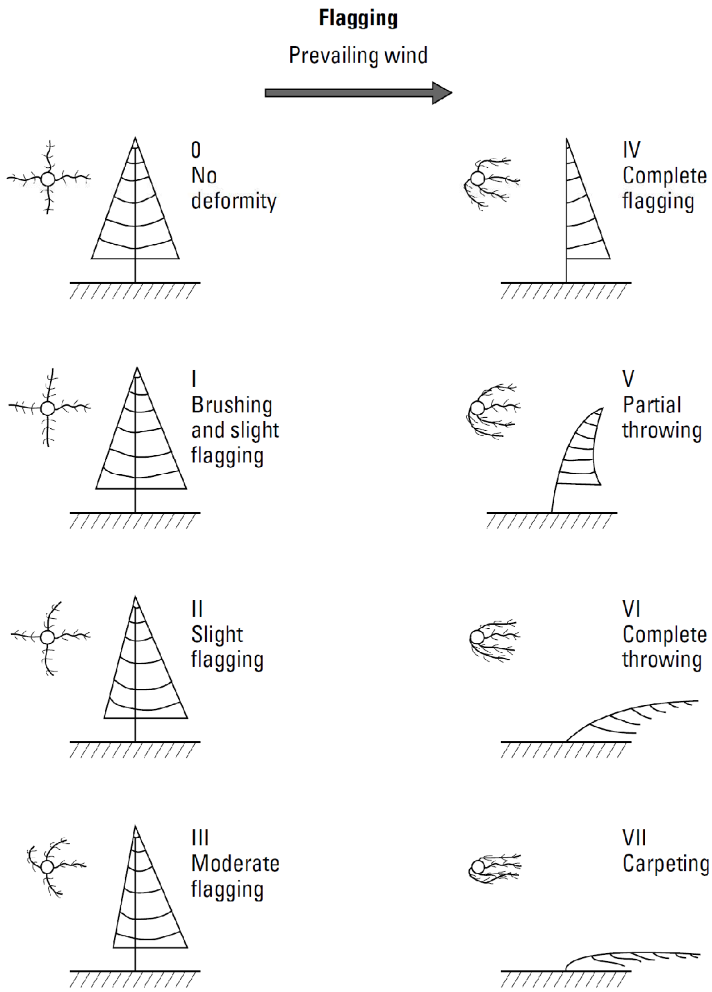


Figure 4-1 Period average wind rose (2001-2005) for the OR Tambo International Airport [13]

Ian Woofenden [9] and Wind Energy Explained [11] describe various methods that can be used and factors to look out for to help with determining ones average wind speed. The basic factors are wind patterns due to uneven heating, this is from onshore or offshore winds, and also from up and down valley winds that heat and cools through the day and night cycle. Another factor is the shape of the land, the topography. Tall structures will have a negative effect on the flow of the wind by generating turbulent air.

Ian Woofenden [9] and Wind Energy Explained [11] recommends getting a bird's eye view on the potential site and determining if it is located in a valley or on a ridge, or if there are tall structures nearby. This will help one to determine if the wind will flow evenly or if it will be turbulent and where a good wind turbine site would be. A list of the methods recommended by Ian Woofenden [9] to determine a sites average wind speed is given below:

- Direct measurements at the potential site at the potential height.
- Setup of a mini test turbine with an energy meter.
- Collect data from various other sources like, neighbours, weather services, government sources, local airports and other WGS owners.
- Use the Griggs-Putnam Index [9], (Figure 4-2 below) to look at how the wind has effected vegetation in the area of the site thus linking tree flagging to an average wind speed.



Average wind speed	I	II	III	IV	V	VI	VII
mph	7-9	9-11	11-13	13-16	15-18	16-21	22+
m/s	3-4	4-5	5-6	6-7	7-8	8-9	10+
Km/h	11-14	14-18	18-21	21-25	25-29	29-32	36+

Figure 4-2 The Griggs-Putnam Index – Links tree flagging to average wind speeds [9]

4.2 Tower

Another frequently overlooked area of the wind generator system is the tower. A general rule of thumb also mentioned by Ian Woofenden [9] is that the lowest blade must be at least 10 m above anything within a 150 m range of it. From Mukund R. [10], the power that can be extracted by the blades from the wind is customarily expressed as:

$$P_O = \frac{1}{2}\rho \cdot A \cdot V^3 \cdot C_p \qquad \textit{(Eq. 4.2)}$$

where

P_O = the generators output power, the mechanical power extracted by the blades

ρ= air density, kg/m^3

A = swept area of the blades, m^2

V = wind speed, m/s

C_p = power coefficient of the rotor, also known as rotor efficiency

Figure 4-3 and Figure 4-4 below shows the physical differences of the three different towers types.

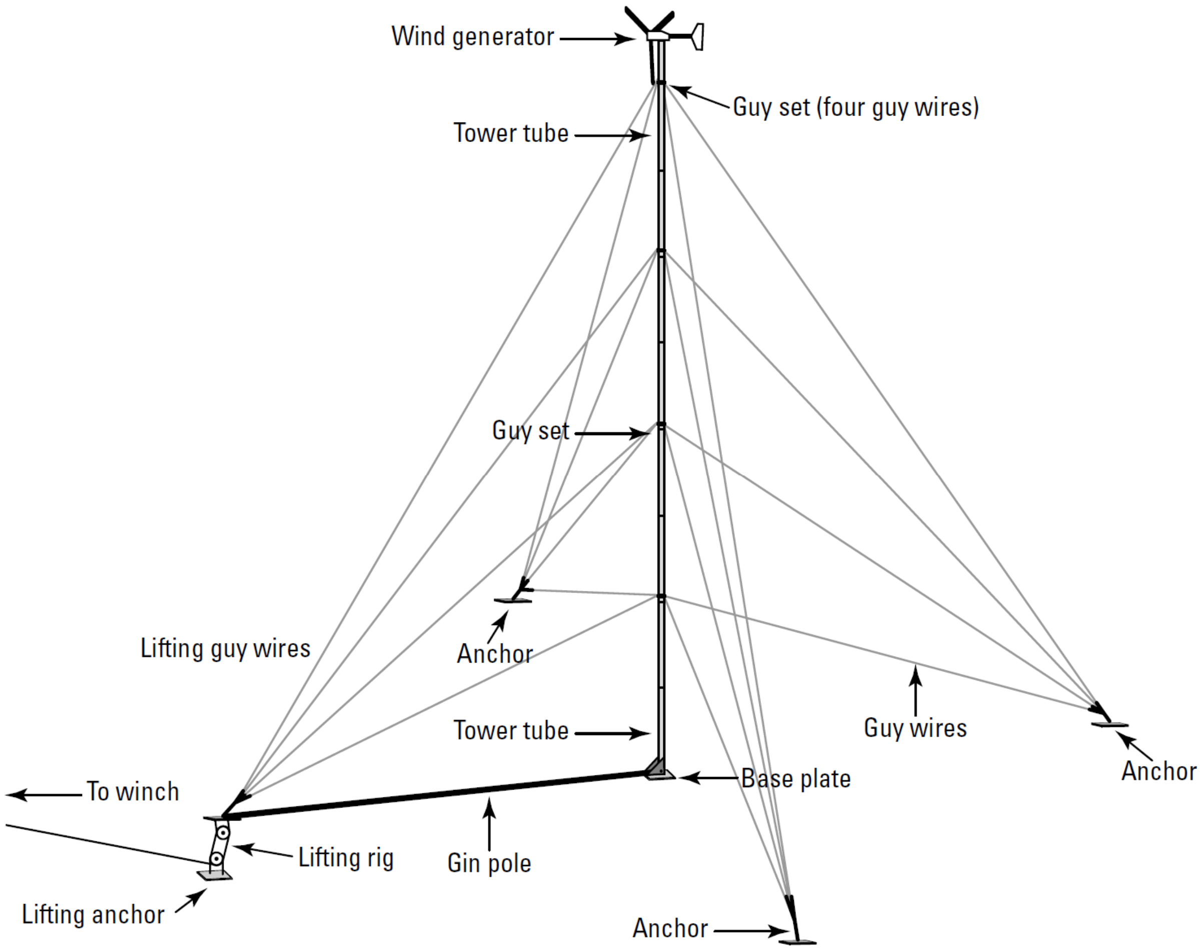


Figure 4-3 Tilt-up Tower [9]

More is said on the rotor efficiency in Section 4.3. From the above equation one can see that the wind speed has a cube influence on the generator output power and this is why according to Ian Woofenden [9] and Mukund [10] it is important to get the generator as high as possible into the air. Making the tower 5 m higher than calculated or estimated could be the easiest way of getting an increase of power output, thus increasing energy production.

In Wind Power for Dummies [9] the different types of towers available are described shortly and compared to each other in terms of footprint, ease of maintenance and cost. A summary of this comparison can be seen in Table 4-1 below.

Table 4-1 Tower Types

Tower Type	Footprint	Maintenance	Cost
Tilt-up	large	easy	low
Fixed guyed	medium	hard	medium
Free-standing	small	hard	high

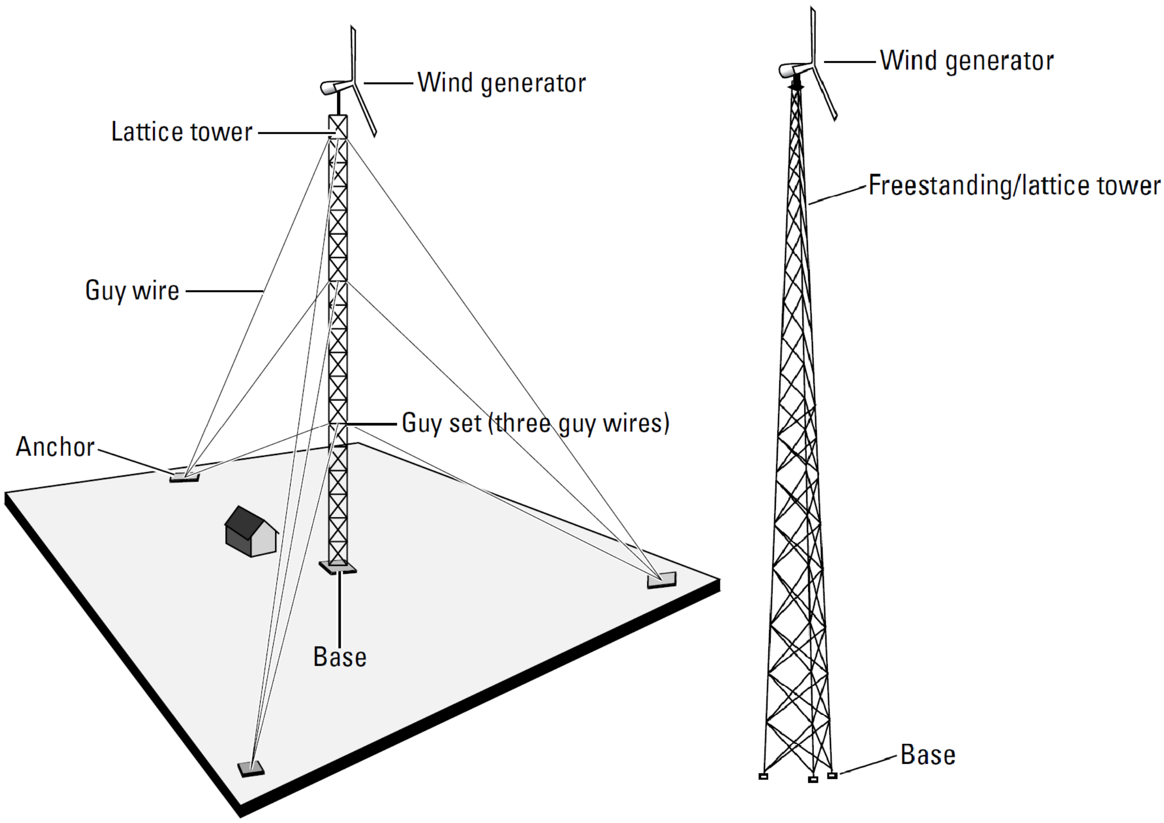


Figure 4-4 Fixed Guy-rope Tower (Left) and Free-standing Tower (Right) [9]

4.2.1 Vertical-Axis Wind Turbines (VAWT)

According to Bianchi et al. [12], the most successful VAWT is the Darius rotor show in Figure 4-5. One of the most attractive features of this type of wind turbine is that the generator and transmission devices are located at the ground level. This type of wind turbine can also capture wind in any direction, without the need to yaw, but since the rotor is mounted vertically, the rotor intercepts winds that have less energy, thus, having a reduction in wind capture.

Figure 4-5 Vertical-Axis Wind Turbine [14]

Another disadvantage is that, despite having the generator and transmission device at ground level, maintenance is not easy, as the maintenance usually requires rotor removal. Adding to the disadvantages is the fact that these types of wind turbines are supported by guy-ropes that take up large area of land. Due to the above mentioned reasons, the use of VAWTs has decreased during the last decade [12].

4.2.2 Horizontal-Axis Wind Turbines (HAWT)

The rotor of the Horizontal-Axis Wind Turbine (HAWT) is mounted with its axis horizontally on the tower as can be seen in Figure 4-6, thus the rotor axis is parallel to the ground level. HAWTs come in many different types and are usually classified according to the following [11]:

- Rotor orientation – Upwind or downwind of the tower
- Hub design – Rigid or Teetering
- Rotor Control – Pitch vs. Stall
- Number of Blades – Two or three blades
- Alignment with wind – Free yaw or active yaw

An upwind and downwind configuration is illustrated in Figure 4-7 below. In upwind turbine designs, the rotor faces the oncoming wind directly. An advantage of upwind machines is that the wind shade behind the tower is avoided when compared to downwind designs.

When looking at the aerodynamics of the tower, it is seen that the tower produces turbulent air behind itself. Therefore, it is recommended to use an upwind design where the blades are not in the turbulent air behind the tower.

Figure 4-6 Horizontal-Axis Wind Turbine [14]

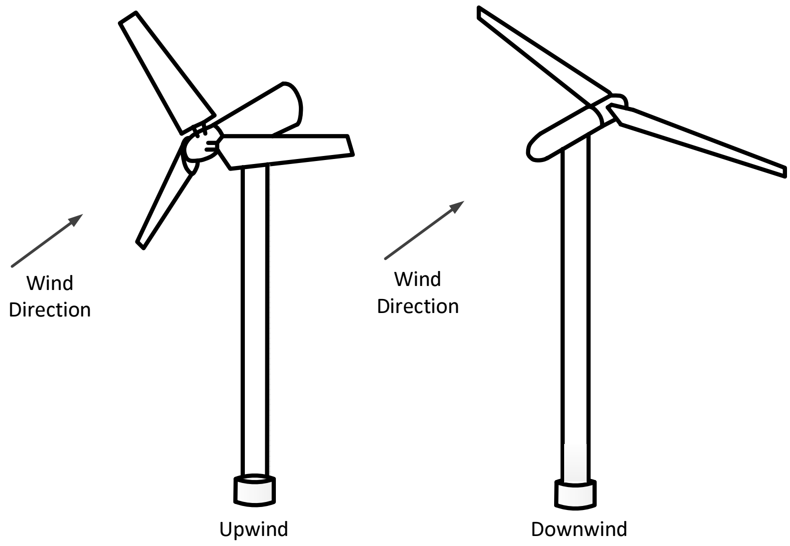


Figure 4-7 Upwind and Downwind HAWTs [11]

Despite the problem with turbulence, downwind machines are still being built due to the fact that downwind machines do not need any additional mechanism for keeping the machine in line with the wind [15].

Advantages of HAWTS are that they are more efficient than VAWTs, meaning HAWTs extract more useable power from the wind than VAWTs. The higher the rotor is from ground, the better, because wind speeds increase with increase in height (see Table 8-1 in Section 8.2.2). This is because higher up in the air, there are no structures that will disturb the natural flow of the wind, and the wind can then move more freely, which allows for higher wind speeds.

When using a VAWT, these higher wind speeds cannot be accessed properly because of design limitations. But, with a HAWT, these high speed winds can easily be accessed by increasing the tower height, which is an important advantage above VAWTs. On large wind turbines (10 kW and higher), the pitch of the blades are controlled to change the angle of attack. This allows the wind turbine to extract the optimum energy from various wind speeds.

Some disadvantages of HAWTs are that they are not easily maintainable, as the rotor and generator is positioned high up in the air. The construction of HAWTs requires specialised equipment and personnel. The HAWT needs a huge tower construction to support the large blades and generator [15].

The advantages outweigh the disadvantages by far. The HAWT is the most produced and commercially available type of wind turbine. The VAWT will only come back in the future, if the necessary advances in technologies become available to make such a design viable. From this point onwards, if a WT is mentioned, it should be seen as being a horizontal type machine.

4.3 Wind Turbine Blades

Why do wind turbines have three blades and not four or five? This is a common question asked among those not familiar with wind turbines and their aerodynamics. Many more aspects determine the number of blades that should be used, but the main aspects are aerodynamic efficiency, cost, noise, flickering (a visual aspect), stability and performance [16].

When designing wind turbines, stability as mentioned above is one of the important factors to consider. Rotors with an even number of blades tend to give stability problems when used on a wind turbine structure that is stiff. The problem is shown in Figure 4-8.

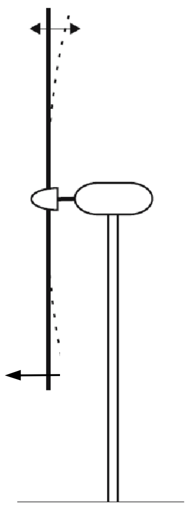


Figure 4-8 Even Bladed Machine with Stability Problems [16]

As the one blade is moving into the top most position, it bends backwards, as it is getting the maximum power from the wind, the other blade moves in front of the tower, into the wind shadow, where there is not much wind power due the tower aerodynamics. Most wind turbine rotors have three blades and this design is also called the classical Danish concept [16]. Three-bladed designs have a lower flicker frequency, because they turn slower and have a calming affect when compared to the two-bladed designs that have a higher rotational speed and therefore a higher flicker (a visual effect) frequency [16].

One advantage of two-bladed designs is the savings in cost by producing two blades instead of three blades. The disadvantages though, are that two-bladed machines need higher wind speeds to produce the same power that three-bladed machines produce at lower wind speeds. Rotating at higher speeds has higher noise levels as result, as well as a higher flicker frequency [16].

Also, as shown in Figure 4-8, the top most blade of an even bladed design gets pushed backwards whilst the blade at the bottom passes into the wind shade in front of the tower. This causes an imbalance on downwind HAWTs and can cause the blades to hit the tower. Thus a complex rotor, containing shock absorbers is needed to keep the blades from hitting the tower. The complex rotor can increase cost, rendering the use of fewer blades useless.

Single-bladed rotor designs do exist, but a single-bladed design needs a counter weight to balance the rotor. Therefore, there are no weight savings when compared to two-bladed designs. The problems mentioned on two-bladed designs are even worse for one-bladed turbine designs.

Five-bladed or more-bladed designs exist, but here the cost plays a factor, as the more blades are used, the higher the cost will be. Another important factor is the increased drag that is added if more blades are used. The increased drag introduces more turbulent air into which the next blade moves and will decrease the blades energy conversion efficiency.

Revisiting (Eq. 4.2) for the output power of the blades in Section 4.2, the rotor efficiency C_p also affects the turbine’s energy output. There is a limitation when converting the kinetic wind energy into mechanical energy. If too much energy is extracted from the wind, the wind will be slowed down as it leaves the rotor of the turbine. This in turn would slow the wind entering the rotor of the turbine, bringing it to a complete halt, meaning no energy is being extracted. If the wind moves too freely through the rotor of the turbine, no energy would be extracted from the wind. There is a solution to this problem, and that is, that an ideal wind turbine should slow down the wind entering the rotor by 2/3 of its original speed.

Betz’ Law states that one can only convert less than 59% of the kinetic energy in the wind to mechanical energy by using a wind turbine [17]. This is the fundamental physical law for the aerodynamics of wind turbines and the main reason why it is important to convert the mechanical energy, due to the kinetic wind energy, to electrical energy as efficiently as possible.

Thus, all manufacturers are striving to get to a C_p = 0.59 on their blades. High speed generators get as close as C_p = 0.5, where low speed generators can be found with power coefficients between C_p = 0.2 to C_p = 0.4 according to [18].

4.4 Summary

The location of a WGS is as important as the components of which the WGS is made up of. The location can actually be seen as a component in a WGS. It does not matter if one has the best generator or the highest tower, if the wind generator is on a location with no wind, it is useless. From the chapter it is also apparent that having a site with high wind speeds does not necessarily indicate that the site is good for a WGS setup. It is the average wind speed that contributes the most to WGS.

The continuous flow of wind is what generates the most energy. Important factors to look out for when considering a potential wind site are nearby tall structures, tall vegetation or trees and the surrounding landscape as these all have an effect on the flow of the wind, meaning less usable wind for the WGS.

A wind rose (Figure 4-1) obtained from the local weather station or the Griggs-Putnam index (Figure 4-2) are some of the methods discussed that can be used to determine a sites potential average wind speed and was mentioned in Section 4.1.

Next, one of the most overlooked components, the tower was discussed. The importance of having the generator as high up as possible was discussed, as the higher one moves up into the atmosphere the higher the wind speed become, Table 8-1 obtained from the Danish Wind Industry Association [19] confirms this. It was seen from Equation (Eq. 4.2) that the wind speed has a cube-three influence on the output power of the generator.

Two different tower types, VAWTs and HAWTs were discussed in terms of advantages and disadvantages. Two HAWT configurations, upwind and downwind were also shortly discussed in terms of advantages and disadvantages.

The influence of selecting a one-bladed, two-bladed, three-bladed or more bladed WGS was also discussed and it was seen that one-bladed and two-bladed machines have high rotational speeds, thus a high flicker frequency when compared to three-and more-bladed designs. One-and two-bladed designs can also become unstable due to the wind tower shadow effect and can cause unwanted vibrations that could rip the generator or blades apart.

The saving on cost and efficiency is higher when using the one-and two-bladed designs, when compared to three-and more-bladed designs. The three bladed designs are more stable than the less-bladed designs and also the most popular blade configuration found in the market. More-bladed designs do exist, but cost and efficiency becomes a problem with these designs. Introducing more blades creates more drag, which in turn creates more turbulent air that has a great effect on the efficiency of the blades as they can't move freely through the wind as they are supposed to.

The chapter is concluded with Bet's Law [17] that states that it is physically impossible for a blade design to extract more than 59% of the energy from the incoming wind without stalling the blades.

5 Wind Turbine Generators

This chapter reviews information on one of the main components of the WGS. The wind turbine generator converts the mechanical energy from the blades to electrical energy. Wind generators come in many different types and sizes. This chapter will mainly cover permanent magnet generators as they are mostly used in small wind turbines.

5.1 Generator Types

To convert the wind energy to electrical energy a generator is needed. Various WTG exist and only the main types are discussed. In this dissertation the focus is on small wind turbines that mainly use permanent magnet generators (PMG) to generate electrical power, therefore a more in depth discussion will be given on the different types of PMGs.

As was said above, a wide variety of wind turbine generators exist. In small wind turbine systems that range from a few 100 W up to 10 kW, it is preferred to use permanent magnet generators (PMG). PMGs are used in wind turbine systems with ratings of up to 10 kW, but it is recommended to use induction type generators from the range of 10 kW and up as PMG larger than 10 kW becomes quite expensive.

5.1.1 Direct Current (DC), Synchronous and Induction Type Generators

The DC generator, synchronous generator and induction generator are used in large type wind turbine systems. These generators are also spoken of as machines. The reason for this is that these generators, and most other generator types, can also operate as electrical motors, thus collectively calling them machines.

In large wind turbines that are connected to the electrical grid, the turbine is brought up to speed by powering the machine from the grid (thus running as a motor), and when the required speed is achieved, the machine is left to run as a generator, powered from the wind energy. All these machines are alternating current (AC) machines because of the conductor that rotates in the magnetic field of alternating north and south poles [10].

The **DC machine** uses a commutator to convert AC into DC. The commutator consists out of carbon brushes that slide across copper segments to which the coils (conductors) on the armature are connected. The positive and negative terminals are continuously connected to the conductor, generating the positive and negative voltages respectively.

As this commutator is based on a mechanical switch-mechanism, it is not very reliable and will result in high maintenance costs. One of the advantages of DC machines is that their speed can easily be controlled. Because most appliances run on AC electricity, an inverter is needed to convert the DC voltage to a more useable AC form.

The DC machines of late are designed to use permanent magnets in place of the field current previously used, thus replacing the commutator and eliminating the reliability and maintenance issues. These machines have the permanent magnets situated on the rotor, and the static stator carries the conductor windings that produce the AC. The AC can then be rectified to DC by using solid state rectifiers or other methods of rectification discussed in Section 6.1.

Synchronous machines are well known machines that are used to generate most of the electrical power consumed in the world. The synchronous machine is a linear machine, meaning that it operates at a constant speed related to a fixed frequency and because of this linearity the synchronous machine is not appropriate for use in variable speed operated wind farms [10]. The rotor field of the synchronous machine requires DC to be excited. This DC is applied via sliding carbon brushes on slip rings situated on the rotor shaft.

This configuration has a few disadvantages. Again, there are reliability and maintenance cost issues involved. These issues can be eliminated or reduced by using the reluctance rotor, where the synchronous operation is realized by using the reluctance torque [10]. This not only improves the reliability, but also reduces the cost. The use of the reluctance rotor has one drawback and that is that the machine rating is limited to tens of kW.

The **induction machine** is mostly known for its use as a motor in industrial applications to drive a mechanical load of some sort and is therefore a recognised technology. The induction machine requires no DC field power and has a rugged brushless construction. The induction machine eliminates the previously mentioned disadvantages of the DC machine and synchronous machine simultaneously.

The result is a machine that is very reliable, has low maintenance cost and has improved transient performance. The above mentioned reasons are why induction machines are used in small and large wind farms and are used in wind turbines with numerous ratings up to several megawatts[10]. The induction machine needs an alternating excitation current. The induction machine is either self-excited or externally excited. Since the induction machine’s excitation current is mainly reactive, a standalone system is self-excited by shunt capacitors.

When the induction machine is used as a generator and connected to the grid, the generator draws the excitation power from the grid and the synchronous generators connected to the network must be able to supply this reactive power. The induction machine is economical and reliable and most large wind turbine systems use induction machines as the electrical generator [10].

The PMG machine generates a poly-phase variable frequency, variable magnitude AC output. The permanent magnets are situated on the rotor on rotor disks and the field coils are situated on the stator. A more in depth discussion on the various types of PMGs will follow in the next Section 5.1.2.

5.1.2 Permanent Magnet Type Generators

The literature acquired, mostly describes topologies in terms of the path that the magnetic flux takes, given that modern magnetic materials are used. By using modern magnetic materials, very compact machines can be built [20]. Issues involving cost, manufacturability and the ability to deliver current from a low rotational speed are all important factors to consider.

By using permanent magnets, the efficiency is increased because the only other contribution to deliver enough power to generate the variable flux would be from the wind. The most common PMG configurations will now be discussed.

5.1.2.1 Axial Flux

A popular configuration can be seen in Figure 5-1 below. With no ferromagnetic material in the stator coils, this machine has no cogging torque at start-up [21]. The steel plates of the rotor disk also do not have to be made of laminated materials. An example of this machine that delivers 180 W is available as a design that can be self-built to deliver power to rural households and rural communities that have no access to mains electricity [22], [23].

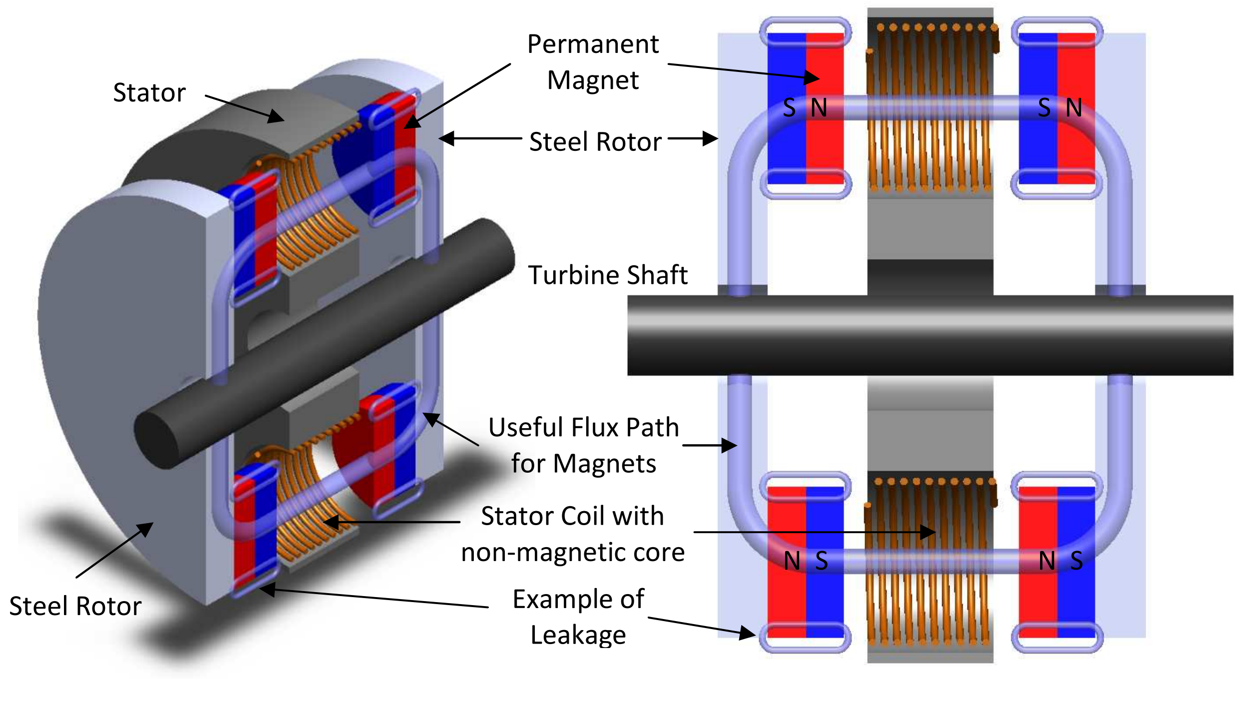


Figure 5-1 Axial Flux PMG – Non-Magnetic Core [21]

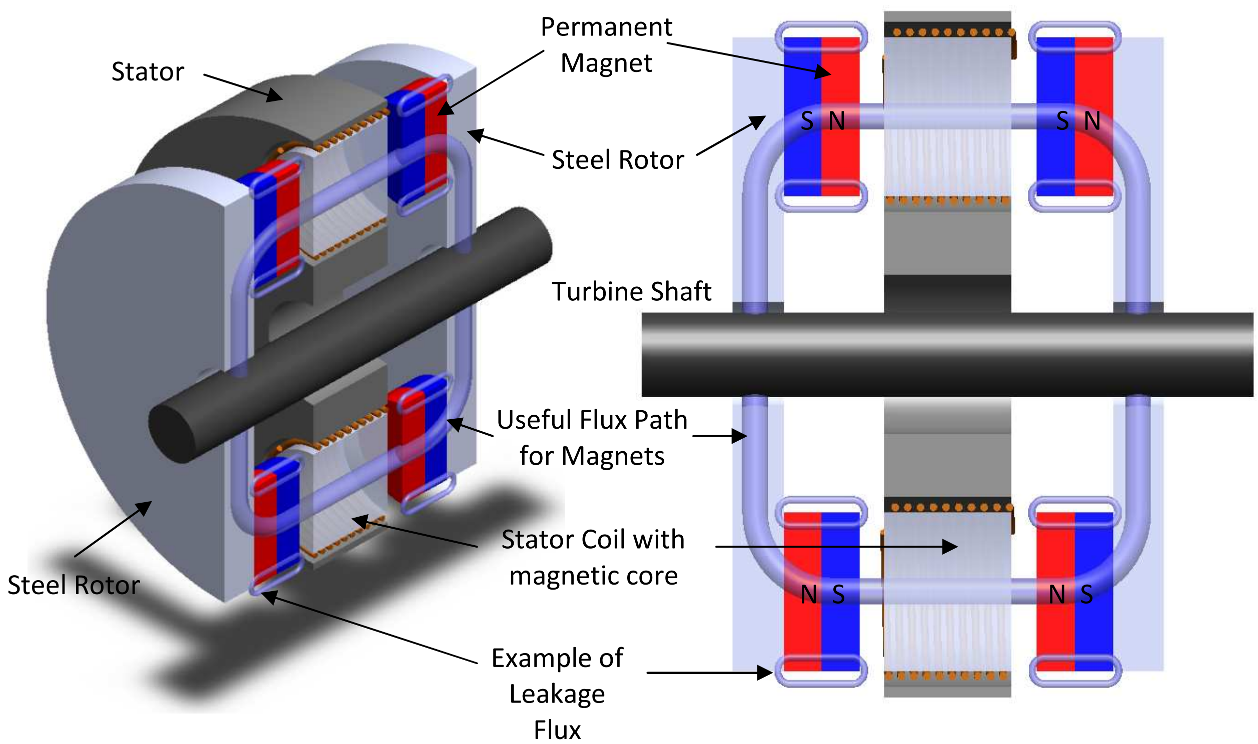


Figure 5-2 Axial Flux PMG – Magnetic Core [24]

At low rotational speeds the windings are connected in a three-phase star connection to generate low current and a high voltage, while at high rotational speeds, the windings are connected in a three-phase delta connection to lower the voltage and increase the current output capability. The switching between star and delta connection is done by relays. Another variation on the same topology as seen in Figure 5-1 is made by placing magnetic cores in the stator windings and can be seen in seen in Figure 5-2.

A higher load capability can be achieved by the lower reluctance of the magnetic path followed by the flux, but by doing this, two problems are introduced. The alternating reluctance creates high cogging torque at start-up and the cores in the stator windings must be made of laminated powder materials to reduce eddy currents and braking.

Another option is to place the magnets on the stator and the windings on the rotor, as can be seen in Figure 5-3. This topology requires that the stator be made up of a laminated material or machine-able material that consists of a modern powder material [24]. The stators can be directly in line at low speeds to generate the maximum voltage, and at high speeds, the stators can be miss-aligned slightly to produce a lower voltage. This miss-alignment can lead to demagnetising of the permanent magnets at high load currents and this design should be verified with finite element analysis. The cogging torque should be addressed in this design for the pole pieces [24].

5.1.2.2 Circumferential Flux

The advantage of the topology seen in Figure 5-4 is that the cogging torque is virtually zero if the rotor and stator are parallel and concentric. The reluctance of the flux path is also constant. An example of a circumferential type machine is discussed in [21]. The windings are wound in a toroidal form around the stator core, which is made of the appropriate magnetic material in the form of a toroid.

The windings have to be connected in sections per pole pair, to create for example a three-phase star or delta winding. The high flux density of modern magnets could see the return of this topology. A gapless design is discussed in [25]. Although no information on the core is given, it has to be made of laminated metal or manufactured from powder material. These requirements are to minimise the eddy current losses. This prototype is used in a vertical turbine in a region on the Norwegian coast where high wind speeds are common. The generator produces near sinusoidal wave forms. The generator is used to charge batteries used in signal lights.

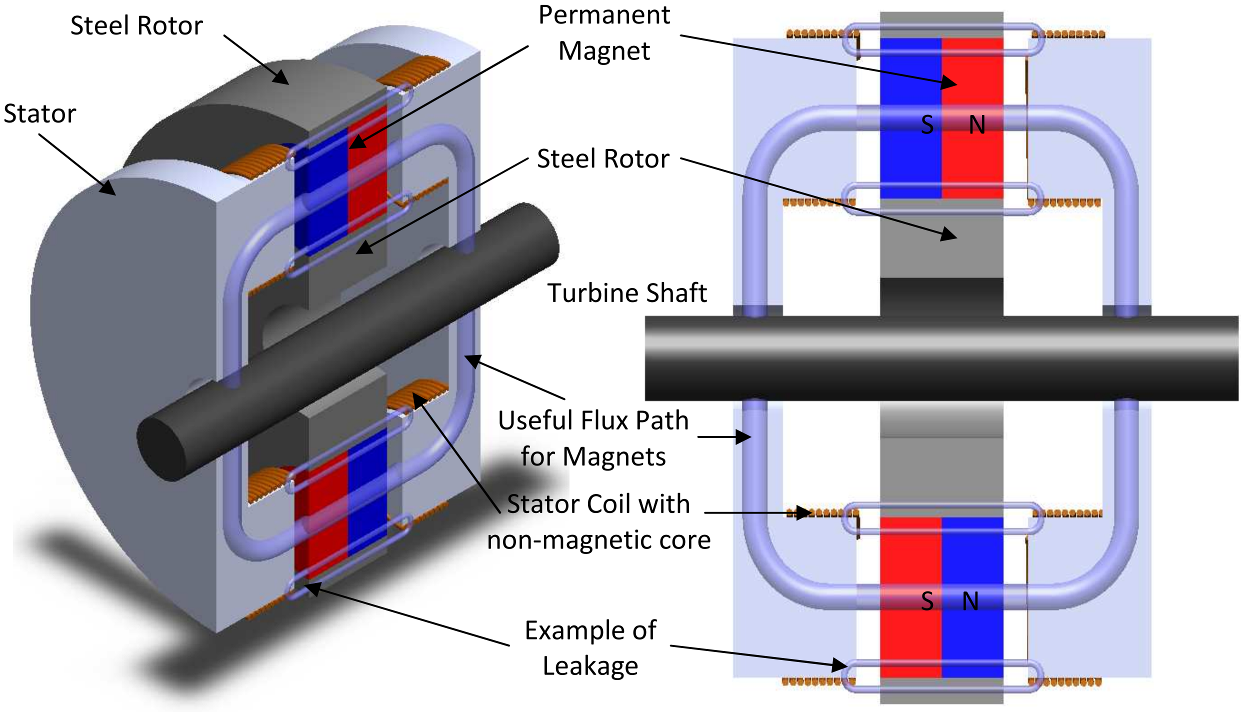


Figure 5-3 Axial Flux PMG – Non-Magnetic Core (Rotor Stator Swopped) [24]

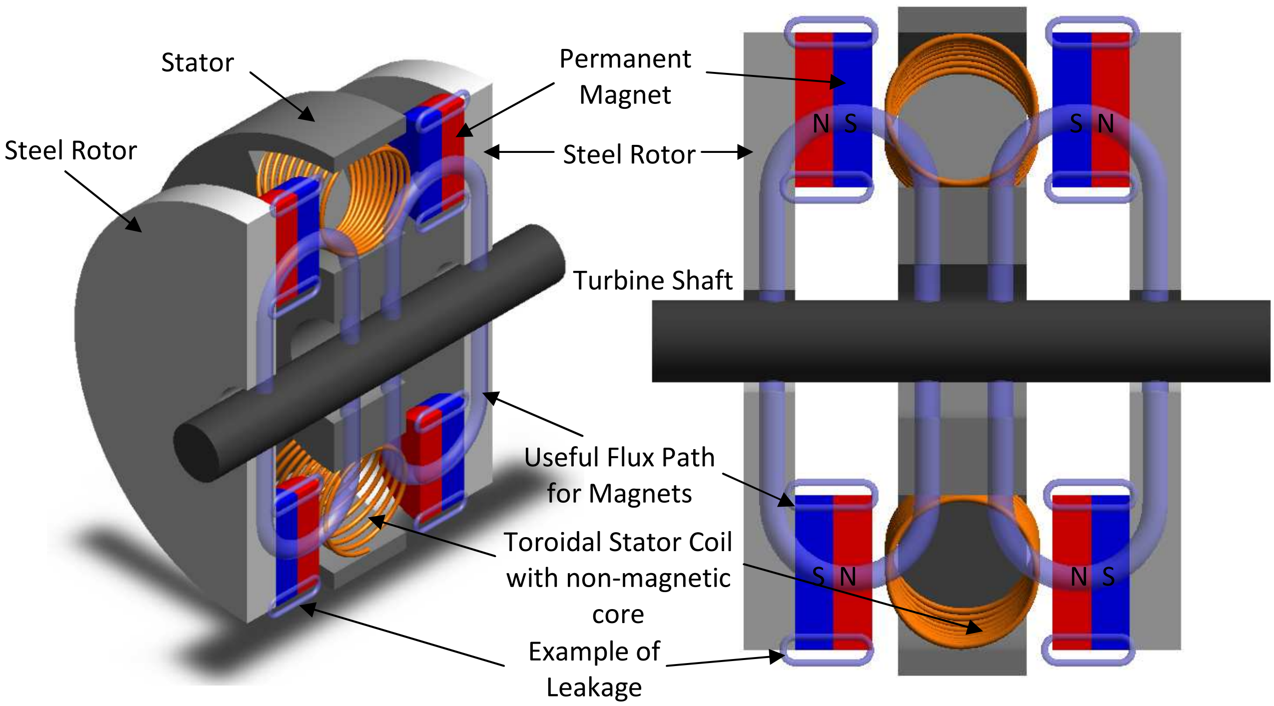


Figure 5-4 Circumferential Flux PMG – Non-Magnetic Core [21]

5.1.2.3 Radial Flux

This conventional topology is by far the most used topology and can be seen in Figure 5-5. These conventional machines are mechanically robust and heavy. The design of these machines is well known and summarised in [26]. New designs with modern magnetic materials as well as modern permanent magnets can be found in [27], [28] and [29].

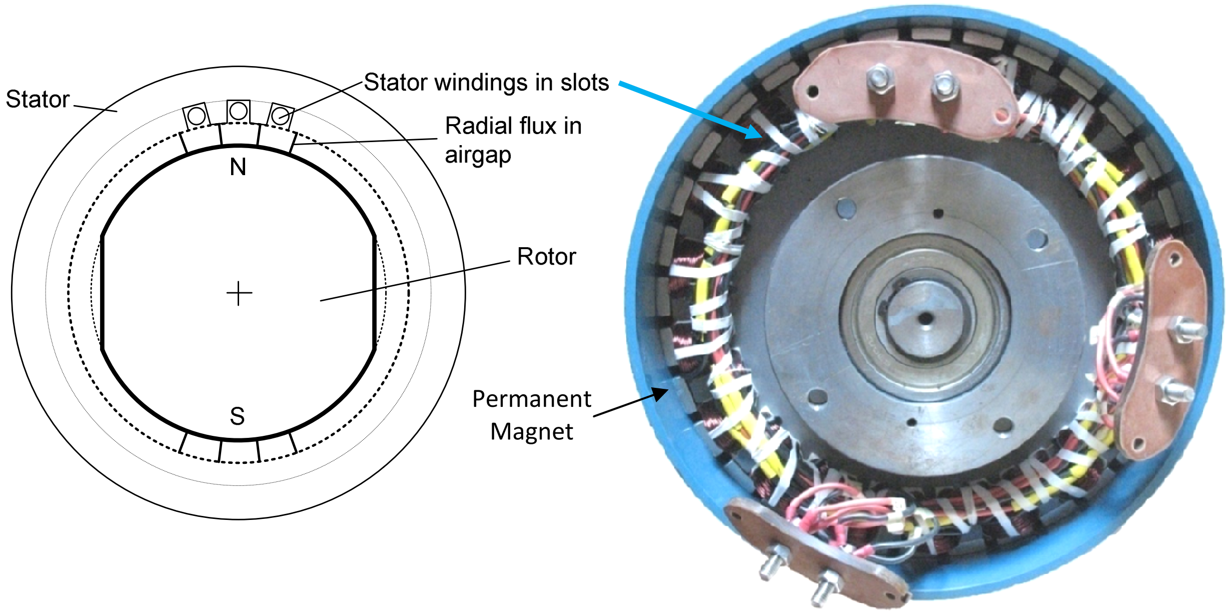


Figure 5-5 Radial Flux PMG

5.2 Summary

In Section 5.1 an overview of the different types of generators that can be used as wind turbine generators was given. The DC machine, a machine that requires a commutator and brushes to convert AC to DC was considered. The DC machine has reliability and maintenance issues due to the commutator and brush configuration. The commutator and brushes can be replaced by permanent magnets to generate the rotor field. But using permanent magnets limits the size of the generator due to the capacity of the permanent magnets.

The synchronous machine has a constant speed at a fixed frequency that is not suitable for use in variable speed wind farms unless power electronics are used to change the frequency. The synchronous machine also requires a DC to excite the rotor field, meaning that slip rings and sliding brushes have to be used. This leads to maintenance, reliability and cost issues.

By using a reluctance rotor in the synchronous machine, the maintenance, reliability and cost issues can be eliminated, but this also limits the use of this machine to smaller units in the tens of kW.

The induction machine requires no DC field power and has a rugged, brushless construction. The induction can be used in small or large wind turbines, but is recommended for large turbines.

The permanent magnet generator is mostly used on small wind turbines with ratings of a few 100 W up to 5 kW. The PMG is discussed in more detail in terms of the magnetic flux path. The axial flux, circumferential flux and radial flux PMGs was discussed in Section 5.1.2.

6 AC-DC-AC Conversion

In this chapter two methods for increasing the PMG output voltage at low wind speeds are discussed, followed by a discussion on the effects of harmonics on the PMG. The conversion from AC-DC, DC-DC and DC-AC will be discussed. The AC output from the wind generator varies in magnitude and in frequency, and is also called a "wild" AC output. This AC power must be converted to DC power to charge batteries and back to AC power, 230 V at 50 Hz to be usable by home appliances. The different mechanisms required to establish this AC-DC-AC conversion is discussed now.

6.1 PMG Connection

At low wind speeds the output voltage of the PMG can be very low, so low that battery charging cannot commence. To enable the PMG to have a higher output voltage at low wind speeds a step-up transformer can be used or the PMG can be star connected. As the wind speed increases, the voltage may become very high and the transformer will need to be removed or the generator will have to be connected in a delta configuration.

6.1.1 Direct- Connection

With the PMG connected straight onto a step-up transformer, there is no room for control. As the wind speed increases the output voltage of the PMG generator will also increase. The voltage may become too high for the AC-DC converter to handle comfortably. The same can be said for the star configuration. The PMG can be connected in star-configuration to enable a higher output voltage at low wind speeds, but as the wind speed increases the output voltage might again become too high for the AC-DC converter to handle. Two methods for getting around this problem are discussed next, auto-transformer voltage control and star-delta voltage control.

6.1.2 Auto-transformer Voltage Control

It is recommended to use an auto-transformer type configuration as this configuration contains taps that will have a different output voltage at different wind speeds. At low wind speeds, the tapping with the high output voltage can be used. As the wind speed increases the transformer can be switched to a tap that has a lower output voltage at a high wind speed. This method closely resembles the auto-transformer starting scheme sometimes used on electrical motors.

6.1.3 Star-delta Voltage Control

Three-phase power is commonly used in power generation and large electrical loads for operation. Three-phase power systems consist of ideally balanced loads, that is, each phase is separated by a fixed phase difference from each other of 120° (2π/3 radians). Two topologies exist in which generators, motors and three-phase transformers can be connected [30]. The windings of these machines can be connected as follows:

- Y - star or wye
- Δ - delta

The star-delta voltage control method also closely resembles the star-delta starting scheme used on electrical motors. At low rotational speeds the windings are connected in a three-phase star connection to generate low current and a high voltage, while at high rotational speeds, the windings are connected in a three-phase delta connection to lower the voltage and increase the current output capability.

The PMG will first be connected in star at low wind speeds. The star configuration will have a high output voltage and low output current as can be seen from the equations ((Eq. 6.2) and (Eq. 6.3)) below. As the wind speed increases, the output voltage can become too high for the AC-DC converter to handle and the PMG will need to be switched to a delta configuration to lower the output voltage and this can be seen in equations ((Eq. 6.4) and (Eq. 6.5)) below.

Therefore, the star-delta configuration can in effect have the same function as an auto-transformer without the cost and size requirements of an auto-transformer. The no-load stator rms phase voltage for a three-phase generator is as follows [31]:

$$E_{rms} = \frac{2\pi}{\sqrt{2}} f N \phi \qquad \textit{(Eq. 6.1)}$$

where

f = frequency at which the stator is rotating (derived from the rpm)

N = Number of coils per phase

ϕ = flux density over pole area

The voltage and current output for a star connected PMG:

$$V_{L-L} = \sqrt{3}V_{ph} \qquad (Eq.\ 6.2)$$

$$I_L = I_{ph} \qquad (Eq.\ 6.3)$$

where

V_{L-L} = line to line voltage

V_{ph} = phase voltage

I_L = line current

I_{ph} = phase current

The voltage and current output for a delta connected PMG:

$$V_{L-L} = V_{ph} \qquad (Eq.\ 6.4)$$

$$I_L = \sqrt{3}I_{ph} \qquad (Eq.\ 6.5)$$

Assuming a balanced three-phase generator, the total power delivered can be found by adding the powers in the three phases. The average power for a balanced circuit is the same for all the phases, the average power can simply be multiplied by three [31]. Therefore we have:

$$P = 3V_{ph}I_{ph} \cos \phi \qquad (Eq.\ 6.6)$$

where

V_{ph} = phase voltage

I_{ph} = phase current

$\cos \phi$ = load power factor

ϕ = power factor angle between the phase voltage and phase current corresponding to any phase

The above equation can be rewritten in terms of line-to-line voltage and line current as follows and the equation is valid for either star-connected or delta-connected balanced systems [31]:

$$P = \sqrt{3} V_L I_L \cos \phi \qquad (Eq.\ 6.7)$$

where

ϕ = still the power factor angle between the phase voltage and phase current corresponding to any phase.

A disadvantage of the start-delta method is the number of connections required. To reach full operating speed the machine requires a switchover to delta. This switchover can result in high current peaks; therefore an increase in switching transients is seen. The star-delta method is relatively cheap and simple when compared to other methods. Cohen [32] recommends using closed-circuit transitions to avoid open-circuit current surges.

6.1.4 Harmonics and Efficiency

The harmonics introduced by the switching of semi-conductor devices like diodes and SCRs found in rectification circuits, will have an effect on the generator much the same way as its harmonics has an effect on the performance of motors. H. Samra and M. Islam [33] found that a non-linear load caused a temperature rise of about 5°F due to harmonics in comparison to their linear load condition.

The harmonics have therefore introduced additional power losses that can affect the overall temperature rise and local over heating of the generator [33]. The results also showed that the various levels of harmonic distortion produced by the non-linear load are related to the voltage regulation of a synchronous generator under various load conditions.

The harmonics introduced can be reduced by using passive and active filters[34],[35] and [36]. These filters are designed to work at a specific frequency range specific to the wind turbines operating speed.

In Nicky et al’s [34] research they used a harmonic trap filter that was tuned to two specific wind speeds, an average wind speed of (7 m/s) and maximum wind speed of (11 m/s). Nicky et al [34] also used a damped filter in conjunction to the harmonic trap filter.

The damped filter introduces low impedance for a wide spectrum of harmonics. Nicky et al [34] found that the harmonic contents of both the current and voltage was reduced. The harmonic losses in the generator were also lower. The total harmonic current distortion was reduced from 23.6% to 6.75% and the total harmonic voltage distortion was reduced from 16.28% to 5.94% [34].

One has to keep in mind that these filters will dissipate power from the generator and this will reduce the overall efficiency.

6.1.5 Summary

The output voltage of the PMG can be controlled via two methods. An auto-transformer can be connected to the output and by selecting different taps according to different wind speeds the output voltage can be controlled.

The PMG can also be star-delta connected depending on the wind speed. At a low wind speed the PMG can be star connected to have a higher output voltage. As the speed increases, the PMG connection should be switched to a delta connection to lower the output voltage. This increase and decrease of the output voltage is to simplify the design of the DC-DC converter and to enable the converter to start charging batteries at low wind speeds.

Harmonics caused by the switching of semi-conductors and relays also has an effect on the system and was discussed in section 6.1.4. Active and passive filters can be used to reduce the harmonics and was also discussed.

6.2 AC-DC Conversion

On large wind turbines, the three-phase power is grid connected and it is not required to convert the AC to DC. On small wind turbines, commonly used in rural areas where there is a need to charge batteries, it is required to convert the AC to DC.

Also, when using a switch mode power supply (SMPS) to up-or-down convert the DC voltage to a voltage level required to charge the batteries, it is required to have a DC voltage as the input voltage to the SMPS, thus, for small wind turbines meant for battery charging, it is required to have a DC voltage as output voltage. To convert AC to DC a rectifier is required.

The two main types of rectification known as conventional diode switching bridge types and controlled switching type are discussed below.

Half-and full-wave rectification can be done on both single-phase and three-phase power supplies. The power required by the DC load usually determines whether full-wave or half-wave rectification will be used. Diodes are used in half-and full-wave rectifiers and a circuit consisting of independent diodes can be built to make up a rectifier circuit, or a package containing the diodes can be used.

By using the package, the rectifier can easily be mounted on a heat sink if one is required. Rectifiers that do not contain any moving parts like the rotating commutators found in DC motors are called static power rectifiers. Static power rectifiers can be divided in two groups.

- Uncontrolled Rectifiers
- Controlled Rectifiers

Uncontrolled rectifiers are used in many electrical appliances and are well known to the electronic and electrical industry. Uncontrolled rectifiers make use of semiconductor diodes to achieve the necessary AC to DC rectification.

Controlled rectifiers make use of gate turn-off thyristors (GTOs), MOSFET-controlled thyristors (MCTs) and the most used device, the thyristor (SCR – Silicon Controlled Rectifier). Uncontrolled and controlled rectifiers can both be implemented to obtain single-or three-phase rectification.

6.2.1 Uncontrolled Rectifier (Diode Rectifier)

Looking at an ideal diode, the diode should conduct current freely in the forward direction and avoid current from flowing in the reverse direction. The practical diode only approaches the ideal diode.

Practical semiconductor diodes have a voltage drop across itself in the forward direction and allow a finite current to flow in the reverse direction. This forward voltage drop is small, but not negligible when working with small voltages. The voltage drop is usually in the range of 0.6 V - 0.7 V.

6.2.1.1 Half-wave rectification

In Figure 6-1, the circuit model is seen. An AC source is series connected with a diode and resistive load. A pure resistive load is used to simplify calculations and inductive and capacitive loads will not be discussed in this dissertation. Using inductive and capacitive loads will cause the current through the load to either lead or lag behind the voltage respectively. Using a pure resistive load, the current and voltage is in phase with each other.

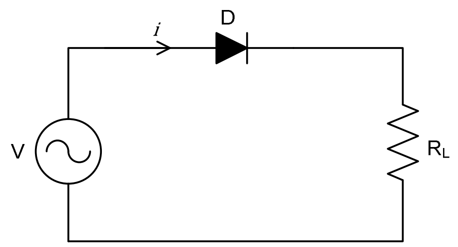


Figure 6-1 Half-wave Rectifier

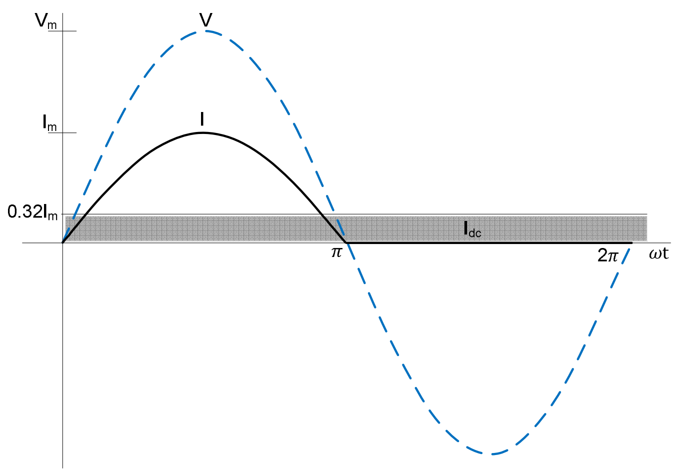


Figure 6-2 Half-wave Rectification Wave Form

An ideal diode is used for the equations below. For the source voltage $\mathrm{V} = \mathrm{V_m} \sin \omega t$ and the resulting current for the different period of the sinusoidal waveform is

$$\begin{cases} i = \dfrac{v}{R_L} = \dfrac{V_{m \sin \omega t}}{R_L} & \Bigg| \; 0 \leq \omega t \leq \pi \\ i = 0 & \Bigg| \; \pi \leq \omega t \leq 2\pi \end{cases}$$

and can be seen depicted in Figure 6-2.

The current through the load resistor is made up of half sine waves and the resultant DC component is about 30% of the peak value [37]. The calculations can be seen below.

$$I_{DC} = \frac{1}{2\pi}\int_0^{2\pi} i \, d(\omega t) = \frac{1}{2\pi}\int_0^{2\pi} \frac{V_{m \sin \omega t}}{R_L} \, d(\omega t) + 0 \qquad \textit{(Eq. 6.8)}$$

$$= \frac{1}{2\pi}\frac{V_m}{R_L}[-\cos \omega t]_0^{\pi} = \frac{V_m}{\pi R_L} = \frac{i_m}{\pi} \qquad \textit{(Eq. 6.9)}$$

6.2.1.2 Full-wave Rectifier

By using the full wave-bridge rectifier circuit shown in Figure 6-3, a higher DC voltage value can be achieved for the same source voltage when compared to a half-wave rectifier. From Figure 6-3, and by looking at Figure 6-4, if the source voltage is positive, the current will flow along the path abcd. As the source voltage reverses, the current will flow along the path dbca.

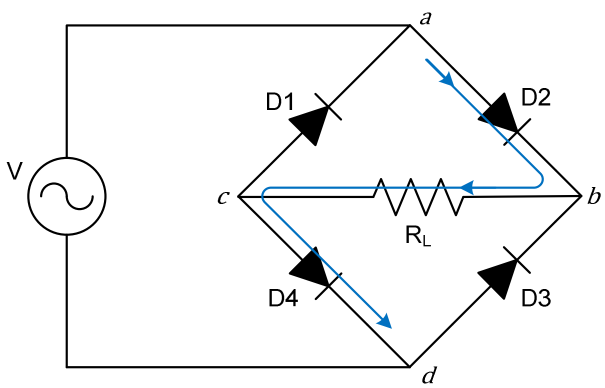


Figure 6-3 Full-wave Bridge Rectifier

The current “seen” by the load resistance will always be in the same direction, resulting in a DC component that is twice as large as in the half-wave rectifier.

$$I_{DC} = \frac{2}{\pi}\frac{V_m}{R_L} = \frac{2I_m}{\pi} \quad \text{(Eq. 6.10)}$$

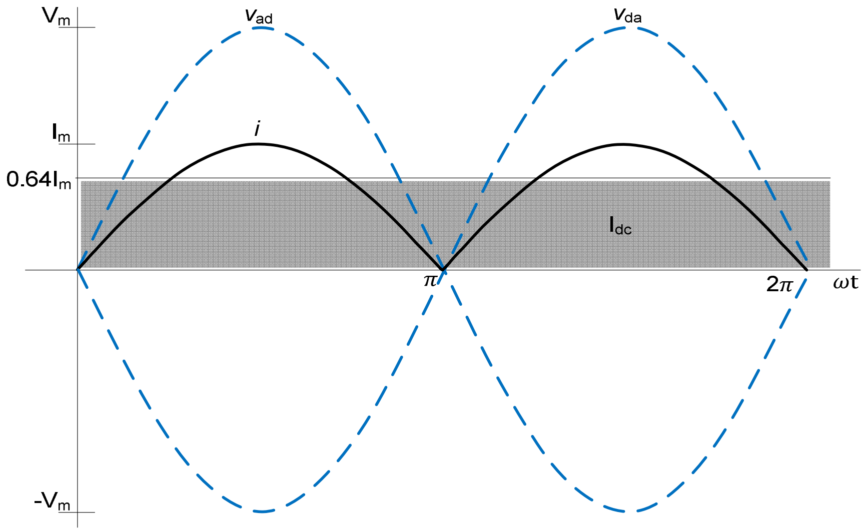


Figure 6-4 Full-wave Bridge Rectifier Wave Form

The bridge rectifier always has two diode voltage drops in series with the load. This fact, and the fact that a bridge rectifier requires four diodes, is to its disadvantage. The bridge rectifier is very cost effective and easy to build, and this is an important advantage. The bridge rectifier is widely used.

Another alternative to the bridge rectifier is the full-wave rectifier with phase inverter. This type of full-wave rectifier is realised by using a more expensive centre-tapped transformer. By using a centre-tapped transformer, the diodes can be reduced to only two diodes and the circuit has a higher operating efficiency to effect.

The voltage v_2 on the second output winding of the transformer is 180° out of phase with v_1 and this centre-tapped winding serves as a phase inverter [37]. See Figure 6-5 and Figure 6-6 below. The current i_1 is sourced through diode 1 whilst v_1 is positive. While v_1 is negative, v_2 is positive and there is no current flowing through diode 1. This causes current i_2 to be sourced through diode 2. The sum of the currents i_1 and i_2 is the current that flows through the load resistance.

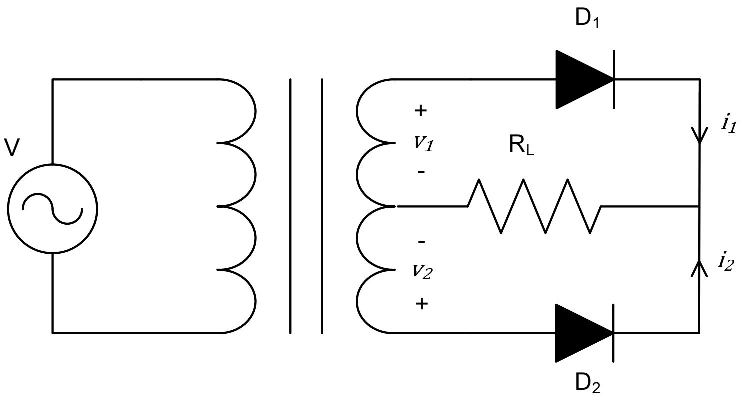


Figure 6-5 Full-wave Rectifier with Phase Inverter

The DC component is the same as for the bridge circuit.

$$I_{DC} = \frac{2I_m}{\pi} \qquad (Eq.\ 6.11)$$

By using a rectifier, a smooth or steady output current is expected, but along with the DC component, large alternating components exist. The AC components can be reduced by using a full-wave rectifier instead of a half-wave rectifier. Although the AC components are reduced by using a full-wave rectifier, the remaining ripple voltage across the load resistance is still not good enough to be used on most electronic equipment that require a steady voltage.

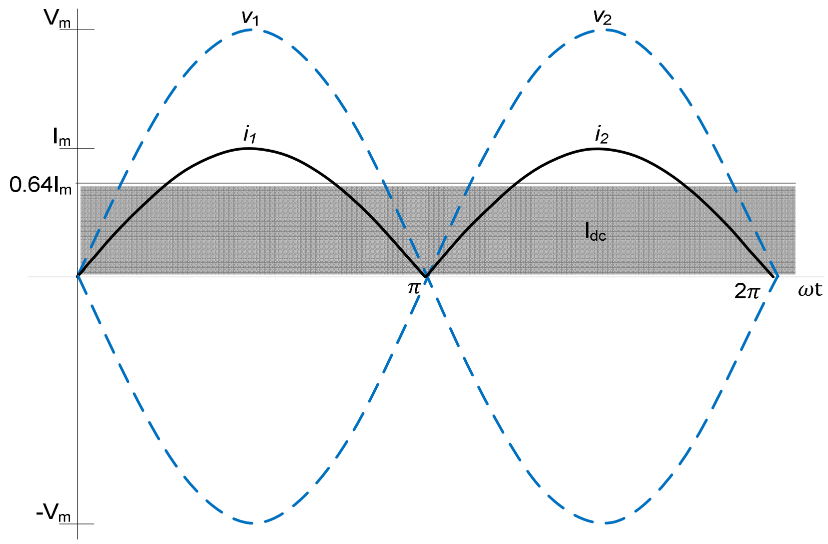


Figure 6-6 Full-wave Rectifier with Phase Inverter Wave Form

The ripple voltage can be greatly reduced by using an electrical filter. The function of the electrical filter is to reject the AC component while letting the DC component through. Using the electrical filter will provide the required direct current. Various electrical filters exist, but the most common filter used on rectifier circuits is the capacitor filter.

The filter consists of a capacitor connected in parallel across the load resistor. The capacitor acts like a "reserve tank" that stores charge during the period that the diode is conducting and sources this charge during the period that the diode is not conducting [37]. The operation can be seen in Figure 6-7, below.

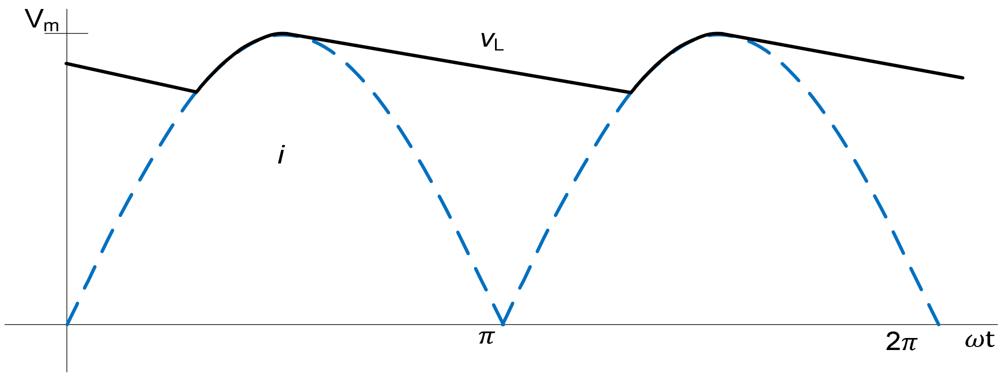


Figure 6-7 Full-wave Rectifier with Smoothing Filter Wave Form

6.2.1.3 Three-phase Rectifier

The rectifiers discussed above were all for use with a single-phase supply. The same rectification principles (half-and full-wave rectification) can be applied to three-phase circuits as was used in single-phase circuits. Three-phase bridge rectifiers, seen in Figure 6-8, are typically used above 1 kW to create a DC supply that is achieved by rectifying the line-line voltage [38].

Three-phase bridge rectifiers produce six pulses (see Figure 6-9) of power near the peaks of the line-to-line voltages and this is what makes using more phases advantageous. The main advantage is that the filter requirements are reduced when compared to single-phase rectifiers [38]. The ripple contained in the DC output is also reduced.

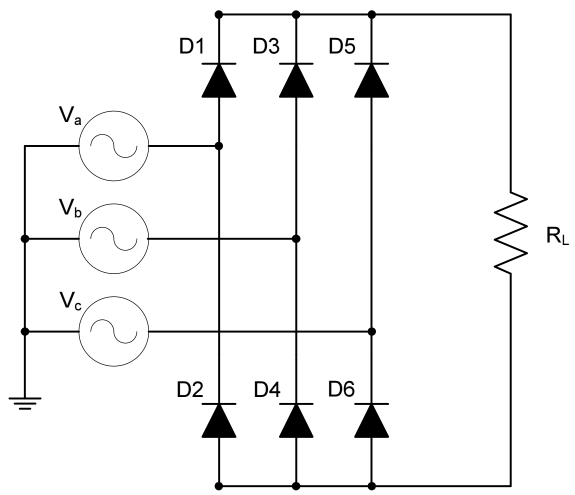


Figure 6-8 Three-phase Bridge Rectifier

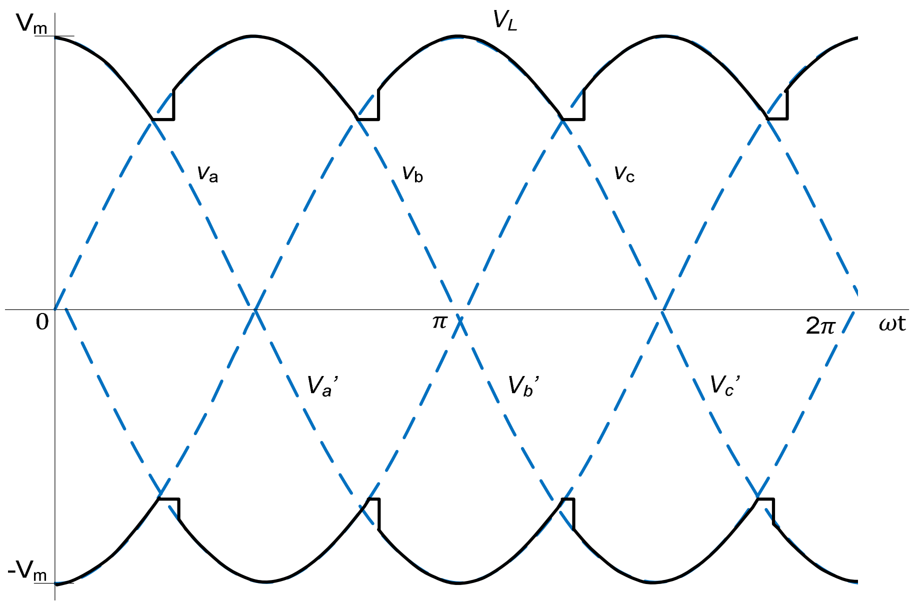


Figure 6-9 Three-phase Bridge Rectifier Wave Forms

6.2.2 Controlled Rectifier

As was mentioned previously, controlled rectifiers generally use SCRs as power switching devices to implement rectification. Phase controlled rectifiers are basically used to convert an alternating voltage with variable amplitude and frequency to a DC voltage of variable magnitude. SCRs are controlled by applying a pulse to the gate of the device. To turn on the SCR, a pulse must be applied to the gate (called the gate pulse) when the device is forward biased.

The SCR is turned off by the commutation of current from one device to another when the incoming AC voltage has a higher instantaneous potential than instantaneous potential of the outgoing wave. Without any external commutation circuitry, there is a natural tendency for the current of the device to be commutated from the outgoing to incoming SCR. The commutation process mentioned here is often referred to as natural commutation [39].

6.2.2.1 Half-wave rectification

A single-phase half wave rectifier can be seen in Figure 6-10. The SCR is turned on at the angle α. At this instant, the full supply voltage is applied to the purely resistive load. The voltage drop across the SCR is neglected. For the purely restive load, the wave form of the output voltage will follow the wave form of the input voltage during the positive half just like in the half-wave diode rectifier. For the negative half of the input wave form, the SCR will be turned off, which also resembles the operation of the half-wave diode rectifier. Thus, the SCR can be used to rectify an AC voltage to a DC voltage like a diode rectifier.

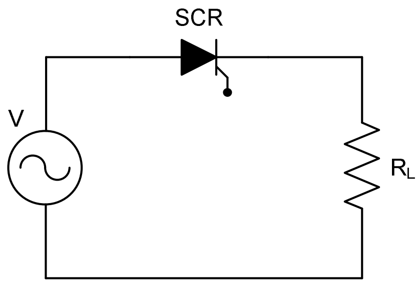


Figure 6-10 Half-wave SCR Rectifier

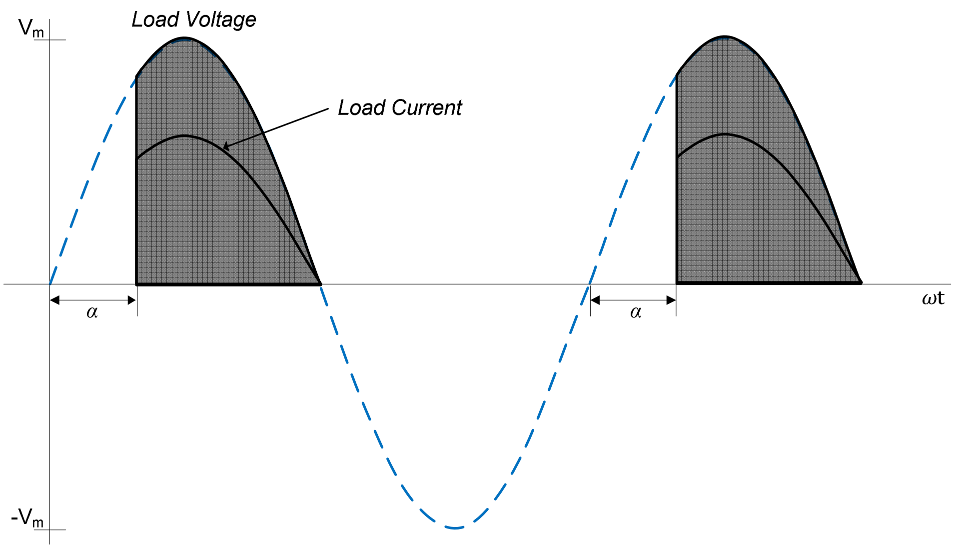


Figure 6-11 Half-wave SCR Rectifier Wave Forms

There is a difference though, the SCR can be controlled, and as seen in Figure 6-11, can be switched on at different angles. This means that the amplitude of the output can be varied, by switching the SCR on at different angles. This is a feature that is not available when using diodes, as they cannot be controlled.

6.2.2.2 Full-wave Rectifier

To obtain a full-wave rectifier, a bridge configuration like that of Figure 6-13, or a centre-tapped transformer of Figure 6-12 can be used. The following equation (Eq. 6.12) gives the average output voltage of a single-phase full-wave rectifier that has continuous current conduction

$$v_{d\alpha} = 2\frac{E_m}{\pi}\cos\alpha \qquad \textit{(Eq. 6.12)}$$

where E_m is the peak value of the input voltage and α is the firing angle [39]. The output voltage for a full-wave rectifier (centre-tapped and bridge) connected to a purely resistive load is shown in Figure 6-14.

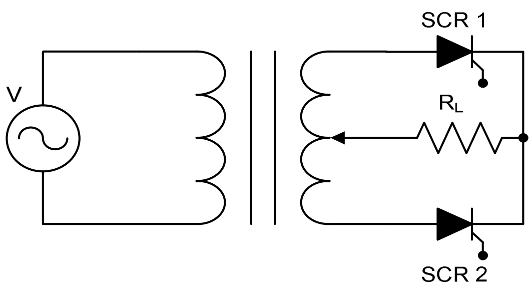


Figure 6-12 Full-wave SCR Rectifier with Phase Inverter

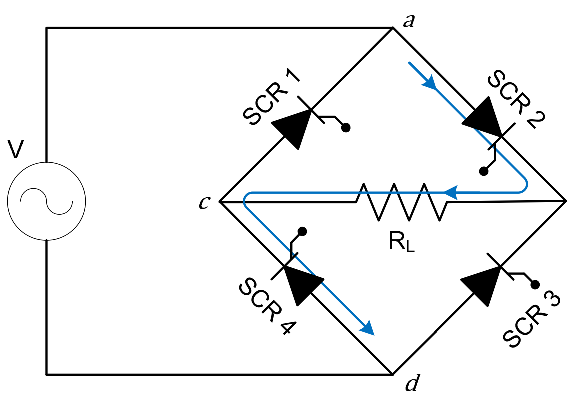


Figure 6-13 Full-wave Bridge SCR Rectifier

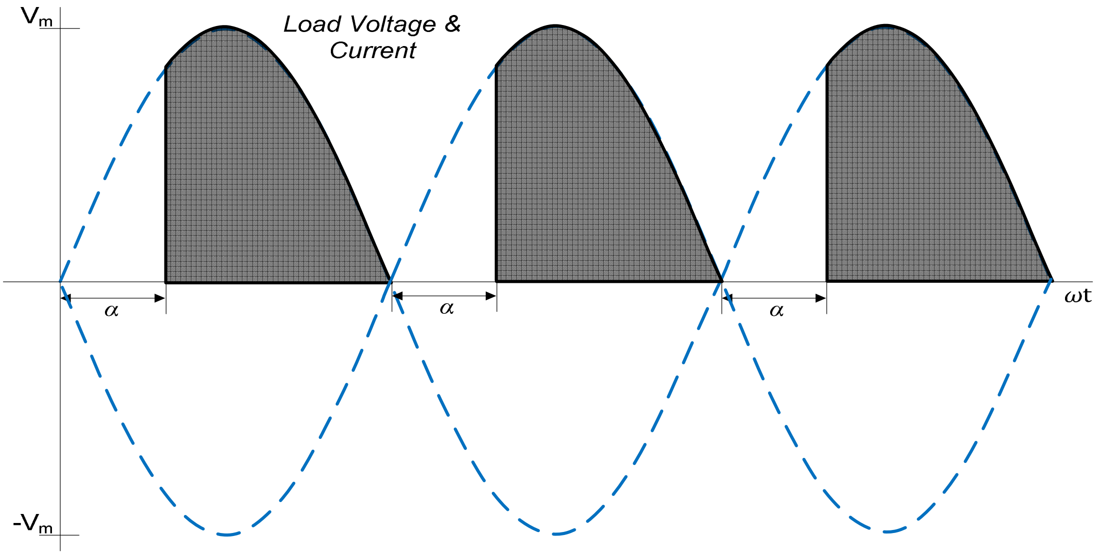


Figure 6-14 Full-wave SCR Rectifier Wave Forms

6.2.2.3 Three-phase Rectifier

A three-phase controlled rectifier can be obtained by replacing the six diodes of the three-phase diode rectifier of Figure 6-8 with thyristors as shown in Figure 6-15. This configuration is commonly used when controlled three-phase rectifiers are used.

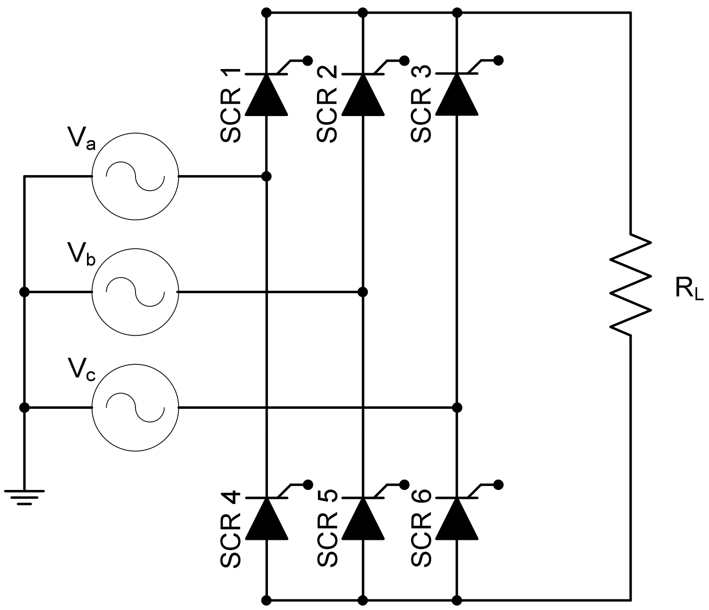


Figure 6-15 Three-phase SCR Rectifier

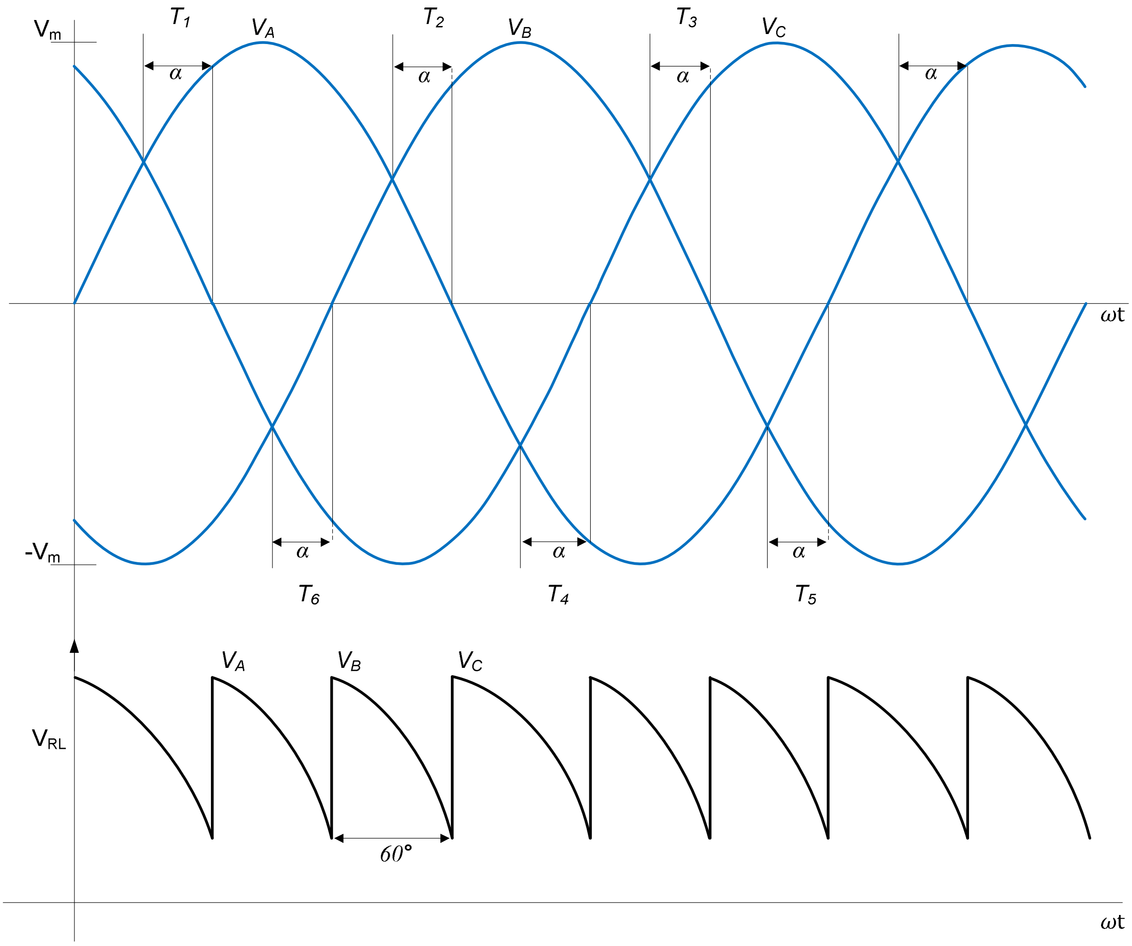


Figure 6-16 Three-phase SRC waveforms

During the positive halves of the voltages of the phases V_a, V_b and V_c, thyristors SCR_1, SCR_2 and SCR_3 are turned on. Thyristors SCR_4, SCR_5 and SCR_6 are turned on during the negative half of the phase voltages.

The crossing point of the phase voltages is used as the reference for the switching angle in each cycle. By varying the firing angle α, the amplitude of the DC output voltage can be controlled. The output voltages can be seen in Figure 6-16. For the three-phase controlled rectifier the output voltage under continuous current can be given as

$$v_o = \frac{3\sqrt{3}}{\pi} E_m \cos \alpha \qquad \textit{(Eq. 6.13)}$$

where E_m is the peak value of the phase voltages [39]. For the above equation (Eq. 6.13) the following conditions exist in terms of the firing angle used.

$$v_o = \begin{cases} 0, & \alpha = 90° \\ +v_o, & 0° < \alpha < 90° \\ -v_0, & 90° < \alpha < 180° \end{cases}$$

Thus at $\alpha = 90°$ the output voltage is zero and for $0° < \alpha < 90°$ the output voltage will be positive and the power flows from the AC source to the load. For $90° < \alpha < 180°$ the output voltage is negative and the rectifier operates in the inversion mode. Thus, if the rectifier is connected to a DC motor, the power can be transferred back to the AC source from the motor. This process is known as regeneration [39].

6.2.3 Summary

To convert an AC voltage to a DC voltage a rectifier is needed. The above sections discussed the two types of rectifiers. An uncontrolled rectifier that is made up of diodes was discussed, and also the controlled rectifier that uses thyristor switch devices to implement rectification, was discussed. These rectifiers can each be connected in the different sub types of rectifier configurations known as:

- Single-phase half-wave rectifier
- Single-phase full-wave rectifier (bridge type and centre-tapped transformer type)
- Three-phase half-wave rectifier
- Three-phase full-wave rectifier.

The configuration is selected, based on load requirements as well as the number of electrical phases available. Full-wave rectifiers are more efficient than half-wave rectifiers and the efficiency is increased by using three or more phases.

An issue not mentioned in the controlled section, is the origination of the gate pulse that is applied to the gate of the thyristors. This pulse is applied by a microcontroller that has code programmed on the microcontroller to control the switching. The control is based on when the AC signal crosses the zero point.

This is called zero-crossing measurement. A zero-crossing-measurement must be done by the microcontroller, which then calculates when to apply the gate signal. The delay of applying the gate pulse to the thyristor gate from the zero cross point, is called the firing angle. Therefore, using an uncontrolled rectifier is far easier than implementing the controlled rectifier. Especially when looking at a three-phase full-wave configuration. Three-phase bridge rectifier packages, which contain all six diodes are commonly available, and are more cost effective than controlled type rectifiers. Implementing a controlled type rectifier can be complex and time consuming.

The uncontrolled rectifier can also be easily supplied to rural areas to be replaced. Although the uncontrolled rectifier is the simpler one to implement, the controlled rectifier has conversion efficiency and output amplitude control to its advantage.

6.3 DC-DC Converter

The DC output voltage from the three-phase uncontrolled full-wave rectifier, connected to the wind turbine generator, is proportional to the speed at which the wind turbine generator is rotating and will not be a constant voltage required to charge batteries.

Therefore, by increasing the rotational speed of the wind turbine generator, the generated output voltage is increased proportionally. To charge batteries a constant regulated DC output voltage is required, and this is why a DC-DC converter, also known as a switch mode power supply, is required. This is an alternative to a controlled rectifier.

The regulation can be done in two ways,

- By using a linear regulator
- By using a SMPS

6.3.1 Linear Regulator

The basic circuit is shown in Figure 6-17. It consists of an electrically variable resistance in the form of a transistor (operating in the linear mode) in series with the output load [40]. An error amplifier is used to sense the output DC voltage by using the sampling resistor network R1 and R2. The output voltage is then compared to a reference voltage (V_{ref}). The error amplifier output voltage drives the base of the series-pass power transistor via a current amplifier.

The phasing is such that if the DC input voltage goes up (as a result of either an increase in input voltage or decrease in output load current) the base of the series-pass transistor (assuming a NPN transistor) goes down [40]. This increases the resistance of the series-pass element and thus brings the output voltage back down so that the sampled output equals the reference voltage.

Disadvantages:

- The linear regulator can only produce a lower output voltage from a higher input voltage. The output voltage always has one end DC common with the input voltage, but DC isolation between input and output is usually required to prevent electrical shock [40].

- The DC input voltage is usually derived from a rectified secondary of a transformer, that has a large weight and size and this is often a serious system constraint.

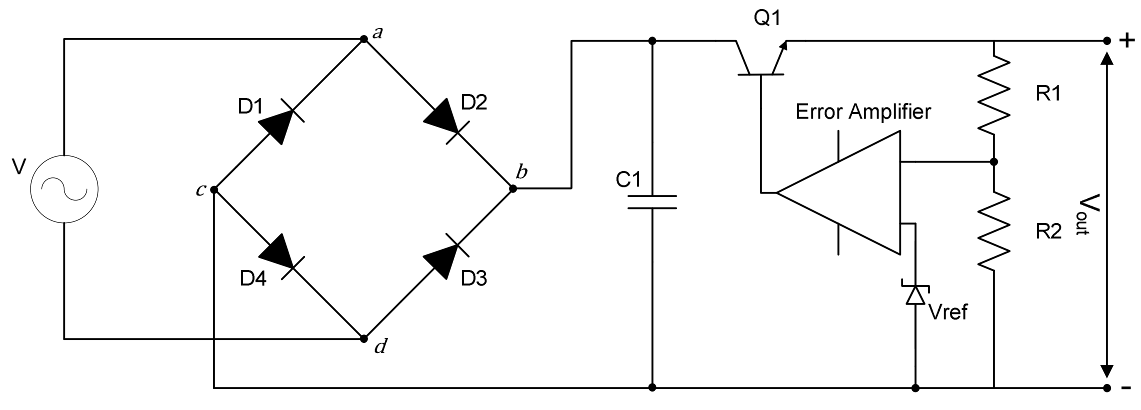


Figure 6-17 Full Wave Rectifier with Linear Regulator

6.3.2 Switch Mode Regulators

Today, quite a few switch mode converters exist. Not all the converter types are discussed here, as there are quite a few types available and switch mode regulators have become a field on its own. Only the basic switch mode converters will be discussed in this dissertation. DC-DC converters offer higher efficiency than traditional linear regulator power supplies.

By using the appropriate topology, the converter can step-down (Buck), step-up (Boost) or, step-up or down (Buck-Boost) its output voltage relative to its input voltage. Topologies exist, that can isolate their input from their output for example the Flyback, Forward and Push-Pull converters. Different methods or techniques for controlling these converters exist but will not be discussed here.

The three basic DC-DC converters use a pair of switches, usually one controlled metal-oxide-semiconductor field-effect transistor (MOSFET) and one uncontrolled (diode), to achieve unidirectional power flow from input to output. The power switch is an integral part of the practical switching power supply, but before the development of the vertical metal-oxide-semiconductor (VMOS) power switch, switching power supplies where generally not practical.

The converters also use one capacitor and one inductor to store and transfer energy from input to output. The capacitor and inductor also serves as a filter that smooth's the output voltage and current [41].

Two distinct modes of operation exist with DC-DC converters:

- Continuous conduction mode (CCM)
- Discontinuous conduction mode (DCM).

In practice, a converter may operate in both modes, which have significantly different characteristics. CCM will be assumed in the following discussions.

6.3.2.1 Buck, Boost, Buck-Boost Converter

Buck Converter

A Buck converter is a DC-DC converter that converts a high level input DC voltage to a desired low level DC voltage. It also forms the basis for a converter called the forward converter, and the circuit typology can be seen in Figure 6-18 below. The switch is usually an electronic device that can operate in two conduction modes, on mode, or off mode. The on and off time periods are controlled with a pulse width modulator (PWM) and a comparator, but are usually not shown.

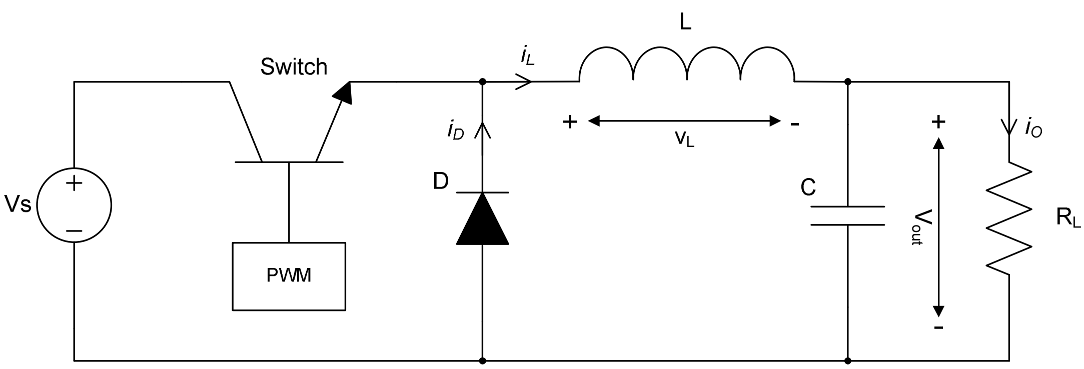


Figure 6-18 Buck Converter Circuit

The on-time of the switch is a fraction of its time period T such that $\mathrm{t_{on}} = \mathrm{DT}$, where D is the duty cycle [42]. When the switch is turned off $\mathrm{t_{off}} = (1 - \mathrm{D})\mathrm{T}$, the free-wheeling diode provides a path to keep up the continuity of the current through the inductor.

The inductor determines the percentage of current ripple and whether the circuit is operating in continuous mode or not. The capacitor C provides the filtering and the value should be large enough to reduce the ripple voltage. The voltage across an inductor is given by $\mathrm{V} = \mathrm{L}\frac{\mathrm{di}}{\mathrm{dt}}$. Two conditions will be looked at. When the switch is open and when the switch is closed.

When the switch is at the on position the above equation is written as:

$$V_{in} - V_{out} = L\frac{di}{dt} \dots\dots(t_{on}) \qquad \textit{(Eq. 6.14)}$$

and for t_{off} (switch off) position

$$V_{out} = L\frac{di}{dt} \dots\dots(t_{off}) \qquad \textit{(Eq. 6.15)}$$

It is also known that the average current through an inductor should be zero. Thus if we set the above equations for t_{on} and t_{off} equal to each other and solve for D, we get:

$$(V_{in} - V_{out})DT = V_{out}(1 - D)T \qquad \textit{(Eq. 6.16)}$$

$$D = \frac{V_{out}}{V_{in}} \qquad \textit{(Eq. 6.17)}$$

From [42], the equation for the peak-to-peak current ripple is found as

$$\Delta I_L = I_{L,max} - I_{L,min} = \frac{V_{out}}{L}(1 - D)T \qquad \textit{(Eq. 6.18)}$$

Thus, from the equation for the duty cycle D we can see that the output voltage of a Buck converter is directly proportional to the duty cycle and the input voltage. Because the duty cycle is usually less than unity, the output voltage is smaller than the input voltage.

This is why it is called a step-down or Buck converter. Since the power flow is from the input to the load, and there is no power flowing back to the input, the circuit is also called a forward converter.

The current through the inductor during t_{on} and t_{off} can be seen in Figure 6-19. The average current through the inductor must be equal to the dc current through the load.

That is,

$$I_{L,avg} = I_{out} = \frac{V_{out}}{R} \qquad \textit{(Eq. 6.19)}$$

The expressions for the minimum and maximum currents through the inductor from [42] is now written as

$$I_{L,min} = I_{L,avg} - \frac{\Delta I_L}{2} = \frac{V_{out}}{R} - \frac{V_{out}}{2L}(1-D)T \qquad \textit{(Eq. 6.20)}$$

$$I_{L,max} = I_{L,avg} + \frac{\Delta I_L}{2} = \frac{V_{out}}{R} + \frac{V_{out}}{2L}(1-D)T \qquad \textit{(Eq. 6.21)}$$

Now looking at the capacitor, the equation (Eq. 6.22) below is derived to calculate the capacitor value in terms of ripple voltage, switching frequency, duty-cycle and inductor requirements.

$$\frac{\Delta V_{out}}{V_{out}} = \frac{1-D}{8LCf^2} \qquad \textit{(Eq. 6.22)}$$

Note that the capacitor ripple defined by (Eq. 6.22) above is not the same as the peak-to-peak voltage ripple for the rectifiers. The peak-to-peak voltage ripple for the Buck converter will be twice of that given by the above equation [42]. The Buck converter can operate in continuous conduction mode or in discontinuous conduction mode. In continuous conduction mode there is always current flowing through the inductor. The minimum current in the continuous mode can be zero at the time of switching.

There are minimum values for the inductor that will ensure that the converter stays in continuous conduction mode and it can be obtained by setting the equation for $\mathrm{I_{L,min}}$ equal to zero, and solving $\mathrm{L_{min}}$.

$$L_{min} = \frac{(1-D)}{2} RT = \frac{(1-D)}{2f^2} R \qquad \textit{(Eq. 6.23)}$$

From the (Eq. 6.18) for ΔI_L we can obtain an expression for the percentage current ripple as

$$\%CR = \frac{\Delta I_L}{I_{L,avg}} \times 100 = \frac{100(1-D)}{Lf} R \qquad (Eq.\ 6.24)$$

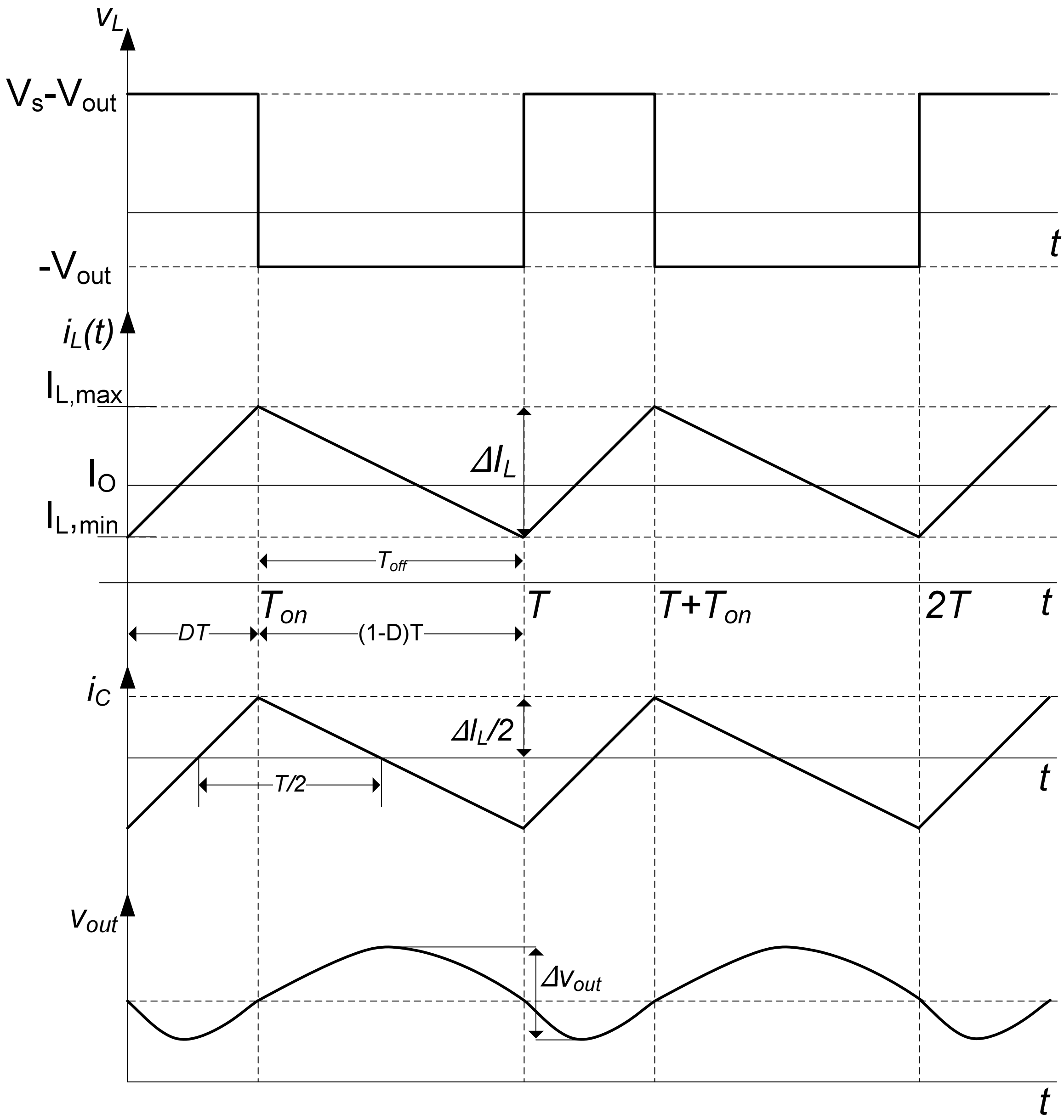


Figure 6-19 Buck Converter Wave Forms for t_{on} and t_{off}, including the current through the inductor [41]

Buck converter advantages:

- Low component count, cost and complexity – Simple to design and implement.
- High efficiency, low switch stress, low ripple on output [43].

Buck converter disadvantages [44]:

- Non-Isolated power supply.
- Prone to failure due to lack of DC isolation.
- To maintain proper regulation of the output voltage, the input voltage must to be 1 V to 2 V higher at the input of the supply.
- Additional protection is required to prevent a short circuit from the input to the load if the semi-conductor power switch fails in a short circuit condition.

According to Moore [43] and Brown [45] a typical efficiency figure of 78% is reachable. A reference manual by ON Semiconductor [46] also suggested a similar efficiency of 75%.

Boost Converter

A Boost converter is a DC-DC converter that converts a low level input voltage to a high level output voltage. The Boost converter is also called the fly-back converter, because the transfer of the energy from the source to the output occurs during the switch-off time only, and can be seen in Figure 6-20.

The on-time of the switch is a fraction of its time period T such that $\mathrm{t_{on}} = \mathrm{DT}$, where D is the duty cycle. When the switch is at the on position for time ($\mathrm{t_{on}}$), the current through the inductor increases from its minimum to its maximum value. Thus, the stored energy in the inductor increases when the switch is closed.

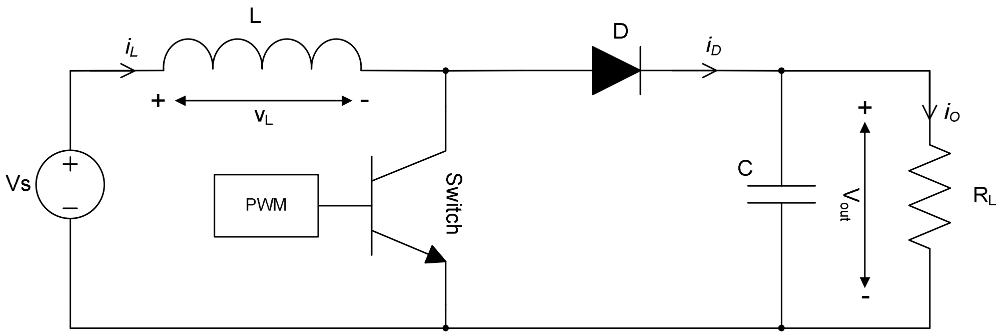


Figure 6-20 Boost Converter Circuit

As the switch is opened, $t_{off} = (1 - D)T$, the inductor current is directed through the diode to the load. The inductor current, thus charges the capacitor and supplies the load current. The diode not only blocks the current flowing towards the input when the switch is closed, but also stops the output voltage from appearing across the closed switch [42].

The inductor determines the percentage of current ripple and whether the circuit is operating in continuous mode or not. The capacitor C provides for filtering. Its value is also large enough so that voltage ripple is small.

The voltage over an inductor is given by $V = L\frac{di}{dt}$. Two conditions will be looked at. When the switch is open and when the switch is closed.

When the switch is at the on position the above equation is written as follows:

$$V_{out} = L\frac{di}{dt} \text{ ......}(t_{on}) \qquad \text{(Eq. 6.25)}$$

and for t_{off} (switch off) position

$$V_{in} - V_{out} = L\frac{di}{dt} \text{......}(t_{off}) \qquad \text{(Eq. 6.26)}$$

It is also known that the average current through an inductor should be zero. Thus, if we set the above equations for t_{on} and t_{off} equal to each other and solve forV_{out}, we get:

$$V_{in}DT = V_{out}(V_{out} - V_{in})(1 - D)T \qquad \text{(Eq. 6.27)}$$

$$V_{out} = \frac{V_{in}}{(1 - D)} \qquad \text{(Eq. 6.28)}$$

From [42] an equation for the peak-to-peak current ripple is found as

$$\Delta I_L = I_{L,max} - I_{L,min} = \frac{V_{in}}{L}DT \qquad \text{(Eq. 6.29)}$$

Thus, from (Eq. 6.26) for V_{out} we can see that the output voltage of a Boost converter is indirectly proportional to $(1 - D)$ and directly proportional the input voltage. Because the duty cycle is usually less than unity, the output voltage is greater than the input voltage. This is why it is called a step-up or Boost converter. The current through the inductor during t_{on} and t_{off} can be seen in Figure 6-21 and remember that this is the source current.

The average power supplied by the input must be equal to the average power delivered to the load. That is,

$$I_{L,avg} = I_{in} = \frac{V_{out}}{1 - D} \qquad \textit{(Eq. 6.30)}$$

Note that the average current in the inductor is not the same as the average load current, which was true for the Buck converter [42]. The expressions for the minimum and maximum currents through the inductor is now written as

$$I_{L,min} = I_{L,avg} - \frac{\Delta I_L}{2} = \frac{V_{out}}{R(1 - D)} - \frac{V_{out}}{2Lf}(1 - D)D \qquad \textit{(Eq. 6.31)}$$

$$I_{L,max} = I_{L,avg} + \frac{\Delta I_L}{2} = \frac{V_{out}}{R(1 - D)} + \frac{V_{out}}{2Lf}(1 - D)D \qquad \textit{(Eq. 6.32)}$$

The peak-to-peak current ripple can also be written as

$$\Delta I_L = \frac{V_{in}}{L} DT = \frac{V_{out}}{Lf}(1 - D)D \qquad \textit{(Eq. 6.33)}$$

Now looking at the capacitor, the equation (Eq. 6.34) below is derived to calculate the capacitor value in terms of ripple voltage, switching frequency, duty-cycle and inductor requirements.

$$\frac{\Delta V_{out}}{V_{out}} = \frac{DT}{RC} = \frac{D}{RCf} \qquad \textit{(Eq. 6.34)}$$

Note that the capacitor ripple voltage defined by the above equation (Eq. 6.34) is not the same as the peak-to-peak voltage ripple for the rectifiers. The peak-to-peak voltage ripple for the Boost converter will be twice of that given by the above equation. The Boost converter can operate in continuous conduction mode or in discontinuous conduction mode. In continuous conduction mode there is always current flowing through the inductor.

The minimum current in the continuous mode can be zero at the time of switching. But there are minimum values for the inductor that will ensure that the converter stays in continuous conduction mode and it can be obtained by setting (Eq. 6.31) for $I_{L,min}$ equal to zero, and solving L_{min}.

$$L_{min} = \frac{R}{2f} D(1-D)^2 \qquad \textit{(Eq. 6.35)}$$

We also can obtain an expression for the percent current ripple as

$$\%CR = \frac{\Delta I_L}{I_{L,avg}} \times 100 = \frac{100(1-D)}{Lf} R \qquad \textit{(Eq. 6.36)}$$

Boost converter advantages:

- Low component count, cost and complexity – Simple to design and implement.
- High efficiency, low input ripple current [43].

Boost converter disadvantages [44]:

- Non-Isolated power supply.
- Prone to failure due to lack of DC isolation.
- High output currents will stress the power switch and the diode and therefore places a limit on the output power capability of this supply.
- Hazardous transients can easily reach the load.
- The supply has a high output ripple [43].

According to Moore [43] and Brown [45] a typical efficiency figure of 80% is reachable. ON Semiconductor [46] also suggested a similar efficiency of 78%.

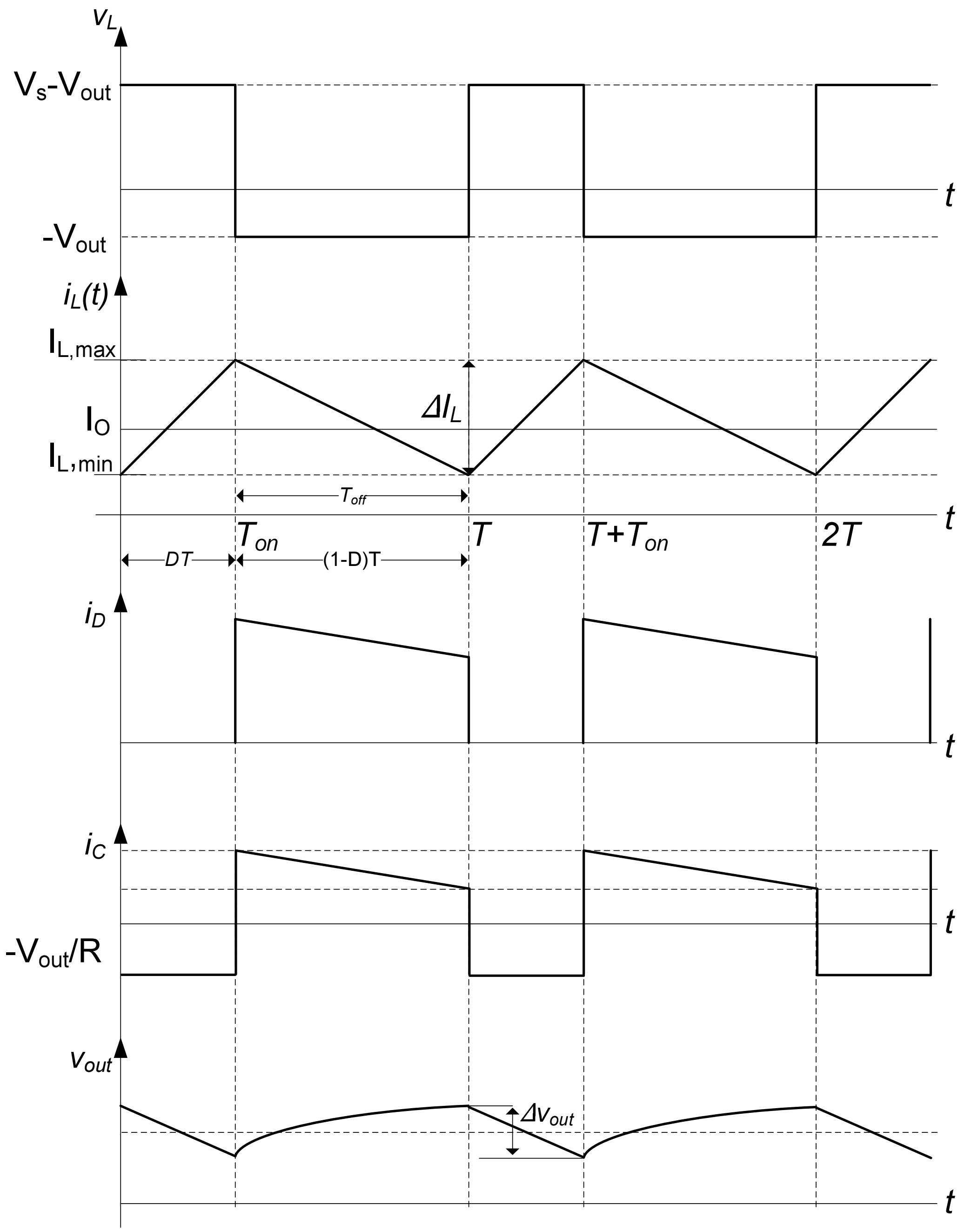


Figure 6-21 Boost Converter Wave Forms for t_{on} and t_{off}, including the current through the inductor [41].

Buck-Boost Converter

The Buck-Boost converter will not be discussed in as much detail as the other converters but for the sake of completeness, the basic circuit, waveforms and equations will be given.

The basic Buck-Boost circuit can be seen in Figure 6-22. The flow of the current through the capacitor and load resistor, together with the polarity of the output voltage, should be noted.

The Buck-Boost converter has the ability to step up the input voltage or to step down the input voltage, meaning that the output voltage can be higher or lower than the input voltage. The inductor circuit controls the flow of energy in this circuit, and this circuit is also known as an indirect converter as the input voltage is not directly connected at any point in time to the output voltage.

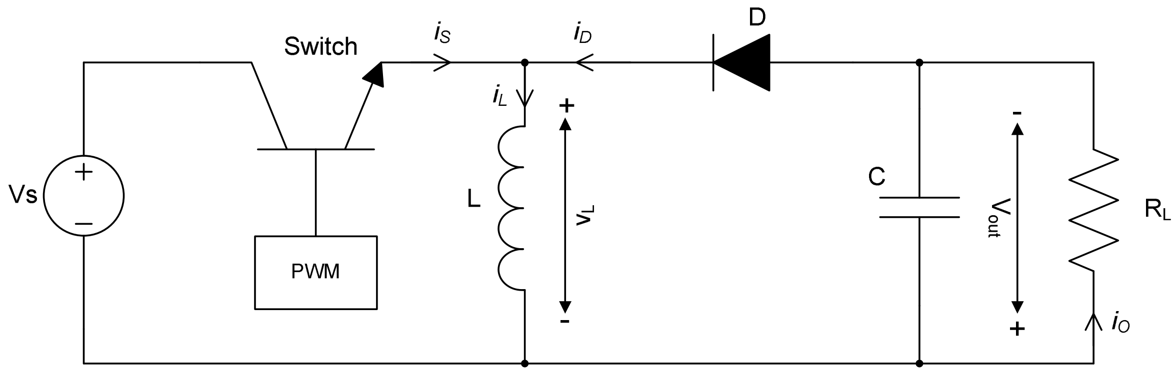


Figure 6-22 Buck-Boost Converter Circuit

The on-time of the switch is a fraction of its time period T such that $\mathrm{t_{on}} = \mathrm{DT}$, where D is the duty cycle. The current is directed toward the load thought the diode D from Figure 6-23 above, during the time that the switch if off; $\mathrm{t_{off}} = (1 - \mathrm{D})\mathrm{T}$. When the switch is closed ($\mathrm{t_{on}}$), the current flow from the source to the load is blocked by diode D and during this time the capacitor supplies the load and the source current is flowing through the inductor.

The diode D maintains continuous current through the inductor and only during the time the switch is open ($\mathrm{t_{off}}$) the current will flow to the load and capacitor. To derive the equations below, Bguru [42] made the assumption that the circuit has been operating for a long time and the inductor current varies from it maximum to its minimum value during each half cycle. As was said, these equations will not be derived and only the final step will be given for the sake of completeness. The output voltage of Buck-Boost converter was derived as in Bguru [42] and is shown by the equation below.

$$V_{out} = \frac{DV_{in}}{1 - D} \qquad \textit{(Eq. 6.37)}$$

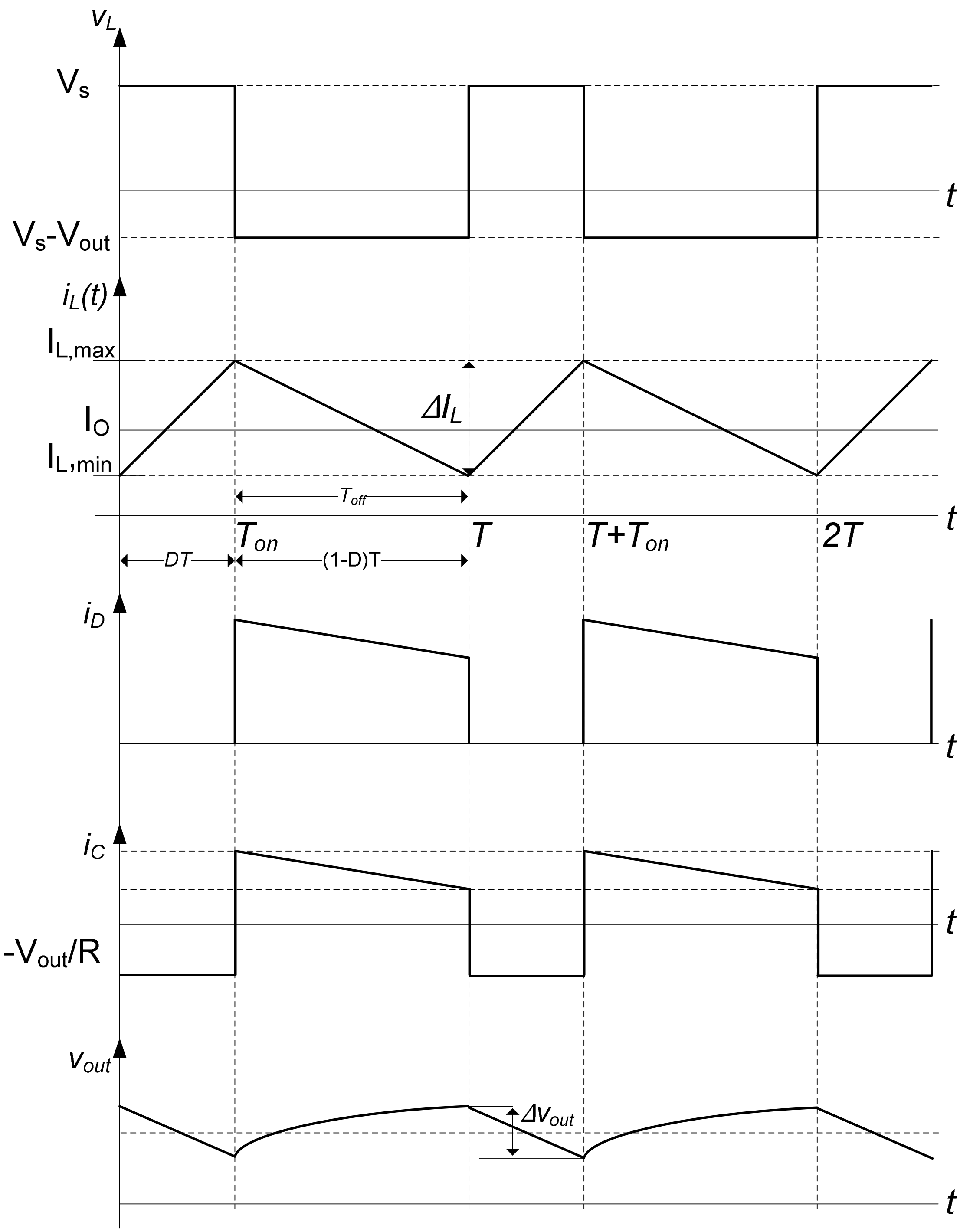


Figure 6-23 Buck-Boost Converter Wave Forms for t_{on} and t_{off}, including the current through the inductor [41]

From (Eq. 6.37) it is evident that V_{out}, the output voltage is directly proportional to D and indirectly proportional to $(1 - D)$, thus when $D = 0.5$, the output voltage will be the same as the input voltage.

The output voltage will be greater than the input voltage if $\mathrm{D} > 0.5$, which evidently corresponds to the Boost converter operation. It can also be seen that if $\mathrm{D} < 0.5$, the output voltage will be less than the input voltage, which correspond to the Buck converter operation. Therefore, the Buck-Boost converter can operate like a buck or boost converter depending on the value of D, the duty cycle.

The output current was derived to be

$$I_{out} = \frac{V_{out}}{R} = \frac{V_{in}}{R}\left(\frac{D}{1-D}\right) \quad \textit{(Eq. 6.38)}$$

The peak-to-peak current ripple is expressed as

$$\Delta I_L = \frac{V_{in}}{Lf} D = \frac{V_{out}}{Lf}(1-D) \quad \textit{(Eq. 6.39)}$$

and can also be written as

$$\Delta I_L = I_{L,max} - I_{L,min} = \frac{V_{out}}{L}(1-D)T \quad \textit{(Eq. 6.40)}$$

The output capacitor value in terms of ripple voltage can be calculated by

$$\frac{\Delta V_{out}}{V_{out}} = \frac{DT}{RC} = \frac{D}{RCf} \quad \textit{(Eq. 6.41)}$$

As the Buck-Boost converter can operate in continuous mode, the minimum inductor value to ensure continuous operation mode can be calculated using the following equation

$$L_{min} = \frac{R}{2f}(1-D)^2 \quad \textit{(Eq. 6.42)}$$

Lastly, the peak-to-peak ripple current as a percentage can be calculated using (Eq. 6.43) below

$$\%CR = \frac{\Delta I_L}{I_{L,avg}} \times 100 = (1-D)^2 = 100\left(\frac{2L_{min}}{L}\right) \quad \textit{(Eq. 6.43)}$$

Buck-boost converter advantages [43], [44]:

- Low component count, cost and complexity – Simple to design and implement.
- Voltage is inversed without the use of a transformer.
- High frequency operation is possible.

Buck-boost converter disadvantages [44]:

- Non-isolated power supply.
- Prone to failure due to lack of DC isolation.
- The duty cycle is limited to below 50% in most cases as it is required to empty the cores storage energy during the switch "off" period.
- The regulator feedback loop can be hard to stabilize.
- The supply has a high output ripple [43].

According to Moore [43] and Brown [45] a typical efficiency figure of 80% is reachable. ON Semiconductor [46] also suggested a similar efficiency of 78%.

6.3.2.2 Forward Converter

Looking at Figure 6-24, one can see that a transformer has been placed between the input voltage and the output stage of a Buck converter. The power switch (SW) is used to control the converter and is controlled by a PWM signal. The PWM signals duty cycle and frequency can be varied.

Not only does the transformer provide dielectric isolation, it provides a step-up or down function as well. One disadvantage of this topology is that the maximum duty cycle can only be about 50%.

Whenever a core is driven in a unidirectional fashion, that is, current only being driven from one direction into the primary, the core must be reset. Magnetization energy, which serves only to reorient the magnetic domains within the core should be emptied, or else the core will "creep−up" to saturation after only a few cycles [47].

Thus, the core needs to be reset. The resetting is done during the period when the transformer is unloaded, thus when the power switch and the rectifiers are not conducting. The resetting is done by drawing current from a winding during this period. Any winding can perform the reset function, but the higher the voltage on the winding, the faster the core will be reset.

This winding is typically the primary winding, but can also be a separate winding with equal turns to the primary winding, and is called the reset winding or auxiliary winding.

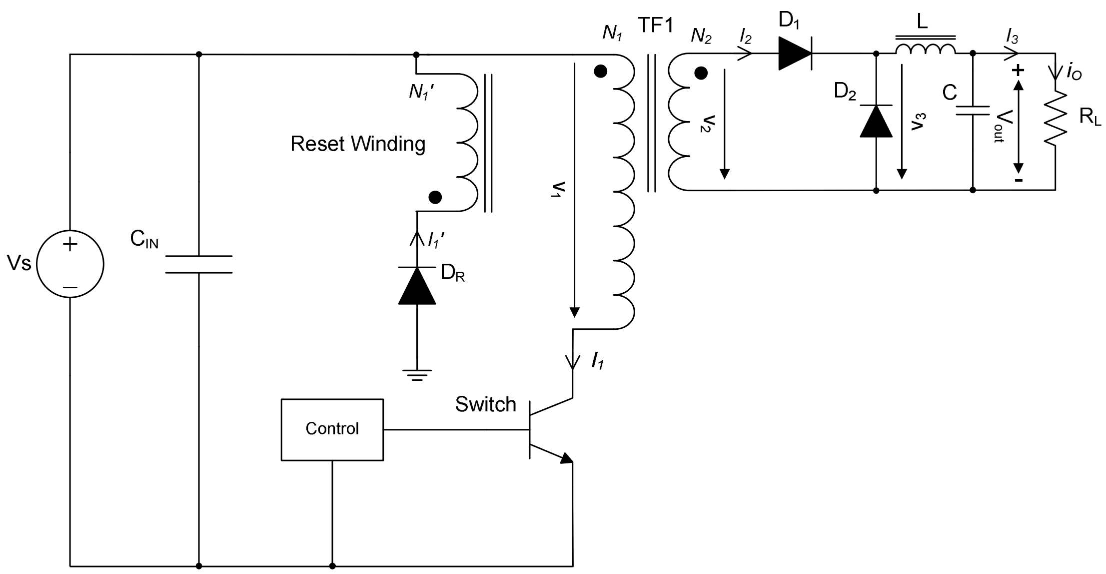


Figure 6-24 Forward Converter Circuit

Current from the reset winding can be returned to the input capacitor and be re-used during the next cycle of operation [47].

The various wave forms can be seen in Figure 6-25. The forward converter transfers the energy during the on-time of the transistor. During this time the voltage V_1 is equal to the input voltage. The winding N_2 is in the same direction as N_1.

When the transistor is on, voltage V_2 at N_2 is given by

$$V_2 = V_{in}\left(\frac{N_2}{N_1}\right) \qquad \text{(Eq. 6.44)}$$

The voltage V_2 drives the current I_2 through the diode D_2 which, during this time, is equal to I_3 through L that charges the output capacitor C_{out}.

During the power switch off time, the magnetic flux of the transformer has to fall to zero. The core is then demagnetized with N'_1 (auxiliary winding or reset winding) through D_1 to V_{in}.

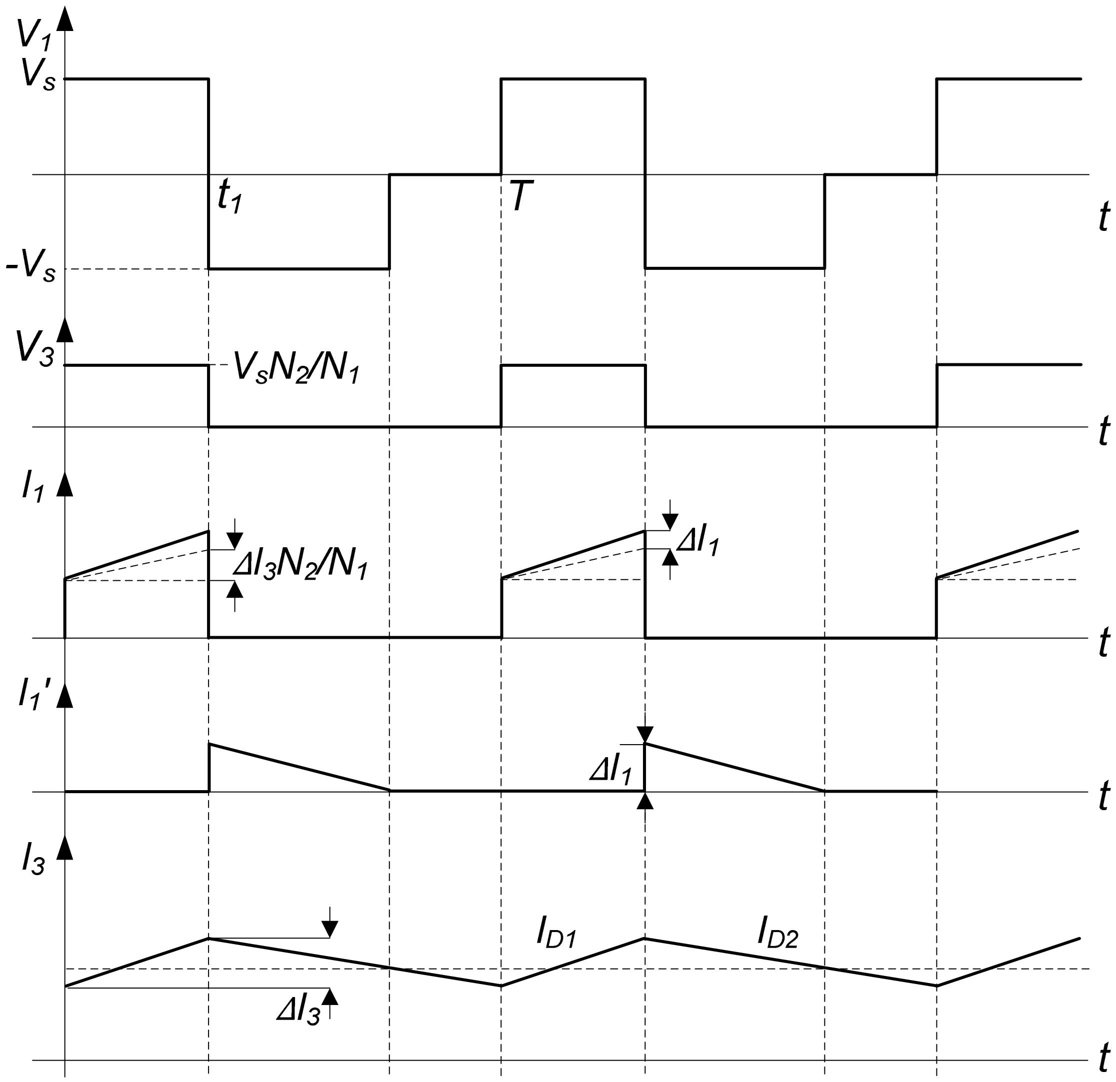


Figure 6-25 Forward Converter Wave Forms [48]

The reset winding and winding N_1 has an equal number of windings. Thus, the demagnetization needs to be an equal time interval to that of the on time. The maximum possible duty cycle for the forward converter is now $\frac{T_1}{T}$ or 0.5.The calculations of the output voltages and duty cycle are almost the same as the calculations for the Buck converter. For V_{out} :

$$V_{out} = V_{in} \times \frac{N_2}{N_1} \times \frac{V_1}{T} \qquad \text{(Eq. 6.45)}$$

The turn's ratio is as follows:

$$\frac{N_2}{N_1} = 2 \times \frac{V_{out}}{V_{in}} \qquad \textit{(Eq. 6.46)}$$

and the reset windings are equal to N_1.

To calculate the L_o the same method used for the Buck converter is used here. The current ripple ΔI_o of the inductor current I_o has to be selected initially. Usually a value of 20% current ripple is acceptable, thus $\Delta I_o = 0.2I_o$. Assuming a maximum duty cycle of 0.5, this leads to

$$L = \frac{V_{out}\frac{T}{2}}{\Delta I_o} \qquad \textit{(Eq. 6.47)}$$

The value of C_{out} is dependent on the acceptable voltage ripple ΔV_{out} of the output voltage. The voltage ripple is mainly determined by the impedance Z_{max} of the output capacitor C_{out}. Thus,

$$\Delta V_{out} \approx \Delta I_L Z_{max} \qquad \textit{(Eq. 6.48)}$$

Forward converter advantages [49]:

- Isolated supply.

Forward converter disadvantages:

- More complex than the non-isolated supplies.
- Requires an extra winding used to demagnetise the core [49].

According to Moore [43] and Brown [45] a typical efficiency figure of 78% is reachable.

6.3.2.3 Flyback Converter

The Flyback converter works on the same principle as the Boost converter. The inductor of the Boost converter is also replaced with a transformer to form the Flyback converter. The Flyback converter theory will be discussed via two modes of operation, continuous conduction mode (CCM) and discontinuous conduction mode (DCM).

CCM (Continuous Conduction Mode)

Looking at Figure 6-26, one can see that a transformer has been placed between the input voltage and the output stage of a Boost converter. The Inductor L_m is for explanatory reasons only and is not a real extra inductor. The inductor L_m represents the inductance of the primary coil of the transformer.

The power switch (SW) is used to control the converter and is controlled by a PWM signal. The PWM signals duty cycle and frequency can be varied. Not only does the transformer provide dielectric isolation, it provides a step-up or down function as well.

When the converter is operated in continuous conduction mode (CCM), it means that the current through the inductor L_m is always greater than zero within a switching cycle. Figure 6-27, shows the waveforms of CCM operation.

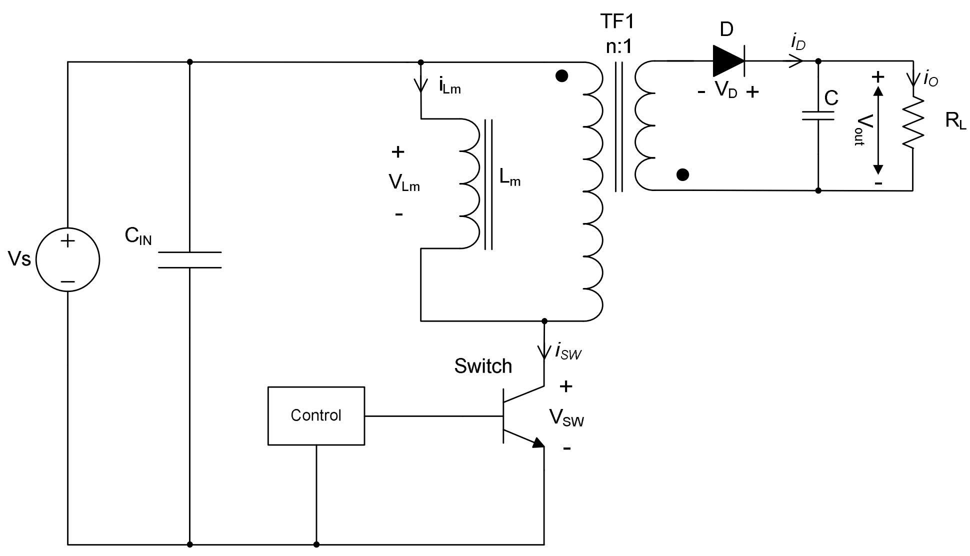


Figure 6-26 Flyback Converter Circuit

Time interval: $\mathbf{t_1 - t_0 = t_{on}}$

Just before t_0 the inductor current was flowing through diode D, but when the MOSFET switches on, D turns off, thereby isolating the input terminal from the output terminal. When the MOSFET turns on, the voltage V_{DS} falls to zero, thus V_D becomes $\left(V_{out} + \frac{V_{in}}{n}\right)$. During the interval $t_1 - t_0$, after the MOSFET has turned on, V_{in} is applied to L_m, thus the current through the inductor increases linearly with a slope as follows:

$$Slope = \frac{V_{in}}{L_m} \qquad \textit{(Eq. 6.49)}$$

Looking at the energy flow, one can see that during the MOSFET on time, the power source supplies energy to L_m. Since the energy in L_m increases when the output is isolated from the input, the capacitor C_o has to supply the output current during this interval.

Time interval: $\mathbf{t_2 - t_1 = t_{off}}$

When the MOSFET turns off at instant t_1, the current through L_m and the MOSFET starts to flow through the diode D. When D turns on, V_{DS} becomes $V_{in} - nV_{out}$. During this interval the voltage applied to L_m is nV_{out} and I_{L_m} decreases at the following linear rate:

$$Slope = \frac{nV_{out}}{L_m} \qquad \textit{(Eq. 6.50)}$$

Looking at the energy flow during this interval, one can see that the inductor energy is delivered to the output and that the energy in L_m is reduced by the amount of energy it delivers to the output. A switching cycle is ended when the MOSFET is turned on again.

The primary side inductance can be calculated by

$$L_p = \frac{V_{in}D}{I_{peak}f_{sw}} \qquad \textit{(Eq. 6.51)}$$

and the primary current as

$$I_p = \frac{2P_{in}}{V_{in}D} \qquad (Eq.\ 6.52)$$

and the secondary current can be calculated by

$$I_{s,peak} = 4I_{s,avg} \qquad (Eq.\ 6.53)$$

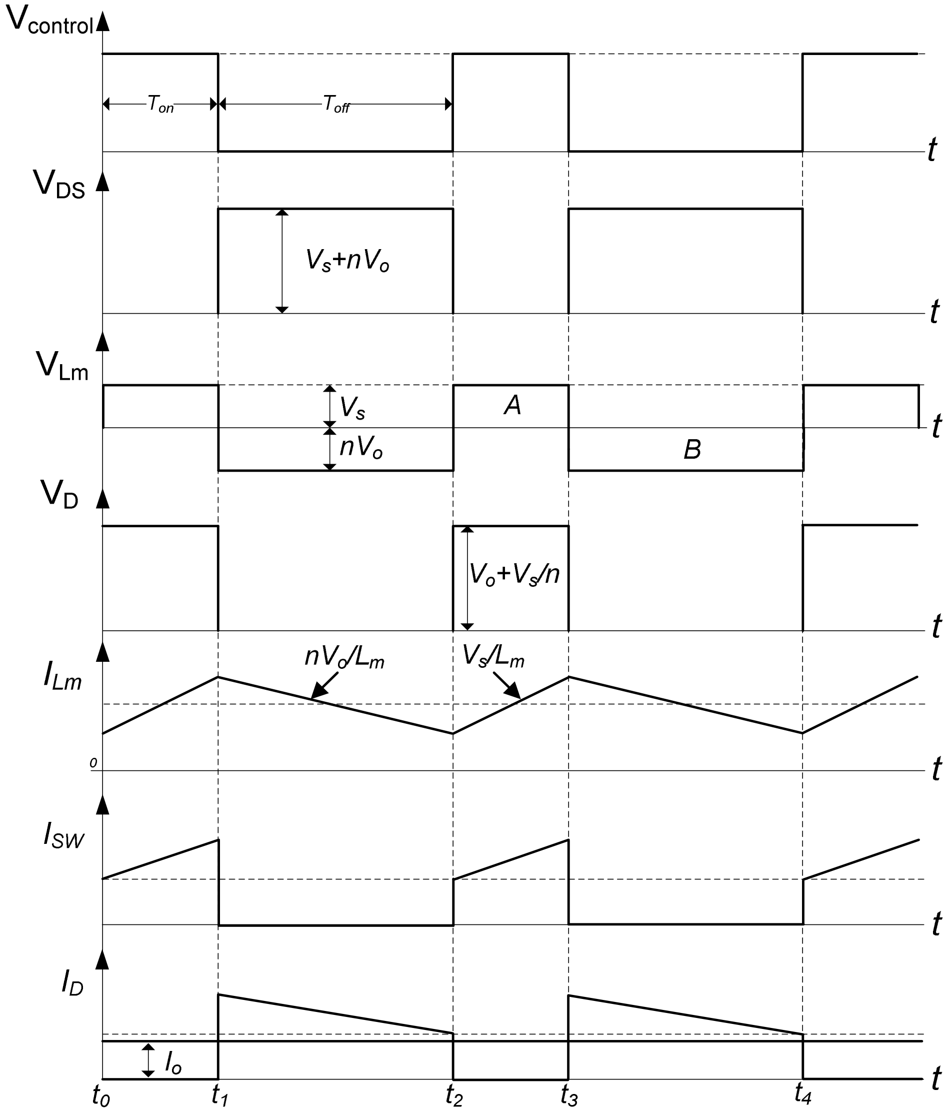
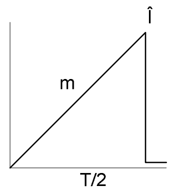


Figure 6-27 Flyback Wave Forms for CCM Operation [48]

The rms current $\mathrm{I_{rms}}$ can be calculated as follows using the rms formula and the figure where $\mathrm{m} = \frac{2\mathrm{I_{peak}}}{\mathrm{T}}$



$$I_{rms} = \sqrt{\frac{1}{T}\int_0^T i^2 dt} = \sqrt{\frac{1}{T}\int_0^{T/2}\left(\frac{2I_{peak}}{T}t\right)^2 dt} = \frac{I_{peak}}{\sqrt{6}} \qquad \textit{(Eq. 6.54)}$$

Input/output Relationship

The law of energy conservation states that $\mathrm{E_{on}} = \mathrm{E_{off}}$. Thus from Figure 6-27, the areas A and B of the waveform $\mathrm{V_{L_m}}$ (the voltage applied to the inductor) must be equal because the average voltage of the inductor or transformer in steady state is always zero [50]. Therefore:

$$V_{in}T_{on} = nV_{out}T_{off} \qquad \textit{(Eq. 6.55)}$$

$$\frac{nV_{out}}{V_{in}} = \frac{T_{on}}{T_{off}} = \frac{D}{D-1} \qquad \textit{(Eq. 6.56)}$$

The input and output currents become:

$$I_{in} = DI_{L_m,avg} \qquad \textit{(Eq. 6.57)}$$

$$I_{out} = N(1-D)I_{L_m,avg} \qquad \textit{(Eq. 6.58)}$$

Thus, the input and output powers are equal. An ideal waveform is shown here, to ignore the effect of leakage inductance. In reality, leakage inductance would cause ringing.

The output capacitance can be calculated for a required voltage ripple using the following:

$$C_{out} = \frac{V_{out}D}{R_{min}\Delta V f_{sw}} \quad \textit{(Eq. 6.59)}$$

where ΔV is the required peak-peak ripple voltage on the output.

DCM (Discontinuous Conduction Mode)

Flyback DCM operation mode is when the inductor current falls to zero during a switching cycle. As can be seen in Figure 6-28, the voltage applied to the inductor V_{L_m} becomes complex in DCM.

Thus, to avoid computation difficulties, T_{off} is not used, instead, three input and output relationships of the converter are derived by using T_{off}^*, the time when the output rectifier diode is actually conducting. The boundary condition between CCM and DCM is given by:

$$I_{in} + I_{out} = \frac{V_{in}}{2\,L_m}\,T_{on} \quad \textit{(Eq. 6.60)}$$

By again using the fact that in steady state operation, the average inductor voltage is always zero, the areas A and B of V_{L_m} in Figure 6-28, must be equal and can be used to derive the following relationships:

$$V_{in}T_{on} = nV_{out}T_{off}^{\ *} \quad \textit{(Eq. 6.61)}$$

$$\frac{nV_{out}}{V_{in}} = \frac{T_{on}}{T_{off}^{\ *}} = \frac{D^*}{D^* - 1} \quad \textit{(Eq. 6.62)}$$

Now by deriving the above equation again by using I_{out} and the fact that the input and output powers are equal, V_{out} is obtained to be:

$$V_{out} = \frac{(V_{in}T_{on})^2}{2\frac{I_{out}}{n}L_m\left(T_{on} + T_{off}\right) + V_{in}} \quad \textit{(Eq. 6.63)}$$

The input power is given by:

$$P_{in} = \frac{1}{2} L_m I_{L_m,peak}^2 f_{sw} \qquad (Eq.\ 6.64)$$

where f_{sw} is the switching frequency.

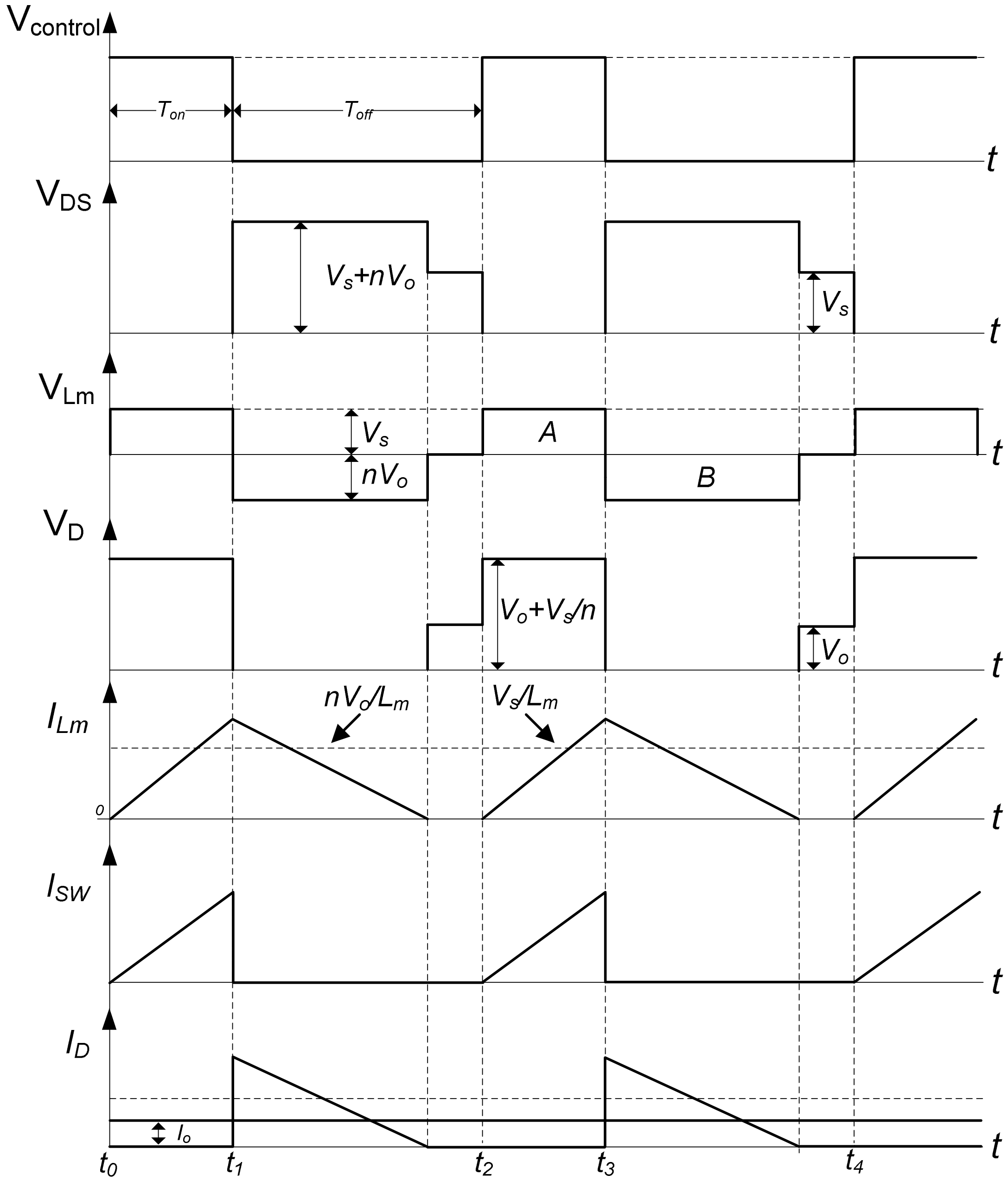


Figure 6-28 Flyback Wave Forms for DCM Operation [48]

Discontinuous Mode Flyback - Advantages [51]:

- Because there are no filter inductors in series with each output (as in buck regulator circuits), all output voltages will track each other within ±5% to ±10% without post-regulation. This minimizes the headroom required and its associated losses in the +12 V linear post-regulator. Dynamic cross regulation is also very good with this topology.
- Only one rectifier is required in each output, reducing overall component and assembly costs.
- Rectifier reverse recovery time is not critical as the forward current is zero, well before the reverse voltage is applied.
- The Flyback transformer used in the discontinuous mode is much smaller as the inductive energy stored is only 1/5 to 1/10 of the energy required in comparable continuous mode circuits.
- Turn-on circuits are simplified as the load current in the power switch is zero during turn-on. There is no concern for turn-on losses or turn-on snubber circuits.
- Closing the feedback loop is simplified due to the single pole roll off characteristic of the power circuit.
- Transient response is excellent. The circuit can be designed to correct for large step changes, in-line or load, in little more than one cycle of the switching frequency.
- Conducted EMI is reduced because transistor turn-on occurs with zero collector current. The triangular waveforms of the discontinuous mode contain only the odd harmonics which are attenuated much more rapidly than the even harmonics present in the rectangular waveforms of continuous mode Flyback circuits or buck regulators.

Discontinuous Mode Flyback – Disadvantages:

- Switching transistor and rectifier peak currents are nearly two times greater than in the comparable continuous mode circuit. However, the average currents are the same and transistor and diode dissipation is only slightly greater than in the continuous mode.
- Output filter capacitor ESR (Equivalent Series Resistance) and ESL (Equivalent Series Inductance) requirements are stringent due to the high peak currents encountered in the discontinuous mode.
- Capacitance values must be nearly twice the comparable continuous mode requirements, and 10 to 20 times larger than a buck regulator with the same output capability. Nevertheless, transient response is much better because the Flyback transformer inductance is so small.

According to Moore [43] and Brown [45] a typical efficiency figure of 80% is reachable.

6.3.2.4 Other Switching Converters

Many other switch mode converters exist like the Cúk SMPS, Push-Pull converter, Half-Bridge converter and the Full-Bridge converter, to mention a few. The Cúk converter can be derived from a boost and then buck converter and has increased efficiency, low input and output current ripple, minimal RFI (Radio Frequency Interference) and a small build size to its advantage.

The Push-Pull converter belongs to the feed forward converter family and has two switching devices controlling the energy flow through a transformer. The two switches must not be on at the same time. Also, due to the magnetic behaviour of this converter, the circuit must be uniform to prevent the transformer from saturation. If the transformer saturates, it will destroy both switching devices. This means that the conduction times of the switching devices should be exactly equal and the two halves of the centre tapped transformer primary should be magnetically identical.

The Half- and Full-Bridge converters are similar to the Push-Pull converter, but a centre-tapped primary transformer is not needed and the reversal of the magnetic field is accomplished by reversal of the primary winding current flow. These types of converters are usually found in high power converters and are more complex than the other converters to control.

The Half-Bridge converter uses two switches, were the Full-Bridge converter uses four switches to control the energy flow. The above converters are only mentioned for completeness and will not be discussions in full detail in this dissertation. Please refer to the relevant references for more in depth discussions on the operation of these converters.

6.3.3 Summary

From the above sections it is evident that SMPSs have become a field of study of its own. There are many configurations available, each with their own advantages and disadvantages. The Buck, Boost and Buck-Boost converters serve as the basic blocks of which the other converters are derived from. The Buck, Boost and Buck-Boost converters have no electrical isolation between their input and output voltages.

The Forward, Flyback, Cúk, Push-Pull, Half- and Full-Bridge converters all use a transformer to accomplish electrical isolation between their input and output voltages. This isolation is very important when it comes to the safety aspect of the user.

The converters are also mentioned in order of complexity. Where the Buck and Boost are the simplest converters to implement and the Full-Bridge converter the most complex. The same order is also true for output power.

The Buck and Boost converters have the lowest output power capabilities, from 1 W to 150 W, and the Full-Bridge converter has the largest output power capability, from 500 W to a few kilo watts.

These values are not absolute values, but are recommended values at the time. Future enhancements of MOSFETS (switches), diodes, capacitors and inductors will enable these converters to have higher output power capabilities than is possible at the time. The conversion efficiency was also mentioned and these figures are also dependant on future technology and enhancements.

6.4 DC-AC Converter

6.4.1 Inverter

The wind generator has an AC output also known in the wind small turbine industry as “wild” AC. This is because there is no control over the voltage amplitude and frequency that is generated by the permanent magnet generator as the permanent magnets used in the generator induces a constant magnetic field. The magnitude and frequency of the PMG AC output increases and decreases as the wind speed increases or decreases. In other words, the faster the blades turn, the higher the PMG output voltage and frequency.

The household appliances in one’s home requires a constant AC input of 230 VAC at a constant frequency of 50 Hz and cannot work of this “wild” AC. The “wild” AC output of the PMG is converted to DC by the rectifier mentioned in Section 6.1.

This DC voltage is too high for battery charging and is converted to a lower DC voltage by the DC-DC converter discussed in Section 6.3. This voltage is then fed to the battery charger, which will be discussed in Section 7.2.

The battery voltage of usually 12 V – 48 V is still not adequate to run home appliances from, and this is where the inverter is introduced into the wind generator system, to convert the DC voltage to an AC voltage appropriate for every day home appliances to run from [52].

Inverters come in single-phase and poly-phase configurations. Home appliances run on single-phase power and therefore only single-phase inverters will be discussed.

Inverters in general can be classified into two types, voltage source inverters (VSIs) and current source inverters (CSIs). A VSI is an inverter that uses a DC voltage source as input, and has an independently controlled voltage output [49]. CSI use a DC current source as an input and is used for mostly high power motor drive applications [53] and will therefore not be discussed.

VSIs can be subdivided into three categories [49], [53]:

- **Pulse-width-modulated inverters** – The input DC voltage is constant in magnitude and therefore the inverters must control the magnitude and frequency of the AC output. This is achieved by applying PWM to the inverters switching devices and this is why these inverters are called PWM inverters. Various PWM techniques exists to shape the output of the AC voltage to be as close to a sine wave as possible, but only the sinusoidal PWM technique will be discussed.
- **Square-wave inverters** – The DC input voltage is controlled in this case in order to control the magnitude of the AC output voltage. This leaves only the frequency control of the output voltage to the inverter. The output AC voltage has a waveform that resembles a square-wave; hence these inverters are called square wave inverters.
- **Single-phase inverters with voltage cancellation** – The voltage cancellation technique can only be implemented on single-phase inverters and not on three-phase inverters. These converters combine the characteristics of the above converters. The output AC voltage magnitude and frequency is controlled by the inverter even though the input DC voltage is constant and the PWM technique is not used and hence the output voltage is like a square wave.

6.4.2 Modulation Techniques

6.4.2.1 Pulse-width Modulation Technique

As mentioned above it is required to have an AC output voltage that closely follows the shape of a sinusoidal wave form and the inverter should be able to do this on a continuous basis. The inverter will accomplish this by properly switching the inverter switching devices.

The PWM technique fulfils the above requirements through one leg of a VSI by comparing a modulating signal v_c (the desired AC output voltage) to and a triangular waveform v_Δ called the carrier signal [49].

A special case called the sinusoidal PWM scheme (SPWM) is achieved when the modulating signal v_c is a sinusoidal at frequency f_c and amplitude $\hat{v}_c$, and the carrier triangle signal v_Δ is at frequency f_Δ and amplitude $\hat{v}_\Delta$.

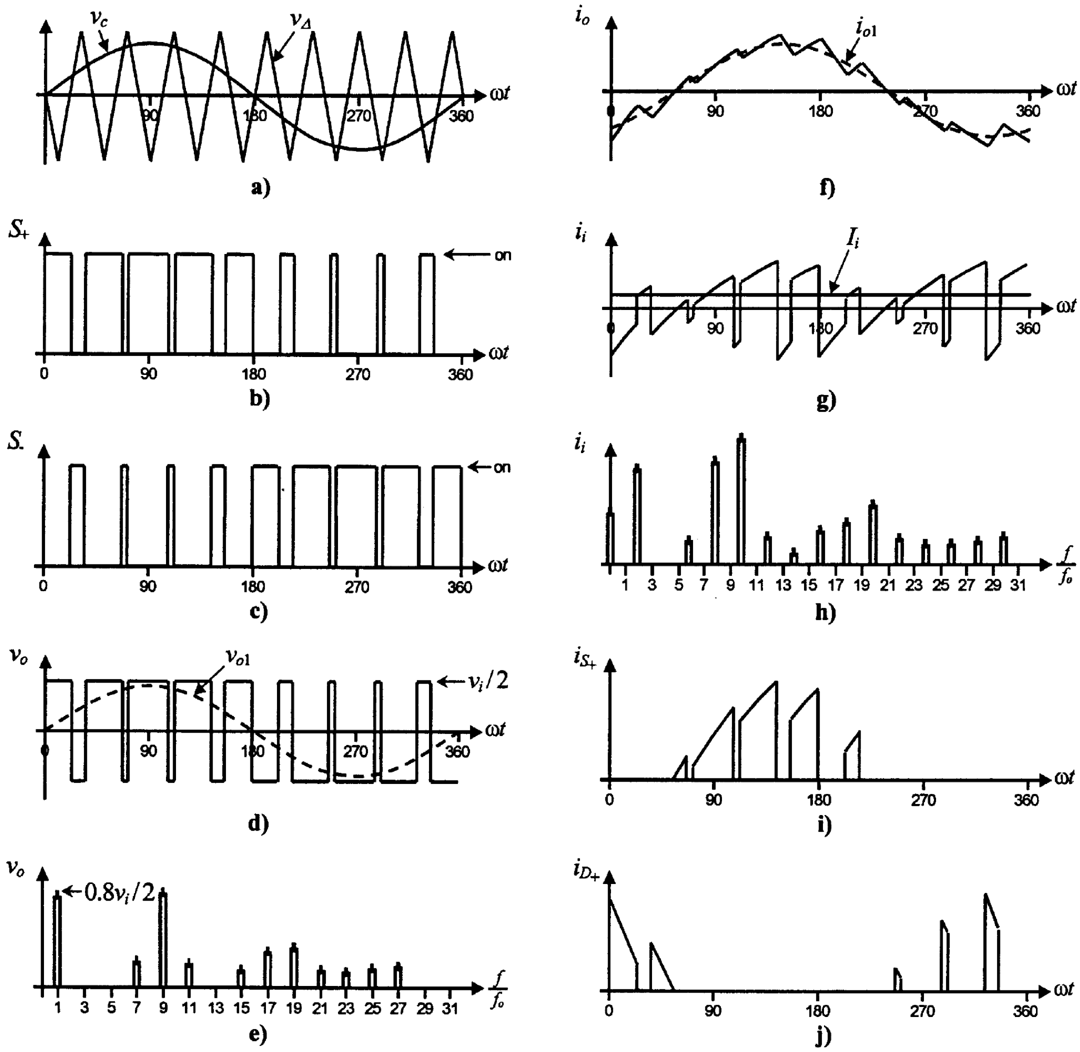


Figure 6-29 The half-bridge VSI. Ideal waveforms for the SPWM: (a) carrier and modulating signals; (b) switch S_+ state; (c) switch S_- state; (d) AC output voltage; (e) AC output voltage spectrum; (f) AC output current; (g) DC current; (h) DC current spectrum; (i) switch i_{S+} current; (j) diode i_{D+} current [49].

For this case the modulation index m_a (amplitude-modulation mode) is defined as

$$m_a = \frac{\hat{v}_c}{\hat{v}_\Delta} \qquad \textit{(Eq. 6.65)}$$

and the normalized carrier frequency m_f (frequency-modulation ratio) is

$$m_f = \frac{f_\Delta}{f_c} \qquad \textit{(Eq. 6.66)}$$

In Figure 6-29(e) one can see that the AC output voltage resembles a sinusoidal waveform and contains harmonics that features [49]:

- the amplitude of the fundamental components of the AC output voltage.
- for odd values of the normalized carrier frequency m_f the harmonics in the AC output voltage will appear at the normalised frequencies $f_h$centred around m_f and its multiples,

$$h = lm_f \pm k \qquad l = 1,2,3, \dots \qquad \textit{(Eq. 6.67)}$$

where $k = 2,4,6,..$ for $l = 1,3,5 \dots.$; and $k = 1,3,5,..$ for $l = 2,46 \dots.$;

- the amplitude of the AC output voltage harmonics is a function of the modulation index m_a and is independent of the normalized carrier frequency $m_f$for $m_f > 9$;
- the harmonics in the DC link current due to modulation appear at normalized frequencies f_p centred around the normalized carrier frequency m_f and its multiples,

$$p = lm_f \pm k \pm 1 \qquad l = 1,2, \dots \qquad \textit{(Eq. 6.68)}$$

where $k = 2,4,6,..$ for $l = 1,3,5 \dots.$; and $k = 1,3,5,..$ for $l = 2,46 \dots.$;

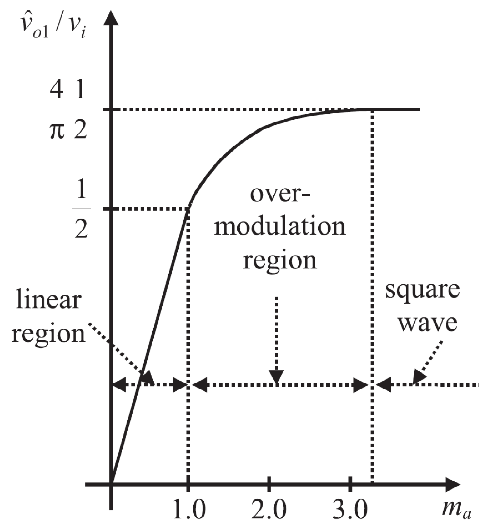


Figure 6-30 Fundamental AC component of the output voltage in a half-bridge VSI SPWM modulated [49].

According to Rashid [49] the following important issues exist:

- if the carrier signal v_Δ and the modulating signal v_c should be synchronised to each other for small values of m_f ($m_f < 21$), to prevent sub-harmonics present in the AC output voltage.
- for large values of m_f ($m_f > 21$), the sub-harmonics are negligible if an asynchronous PWM technique is used, but this should be avoided due to potential very low-order sub-harmonics.
- in the over-modulation region ($m_a > 1$) some intersections between the carries and the modulating signal are missed that leads to the generation of low-order harmonics, but a higher fundamental AC output voltage is obtained. A disadvantage of this is that the linearity between m_a and $\hat{v}_{o1}$ seen in the linear region of Figure 6-30 does not hold for this over-modulation region and a saturation effect can be observed.

According to Rashid [49] these features mentioned above simplifies the design of filtering components, but unfortunately the maximum amplitude of the fundamental AC voltage is $v_i/2$ in the SPWM mode.

Higher voltages can be obtained by using the over-modulation region, but lower-order harmonics will appear in the AC output voltage. If the modulation index is very large ($m_a > 3.24$) [49], the AC output voltage becomes a square AC output voltage and this is called the square-wave modulating technique.

6.4.2.2 *Square-wave Modulation Technique*

If the modulation index of the SPWM technique is very large ($m_a > 3.24$) [49], the AC output voltage becomes a square AC output voltage and this is called the square-wave modulating technique. Figure 6-31 below shows:

- the normalized AC output voltage harmonics are at frequencies $h = 3{,}5{,}7{,}9, \ldots$, and for a given DC link voltage
- the fundamental AC output voltage features an amplitude given by

$$\hat{v}_{o1} = \hat{v}_{aN1} = \frac{4}{\pi}\frac{v_i}{2} \qquad \textit{(Eq. 6.69)}$$

- And the harmonics feature and amplitude given by

$$\hat{v}_{oh} = \frac{\hat{v}_{o1}}{h} \qquad \textit{(Eq. 6.70)}$$

- It can be seen that the AC output voltage magnitude cannot be changed by the inverter, but rather has to be changed by controlling the DC input voltage v_i.

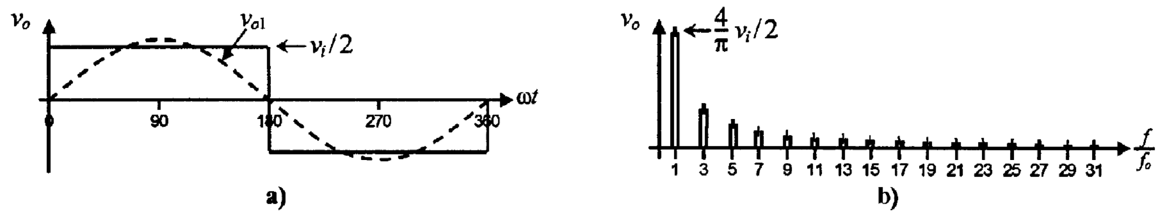


Figure 6-31 The half-bridge VSI. Ideal waveforms for the square-wave modulating technique: (a) AC output voltage; (b) AC output voltage spectrum [49].

6.4.2.3 Output Control by Voltage Cancellation

According to Mohan et al [53] this type of control can only be implemented in a single-phase inverter circuit. This technique is based on a combination of square-wave switching and PWM with a uni-polar voltage switch.

Figure 6-32(a) below shows the inverter circuit where the switches in the two inverter legs are controlled separately similar to PWM control. All switches have a duty ratio of 0.5 that is similar to square wave control.

The resultant waveforms is seen in Figure 6-32(b) for v_{AN} and v_{BN}. The waveform overlap angle α can be controlled. The output voltage is zero during the overlap interval due to both top switches, or both bottom switches being on [53].

If $\alpha = 0$, the output waveform is similar to a square-wave inverter with the maximum possible fundamental output magnitude. In Figure 6-32(c) the variation in the fundamental frequency component as well as the harmonic voltages as a function of α is seen.

The values are normalised with respect to the fundamental frequency component for the square wave ($\alpha = 0$) operation. The total harmonic distortion (determined from the ratio of the RMS value of the harmonic distortion to the value of the fundamental frequency component) is also plotted as a function of α and due to the large distortion the curves are shown as dashed for large values of α [53].

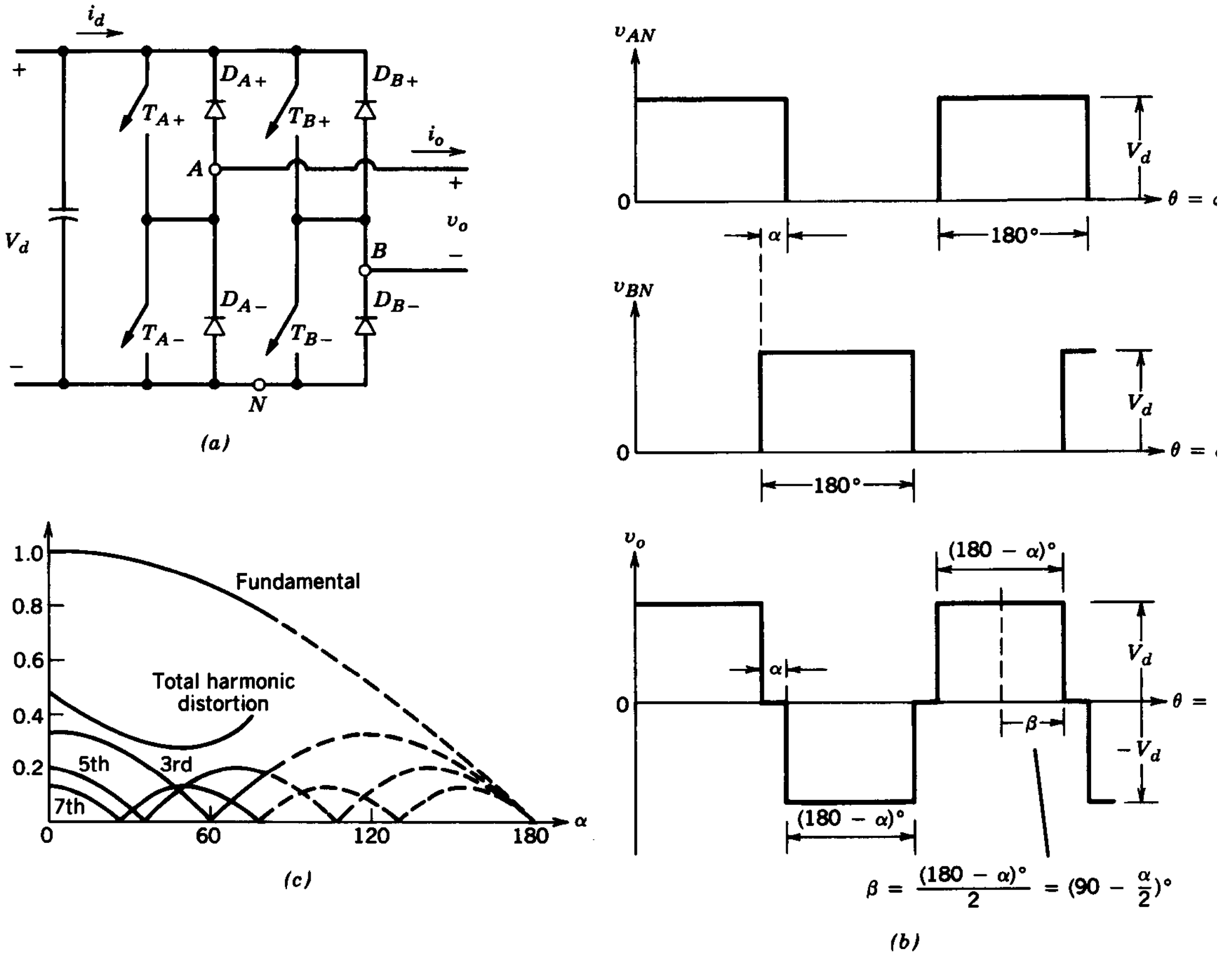


Figure 6-32 Full-bridge single-phase inverter control by voltage cancellation: (a) power circuit; (b) waveforms; (c) normalized fundamental and harmonic voltage output and total harmonic distortion as a function of α [53].

6.4.3 Inverter Topologies

6.4.3.1 Half-bridge Single-phase Inverter

A half-bridge VSI can be seen in Figure 6-33 below. The two large capacitors creates a neutral point N such that the there is a constant voltage $v_i/2$ that is maintained.

A set of large capacitors (C_+ and C_-) is required because the operation of the inverter injects current harmonics that are low-order harmonics [49]. Switches S_+ and S_- cannot be on at the same time as this will cause a short circuit across the DC link voltage source v_i. Table 6-1 Switch states for a half-bridge single phase VSI [49] below shows that there are two defined states (state 1 and 2) and one undefined (state 3) switch state.

To avoid the undefined AC output condition and a short circuit across the DC bus the modulation technique used should always allow for only the top or bottom switch of the inverter leg to be on at a time [49]. The ideal waveforms of the half-bridge inverter are seen in Figure 6-29. The states of switches S_+ and S_- are defined by the carrier based PWM technique.

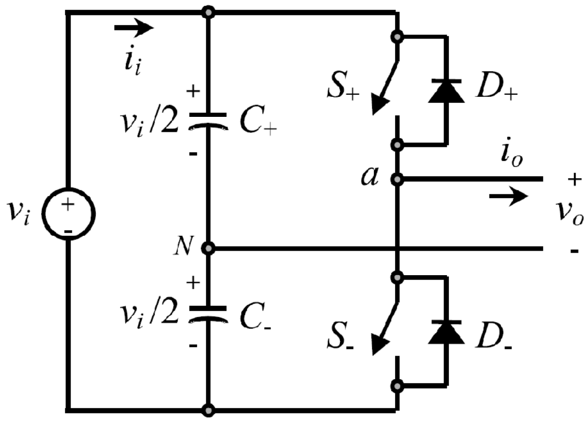


Figure 6-33 Single-phase half-bridge VSI [49]

Table 6-1 Switch states for a half-bridge single phase VSI [49]

State	State #	v_o	Components conducting
S_+ is on and S_- is off	1	$v_i/2$	S_+ if $i_o > 0$ D_+ if $i_o < 0$
S_- is on and S_+ is off	2	$-v_i/2$	D_- if $i_o > 0$ S_- if $i_o < 0$
S_+ and S_- are all off	3	$-v_i/2$ $v_i/2$	D_- if $i_o > 0$ D_+ if $i_o < 0$

6.4.3.2 Full-bridge Single-phase Inverter

The full-bridge VSI inverter is similar to the half-bridge inverter. The only difference is that the full – bridge inverter has a second leg that provides the neutral point to the load. The basic full-bridge inverter circuit can be seen in Figure 6-34 below.

As with the half bridge converter, switches S_{1+} and S_{1-} or S_{2+} and S_{2-} cannot be on simultaneously as it will cause a short circuit condition across the DC link source voltage v_i [49]. For the full-bridge inverter there are four defined switch states (states 1, 2, 3 and 4) and one undefined state as is shown in Table 6-2 below.

To assure the AC output voltage is always capable of being defined the undefined state should be avoided. As with the half-bridge inverter, to avoid a short circuit condition across the DC link and the undefined state, the modulation technique used should ensure that only the top or bottom switch of each leg is on at any instant [49].

The full-bridge inverter AC output voltage is capable of taking values up to the DC link value v_i, and this is twice of that obtained by using the half-bridge VSI topologies. The ideal wave forms for the full-bridge converter can be seen below in Figure 6-35.

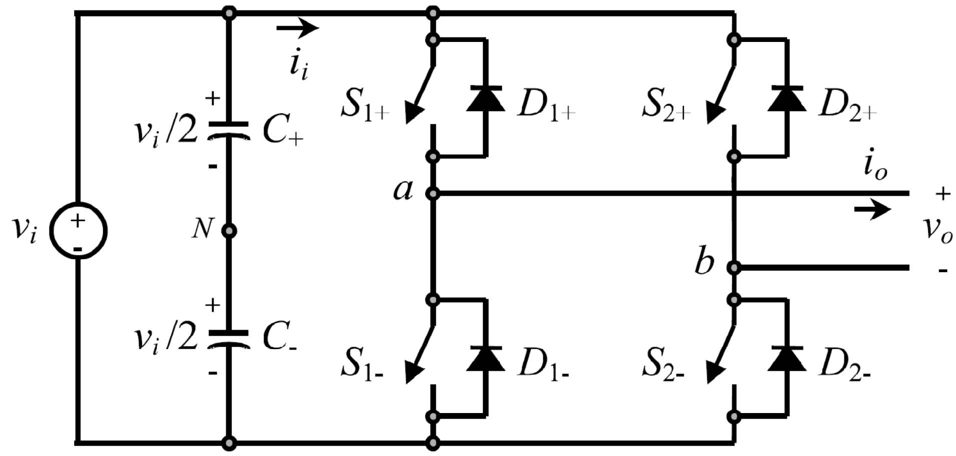


Figure 6-34 Single-phase full-bridge VSI [49]

Table 6-2 Switch states for a full-bridge single phase VSI [49]

State	State #	v_{aN}	v_{bN}	v_o	Components conducting	
S_{1+} and S_{2-} are on and S_{1-} and S_{2+} are off	1	$v_i/2$	$-v_i/2$	v_i	S_{1+} and S_{2-} D_{1+} and D_{2-}	if $i_o > 0$ if $i_o < 0$
S_{1-} and S_{2+} are on and S_{1+} and S_{2-} are off	2	$-v_i/2$	$v_i/2$	$-v_i$	D_{1-} and D_{2+} S_{1-} and S_{2+}	if $i_o > 0$ if $i_o < 0$
S_{1+} and S_{2+} are on and S_{1-} and S_{2-} are off	3	$v_i/2$	$v_i/2$	0	S_{1+} and D_{2+} D_{1+} and S_{2+}	if $i_o > 0$ if $i_o < 0$
S_{1-} and S_{2-} are on and S_{1+} and S_{2+} are off	4	$-v_i/2$	$-v_i/2$	0	D_{1-} and S_{2-} S_{1-} and D_{2-}	if $i_o > 0$ if $i_o < 0$
S_{1-}, S_{2-}, S_{1+}, and S_{2+} are all off	5	$-v_i/2$ $v_i/2$	$v_i/2$ $-v_i/2$	v_i $-v_i$	D_{1-} and D_{2+} D_{1+} and D_{2-}	if $i_o > 0$ if $i_o < 0$

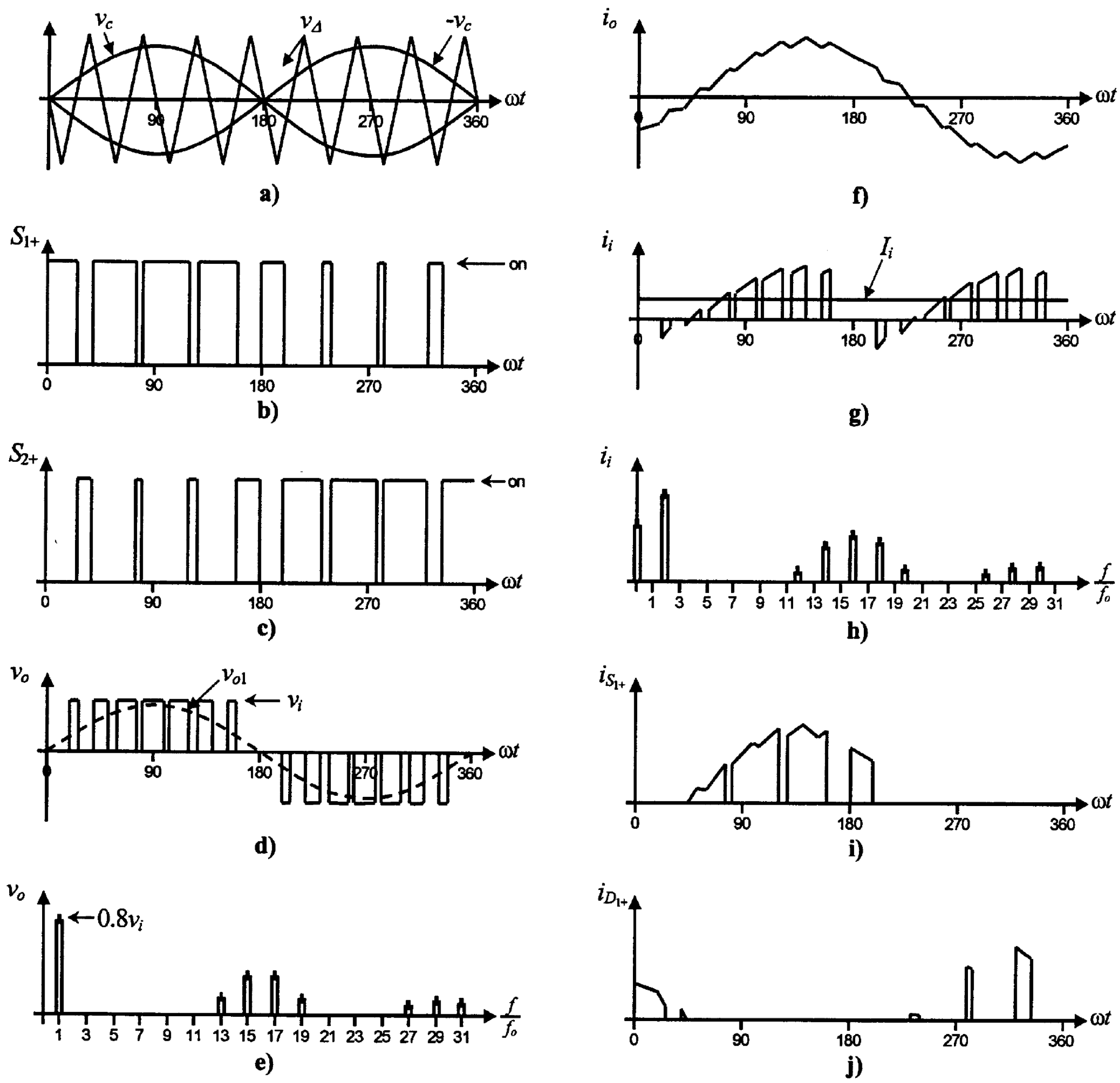


Figure 6-35 The full-bridge VSI. Ideal waveforms for the SPWM: (a) carrier and modulating signals; (b) switch S_{1+} state; (c) switch S_{2+} state; (d) AC output voltage; (e) AC output voltage spectrum; (f) AC output current; (g) DC current; (h) DC current spectrum; (i) switch i_{S+} current; (j) diode i_{D+} current [49].

6.4.4 Summary

Different types of inverter technologies exist and are listed below:

- Square Wave Inverter
- Modified Square Wave Inverter
- Sine Wave Inverter

Square Wave inverters are a dated technology and are not recommended to be used on home appliances as they have low power quality and are not very efficient.

The wave form output from this inverter is not sufficient for today's home appliances and will damage them severely either immediately or with time. The modified square wave inverter is also an old technology but is still widely used. The power quality from a square wave inverter is also low, but it is sufficient to be used in a developing world.

The latest technology on the market is sine wave inverters. These inverters have a near sine wave output and are the recommended technology to be used in current times. Sine wave inverters are more expensive than modified square wave inverters. There are more developments on the sine wave inverter technology and these inverters are called true sine wave inverters.

According to Ian Woofenden [9], sine wave inverters are sufficient to be used with today's home appliances and that pure sine wave inverters are just part of the market hype. A comparison of the half-bridge vs. Full-bridge topologies is shown in Table 6-3.

Table 6-3 Half-bridge vs. Full-Bridge Comparison

	Half-bridge	**Full-bridge**
Input/output [54]	The maximum AC output voltage is half of the DC source voltage.	The full DC source voltage is available as the AC output voltage.
Power Capabilities [53]	Low power applications - require more paralleling of devices if a higher output is required.	Medium and high power applications – require less paralleling of devices

According to Wilmore Electronics Co [55] it is possible to reach half to full load inverter efficiency figures of 60% to 80%. Karl H. Et al [56] did an analysis of a new high efficiency inverter and got efficiency results of 80% to 97%.

Modern controllers exist that usually have more functions built in than just inverting. These functions include charging of batteries, load control, monitoring and data logging of loads. Actually there are controllers that exist that have the AC-DC-AC functions all built into one device. The device can also manage the battery charging and load control.

In this section discussion on inverters was given. The most important point made here is that one should rather use a sine wave converter as it generates the best sine wave at the time for use with most home appliances. In WGS the controller could be an all-in-one device that contains the AC-DC rectification, DC-DC conversion, inverter (DC-AC) and battery charger.

The most important factors to consider when assembling the controller, even when bought as an all-in-one device, is the efficiency, cost and number of components. The more components a device consists of the less efficient it becomes as each components has its own losses (via heat) and more of the energy is wasted in the conversion process. More components also increases the risk of failure, thus the reliability becomes a problem.

7 Batteries and Battery Charging

This chapter provides introductory information on batteries required for renewable energy storage systems. This chapter also includes a discussion on battery charging and a basic charging algorithm is also briefly discussed. There is also looked at the most popular battery charging circuits available for lead-acid battery charging.

7.1 Batteries

For an off- grid WGS that has to source a stable supply of electrical energy to the appliances connected to it, it is critical that the system makes use of batteries. The batteries will serve as a buffer as the wind is variable and so too is the energy supplied by the generator. The appliances will not be supplied of electrical energy directly from the generator, but will rather be supplied of electrical energy via the batteries by the inverter discussed in Section 6.4. The batteries will therefore be the stable source of energy even if the wind supply is variable. The batteries will also serve as backup supply when there is no wind.

Batteries store energy using an electrochemical process. This process is different for each different type of battery. Two main categories of batteries exist [57], called the primary battery and the secondary battery. Basically a primary type battery is a non-rechargeable battery, and the electrochemical reaction within the battery is irreversible. Once the battery is discharged, it is discarded.

Secondary type batteries are better known as re-chargeable batteries. The electrochemical process within the secondary type batteries is reversible. As re-chargeable batteries cycle through a charge and discharge cycle some of the energy is lost in heat due to the conversion of electrical energy to chemical energy and vice versa. The conversion efficiency is between 70% and 80% [10].

7.1.1 Battery Types

Various different types of re-chargeable battery technologies [57] can be found today, and many more new technologies are being actively researched. The different battery technologies are extensively covered in [10] and [57] in terms of energy density (Wh per unit mass and per unit volume), performance and cost. For a more in depth discussion on the different battery types, please see the following references [10], [57]. A summary of these aspects can be seen in Table 7-1.

The six major technologies available today are [10]:

- Nickel-cadmium (NiCd)
- Lead-acid (Pb-acid)
- Nickel-cadmium (NiCd)
- Nickel-metal hydrate (NiMH)
- Lithium-ion (Li-ion)
- Lithium-polymer (Li-poly)
- Zinc-air

Table 7-1 Summary of various battery technologies characteristic and performance [10]

Electrochemistry	Cell Voltage (V)	Specific Energy (Wh/kg)	Specific Energy (Wh/litre)	Operating Temperature (°C)	Overcharge tolerance	Cycle Life (Full discharge cycles)	Relative Cost ($/kWh)
Pb-acid	2.0	30-40	70-75	-10 to 50	High	500-1000	200-500
NiCd	1.2	40-60	70-100	-20 to 50	Medium	1000-2000	1500
NiMH	1.2	50-65	140-200	-10 to 50	Low	1000-2000	2500
Li-ion	3.4	90-120	200-250	10 to 45	Very low	500-1000	3000
Li-poly	3.0	100-200	150-300	50 to 70	Very low	500-1000	>3000
Zinc-air	1.2	140-180	200-220	-	-	200-300	-

Lead-acid batteries are the most common type of rechargeable batteries used for vehicles and stationary equipment like renewable energy applications [10], [58]. As can be seen from Table 7-1, many battery technologies exist with higher power densities, faster charging times and longer life cycles, but in wind energy systems these batteries have not been used extensively when compared to lead-acid batteries due to cost [10], [57].

NiCd batteries are mostly used in rechargeable consumer devices because they are more tolerant to temperature changes and a have a longer deep cycle life when compared to lead-acid batteries [57], [58]. There are two problems with NiCd batteries, one is, that the cadmium contained in the battery is detrimental to the environment and the second problem is that these batteries have a memory effect that occurs if the battery is not used for a long time and not fully charged in suitable intervals [57], [58].

The above mentioned problems are the reason why NiCd batteries are being replaced by NiMH and Li-ion batteries in portable appliances. Only NiCd and lead-acid batteries will be discussed next. For more on the other available technologies, please refer to [57], [58] and [59] for more detail.

7.1.2 Nickel-Cadmium Batteries

NiCd batteries are classified as rechargeable batteries; therefore they fall in the secondary battery type category. NiCd batteries can be used in stand-alone renewable application and have the following advantages that can make them more attractive than lead-acid type batteries [57], [60]:

- Long life.
- Low maintenance.
- Survivability from excess charges.
- Excellent low temperature capacity retention.
- Non-critical voltage requirements.

Compared to lead-acid battery types, NiCd does have the following two main disadvantages:

- High cost.
- Limited availability.

The typical NiCd cell contains a positive electrode made from nickel-hydroxide (NiO(OH)) and a negative electrode that is made from cadmium (Cd). The electrodes are then immersed in an electrolyte solution made from alkaline potassium hydroxide (KOH). As the NiCd cell discharges, the nickel hydroxide changes form ($Ni(OH)_2$). The cadmium now becomes cadmium hydroxide ($Cd(OH)_2$). The freezing point stays low for a NiCd cell due to the concentration of the electrolyte that does not change during the reaction [60].

It should be noticed that the below reactions ((Eq. 7.1, (Eq. 7.2(Eq. 7.3) are reversible. The elements and charge are also balanced on both sides of the equations and the discharge reactions take place from left to right, while the charge reactions take place from right to left.

To make up a 12 V (nominal) NiCd battery, one requires 10 NiCd cells in series. This is due to the nominal NiCd cell voltage of 1.2 V that is lower than the 2.1 V nominal voltage of a lead-acid battery [60]. The voltage of a NiCd cell drops off dramatically once the cell is almost completely discharged, but reasonably stable during the rest of the discharge cycle.

At the positive plate:

$$2NiO(OH) + 2H_2O + 2e^- \leftrightarrow 2Ni(OH)_2 + 2OH^- \qquad \textit{(Eq. 7.1)}$$

At the negative plate:

$$Cd + 2OH^- \leftrightarrow Cd(OH)_2 + 2e^- \qquad \textit{(Eq. 7.2)}$$

Overall NiCd cell reaction:

$$Cd + 2NiO(OH) + 2H_2O \leftrightarrow Cd(OH)_2 + 2NiO(OH)_2 \qquad \textit{(Eq. 7.3)}$$

A NiCd battery can accept a charge rate as high as C/1 and can endure continuous overcharge rates of up to C/15. NiCd batteries are generally sub-divided into the following two primary types [57], [60]:

- Sintered Plate NiCd batteries.
- Pocket Plate NiCd batteries.

Sintered plate NiCd batteries are designed through heat processing of the active materials and thereafter the materials are rolled into a metallic case. The sintered plate NiCd batteries can be installed in any orientation due to the restraining of the electrolyte that prevents any leakage. Common applications for sintered NiCd batteries are electrical test equipment and consumer electrical devices [60].

A disadvantage of sintered NiCd batteries is the so called “memory effect” that occurs if the battery is repetitively discharged to the same capacity level. It is possible in some cases to apply a special charge and discharge cycle to regain some of the battery’s original rated capacity [57], [60].

Pocket plate NiCd batteries are typically of the flooded design and require periodic water additions. These batteries are used typically in remote telecommunication systems and commercial applications [60]. The electrolyte used is an alkaline solution of potassium hydroxide instead of a sulphuric acid solution.

According to James P. and Dunlop, P.E. [60] these batteries can withstand deep discharges and temperature extremes much better when compared to lead-acid battery types. Pocket plate NiCd batteries also don’t have the memory effect that is found in sintered plate NiCd batteries. A high initial cost is to the pocket plate NiCd battery’s disadvantage. The long life time of the pocket plate NiCd does result in the lowest life cycle cost battery for some applications according to James and Dunlop [60].

7.1.3 Lead-acid Batteries

Lead-acid batteries are not the most advanced battery technology available, but it is the only affordable technology for renewable energy storage available today. The lead-acid battery type that is preferred for renewable energy storage systems are deep-cycle charge lead-acid batteries [10], [57].

The market at the moment does not specifically cater for renewable energy systems storage due to the small quantities, so deep charge cycle batteries that are used in industrial fork-lifts and other battery intense industry applications are used for renewable energy storage [9].

The deep-cycle charge batteries are specifically designed to cope with deep discharge and charge cycles that could occur throughout the battery’s life cycle. Two main types of lead-acid batteries exist namely; sealed and flooded type lead-acid batteries [57],[58].

The sealed lead-acid batteries require less maintenance, but are more expensive than the flooded type lead-acid batteries. The life cycle of sealed batteries is also shorter than the flooded type lead-acid batteries.

The basic lead-acid cell that is fully charged consists out of positive plates made up of lead dioxide ($Pb0_2$) and negative plates that are made from sponge lead (Pb). The plates are then flooded in an electrolyte made up of a diluted sulphuric acid solution. If a load is connected to the battery, the current flows from the battery as the active materials are converted to lead sulphate ($PbSO_4$) [60].

The equations below show the electrochemical reactions for the lead-acid cell and during discharge the directions of the reactions flow from the left to the right. The directions of the reactions flow from the right to the left during battery charging. For the equations below, the elements as well as the charge are balanced on both sides of each equation [60].

At the positive plate:

$$PbO_2 + 4H^+ + 2e^- \leftrightarrow Pb^{2+}2H_2O$$
$$Pb^{2+} + SO_4^{2-} \leftrightarrow PbSO_4 \qquad (Eq.\ 7.4)$$

At the negative plate:

$$Pb \leftrightarrow Pb^{2+}2e^-$$
$$Pb^{2+} + SO_4^{2-} \leftrightarrow PbSO_4 \qquad (Eq.\ 7.5)$$

Overall lead-acid cell reaction:

$$PbO_2 + Pb + 2H_2SO_4 \leftrightarrow 2PbSO_4 + 2H_2O \qquad (Eq.\ 7.6)$$

The plates on the inside should never be left exposed as this will cause the battery to fail. The flooded type batteries cost less than the sealed type of batteries and have a longer life too. The only issue here is that the batteries require regular maintenance. This maintenance includes regular cleaning of the terminals and the topping up of the batteries electrolytic fluid [57], [60].

The typical life cycle of flooded type lead-acid batteries, if maintained relatively well, has been found to be 10 - 20 years and more [57],[60],[61]. For sealed lead-acid batteries the life cycle has been found to be around 5 - 15 years [57],[60], [61]. These figures give a rough idea of what could be expected in terms of the life cycle, but are manufacturer specific and the life cycle of batteries to be bought should always be obtained beforehand.

Many different battery technologies are being researched and built today, but most of these technologies are far too expensive for renewable energy storage systems. Lead-acid type batteries have also been around for almost 100 years [62] and the technology have been proven over and over and the safety and maintenance issues are well known.

Lead-acid batteries are used for starting, lighting and electronic devices found on cars. Car batteries are designed to provide a large current for a short period of time and are not designed to be regularly discharged to more than 25% of their rated capacity.

Therefore, for applications like renewable storage systems, where as much of the stored energy as possible is to be extracted before a recharge, one should rather use deep-cycle lead-acid batteries as they are designed to be frequently discharged to at least 50% of their rated capacity[57], [61].

A common name used to express the percentage of rated capacity to which a battery is discharged is called the depth of discharge (DOD) of a battery. It can also be expressed as the state of discharge (SOC), which is the residual capacity of the battery in terms of the full charge capacity, for example, if 20 Ah of a 200 Ah hour battery has been discharged, the DOD would be 10%, and the SOC would be 90% [58]. The main factors that determine the length of the batteries life is the way it is charged and discharged, and the temperature they operate in [63].

Table 7-2 Advantages and disadvantages of various lead-acid and NiCd battery technologies [60]

Battery Type	**Advantages**	**Disadvantages**
Nickel-Cadmium		
Sealed Sintered-Plate	Widely available, excellent low and high temperature performance, maintenance free	Only available in low capacities, high cost and suffer from memory effect
Flooded Pocket-Plate	Excellent deep cycle and low and high temperature performance, tolerance to overcharge	Limited availability, high cost, water additions required
Flooded Lead-Acid		
Lead-Antimony	Low cost, wide availability, good deep cycle and high temperature performance, can replenish electrolyte	High water loss and maintenance
Lead-Calcium Open Vent	Low cost, wide availability, low water loss, can replenish electrolyte	Poor deep cycle performance, intolerant to high temperatures and overcharge
Lead-Calcium Sealed Vent	Low cost, wide availability, low water loss	Poor deep cycle performance, intolerant to high temperatures and overcharge, cannot replenish electrolyte
Lead-Antimony/Calcium Hybrid	Medium cost, low water loss	Limited availability, potential for stratification
Captive Electrolyte Lead-Acid		
Gelled	Medium cost, little or no maintenance, less susceptible to freezing, install in any orientation	Fair deep cycle performance, intolerant to overcharge and high temperatures, limited availability
Absorbed Glass Mat	Medium cost, little or no maintenance, less susceptible to freezing, install in any orientation	Fair deep cycle performance, intolerant to overcharge and high temperatures, limited availability

This is also the main reason for the vast amounts of research that can be found on battery charging algorithms and battery chargers.

Many charging algorithms exist [10], [57], [58], but most of them follow the basic algorithm that will be explained in Section 7.2.2. A summary of the advantages and disadvantages of lead-acid and NiCd battery types can be seen in Table 7-2 above.

7.1.4 Battery Lifetime

The life time of a battery can be influenced by a number of factors including components and materials used for construction, temperature, frequency and depth of discharges, average state of charge and the charging methods used. The lifetime of the battery should be equivalent to its average state of charge if the battery is not overcharged, used under extreme temperatures or over discharged.

According to James and Dunlop [60] it was found that if a typical lead-acid battery is maintained above 90% state of charge, the battery will be able to provide two to three times more full charge and discharge cycles than a battery that is allowed to reach a 50% state of discharge before the battery is recharged. Therefore, it is suggested to limit the allowable average daily depth of discharge to extend the battery life.

The battery life is usually expressed in terms of cycles or years and is dependent on the type of battery and intended application and is found to be anything between 5-20 years depending on the maintenance and charging discipline [57], [60]. It is difficult to quantify the battery life exactly as there are many factors that play a role in the life of the battery as it is used in various conditions and applications. The following factors will have significant effects on the life time of a battery [57], [60]:

- **Temperature** – A rise of 10 °C doubles the rate of the electrochemical reaction. Corrosion of the positive plate grids are accelerated causing an increase in gassing and electrolyte loss if the battery is operated at high temperatures. At low temperatures the life of lead-acid batteries are reduced significantly.
- **Effects of Discharge Rates** – A high discharge rate or current limits the capacity that can be withdrawn from a battery to an allowable depth of discharge or cut off voltage.
- **Corrosion** – The electrochemical activity within the battery causes one material to undergo oxidation (loss of electrons) and the other material to undergo reduction (gain of electrons). This is an on-going process and can ultimately have an effect on the battery's lifetime. The gassing that takes place in flooded lead-acid batteries can cause corrosion on the terminals of the batteries en will generally require cleaning and re-tightening.

7.2 Battery Charging

7.2.1 Charging Requirements

Lead-acid battery chargers typically have two tasks to accomplish. The first is to restore capacity, often as quickly as practical. The second is to maintain capacity by compensating for self-discharge. In both instances optimum operation requires accurate sensing of battery voltage and temperature [64].

When a typical lead-acid cell is charged, lead sulphate is converted into lead on the battery's negative plate and lead dioxide on the positive plate. Over-charge reactions begin when the majority of lead sulphate has been converted, typically resulting in the generation of hydrogen and oxygen gas.

At moderate charge rates, most of the hydrogen and oxygen will recombine in sealed batteries [64]. In unsealed batteries however, dehydration will occur.

Most deep-cycle lead-acid batteries have a 20-hour rating. The 20-hour rating is the amount of charge that would be removed from the battery if all the battery's energy where to be removed over a 20-hour period. Therefore, for a battery that has a capacity of 200 Ah, the 20-hour rating would result in a charge or discharge rate of 10 A [9].

7.2.2 Charge Algorithm

To meet all the charging requirements of lead-acid batteries, and to prolong battery life and ensure maximum capacity, a charging algorithm, which breaks down the charging cycle into four states, is usually employed. See Figure 7-1, for details.

Assuming a fully discharged battery, the charging states are as follows:

- **Trickle Charging** - When the battery voltage level is very low the battery is trickle charged. A small trickle current is applied when the voltage is at near zero capacity. A trickle charge is applied to avoid high current being supplied by the charger to an electrical short (fault), and to reduce out-gassing when a short (fault) is present [57].
- **Bulk Charge** - When the trickle charge threshold is exceeded, the charger can go into bulk charge mode where the full charge current is applied to the battery and the most of its capacity is restored[10].

- **Over-Charge** - A controlled over-charge is followed by the bulk charge state. This is to restore the full capacity in the shortest time possible. The over-charge rate is dependent on the rate at which bulk charging occurred [64]. Over-charge is stopped once the current is reduced to a low value typically one tenth of the bulk charge rate.
- **Float Charge** - To maintain full capacity a fixed voltage is applied to the battery. The charger will deliver whatever current is necessary to sustain the float voltage and compensate for leakage current. When a load is applied to the battery, the charger will supply the majority of the current up to the bulk-charge current level. It will remain in the float state until the battery voltage drops to 90% of the float voltage, at which point operation will revert to the bulk charge state [10], [57].

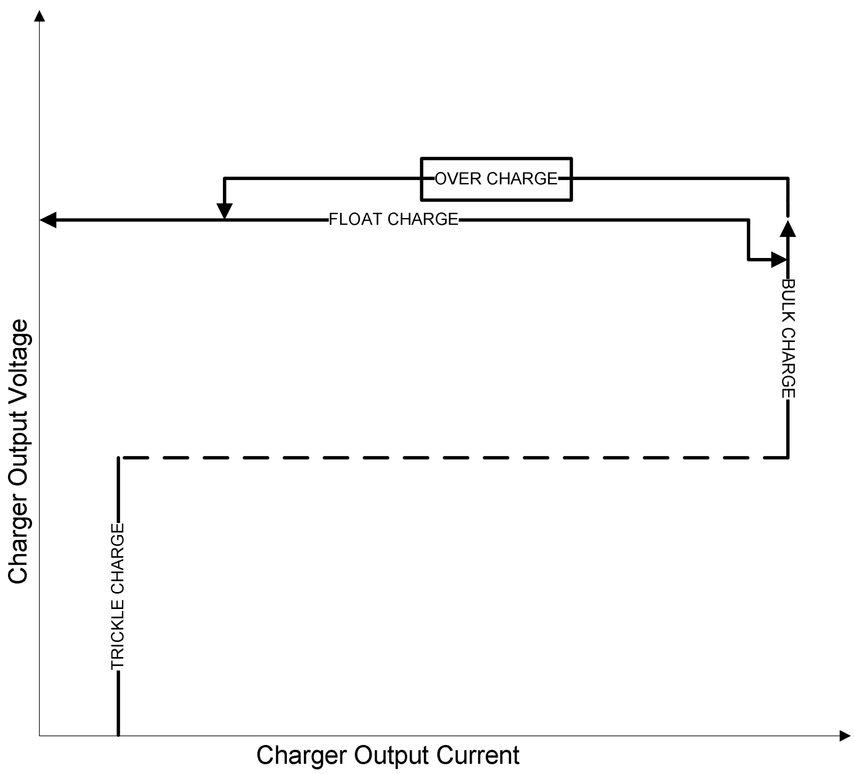


Figure 7-1 Lead- Acid Battery Charge Algorithm [64]

7.3 Battery Chargers

Various different types of chargers exist but mainly fall in the categories listed and discussed below:

- **Linear Regulator** – These types of chargers are simple and cheap to implement, but they have high losses. They work on the same principle as the linear regulator that was discussed in Section 6.3.1. This charger does not have any output filter requirements as it delivers pure DC as there is no switching. This also helps the device not to radiate and conduct emissions and noise. This type of charger also contains a small count of components. A large heat sink is required to cool the series transistor, across which the input voltage is dropped to a lower output voltage. As all the load current flows through the regulating transistor, it is required to be a high power device.
- **Shunt Regulator** – These regulators are mostly found in photovoltaic systems as they are relatively cheap and easy to build. A switch (transistor) controls the charging current and is connected in parallel with the battery and the photovoltaic panel. By shorting (shunting) the output through the switch when the voltage reaches a programmed limit, the battery can be protected from overcharging. The control and charge characteristics of series regulators are usually better when compared to shunt regulators [65].
- **Switch Mode Regulator ("Chopper")** – This type of charger has a high component count and can be very complex. The switch mode charger uses pulse width modulation techniques to regulate the charging voltage. Switch mode chargers have a wide input range with high conversion efficiency across the input range. To reduce the noise that is generated by switching high currents, the switch mode charger requires a large passive output filter, which will smooth the output waveform. The components sizes of the switch mode charges can be reduced by increasing the switching frequency of the circuit [57], [65].
- **Pulsed Charger** – The pulsed charger contains a series transistor that remains on when the battery voltage is low, and as the battery voltage reaches the pre-set regulation voltage, the transistor is pulsed, allowing the voltage to be maintained at the required level. The pulsed charger also has a smaller output filter, as it act like a linear regulator for part of the cycle and as a switch mode supply for the other part of the cycle [65]. The pulsing of the battery gives it time to stabilise. This is due to the low increments of charge current, applied at increasingly higher charge levels during charging. Current limiting is required on pulse chargers which increases their cost and complexity.

7.3.1 Constant-voltage Charging

7.3.1.1 Shallow-cycle constant-voltage charging

Figure 7-2 below shows the typical charging circuit recommended for constant voltage charging of lead-acid batteries [57].

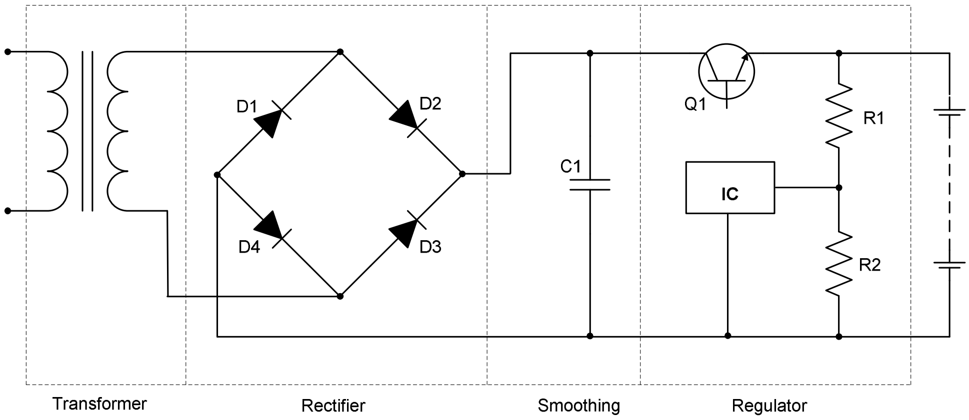


Figure 7-2 Typical constant-voltage charging circuit for lead-acid batteries [57]

According to Crompton [57], a battery is classified as a shallow cycle constant-voltage (CV) battery if 5% 50% of the rated voltage capacity of the battery is removed and under these conditions the CV and limiting current required should be decreased from the values implemented when a deep cycle CV charge is done. The following charging conditions are also listed by Crompton [57] for this specific state:

- Constant Voltage: 2.40 V/cell – 2.56 V/cell.
- Limiting Current: 10% - 15% of the rated capacity.
- Charge time: 10 h - 18 h; in case the capacity of the battery seems like it is decreasing, it is recommended that the charging time should be increased periodically to 20 h - 30 h.

Taper charging can be used to charge batteries in cyclic service, but this method requires control of overcharging and battery temperature and both of these aspects have an adverse effect on the battery life [57].

7.3.1.2 Deep-cycle constant-voltage charging

For a battery to be classified in a deep cycle charge category it has to have at least 50% - 100% of its rated capacity removed [57].

When the battery is in this condition, the constant voltage and the limiting current should be increased and according to Crompton [57] the following are the charging conditions required:

- Constant Voltage: 2.45 V/cell – 2.50 V/cell.
- Limiting Current: 20% - 55% of the rated capacity.
- Charge time: limited to 12 h - 20 h; in case the capacity of the battery seems like it is decreasing, it is recommended that the charging time should be increased periodically to 24 h - 30 h.

7.3.1.3 Float constant-voltage charging

A float charge is required when a battery is used only in emergency situations and should therefore be in a continuous charge condition. To maintain a full charge condition under these circumstances the battery is charged at a sufficient constant voltage and the following are the charging conditions required [57]:

- Constant Voltage: 2.28 V/cell – 2.30 V/cell.
- Limiting Current: 1% - 20% of the rated capacity.
- Charge time: continuous charge.

According to Crompton [57], all lead-acid batteries charge most efficiently in the temperature range 15 °C - 30 °C but if the temperature does fall outside the 0 °C - 40 °C range it is required that temperature compensation would be built into the charger to enhance the charge efficiency of the batteries. A temperature compensator should be built into the charger that can operate at 4 *m*V/°C per cell at 25 °C [57]. Figure 7-3 below shows the constant-voltage charge voltages for various battery temperatures and modes of charging.

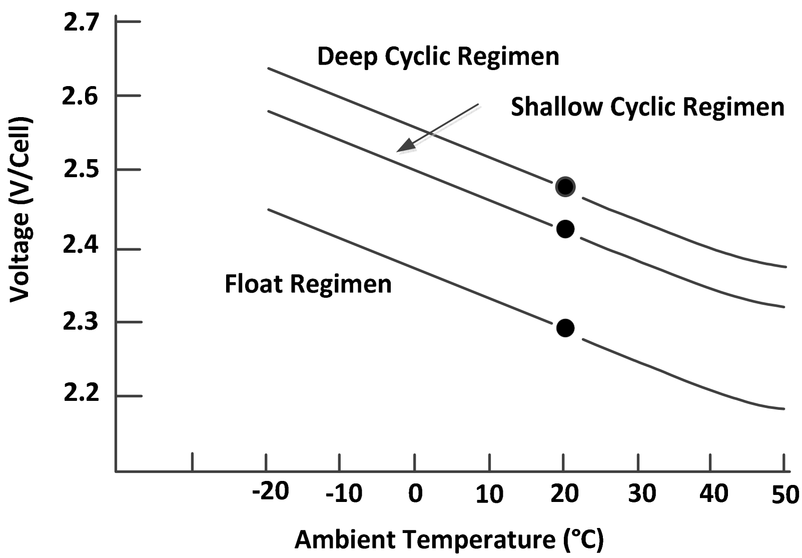


Figure 7-3 Charge voltage per cell versus temperature [57]

7.3.1.4 Two-step cyclic voltage-float constant-voltage charging

Two-step cyclic voltage-float CV charging is used in applications that require a lead-acid battery that is in standby mode to be re-charged rapidly after it has been discharged. Crompton [57] recommends that for this situation the two-step charger will be most efficient; meaning the converter is capable to switch from a cyclic voltage to float voltage charge. For the above mentioned circumstances the charging conditions are as follows:

- Initial constant voltage: 2.45 V/cell - 2.50 V/cell.
- Float constant voltage: 2.28 V/cell - 2.30 V/cell.
- Limiting Current: 20% - 40% of the rated capacity.
- Initial charge time: time required to reach 2.50 V/cell.
- Float charge time: continuous charge.

It is possible to apply a high charge rate without a serious sacrifice on battery life. The battery can be restored to 90%-95% of the full rated capacity within a 1 h - 3 h period [57]. To accomplish this, the following characteristics are required:

- Constant Voltage: 2.50 V/cell - 2.55 V/cell.
- Limiting Current: 100% of the rated capacity.
- Charge rime: 1 h - 3 h.

Charging at a high rate should not be allowed to continue beyond the 3 h period as greater than normal amounts of gassing will occur. A two-step charging circuit can be seen in Figure 7-4.

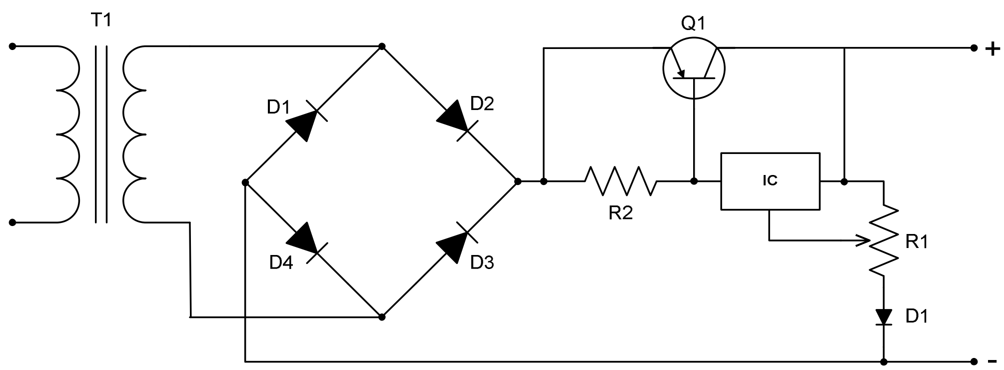


Figure 7-4 Two-step cyclic voltage-float constant voltage charger [57]

7.3.2 Constant-current Charging

Constant-current charging is one of the best methods to quickly restore charge relatively fast without it having a negative effect on battery life. Constant-current charging is particularly effective if cells or batteries are re-charged in series. Constant-current charging works to eliminate the charge imbalance in a starved battery [57],[66].

The main focus of constant-current charging is to maintain a constant charge current no matter what the current battery state of charge or battery temperature is. Constant-current chargers are very reliable if properly designed and are inexpensive. The constant-current charger characteristics are designed in such a way that the charger will only have small variations in charging current at the operating point throughout the entire charging range of the battery.

Figure 7-5 below illustrates this concept and a theoretical charger voltage-current output characteristic can be seen.

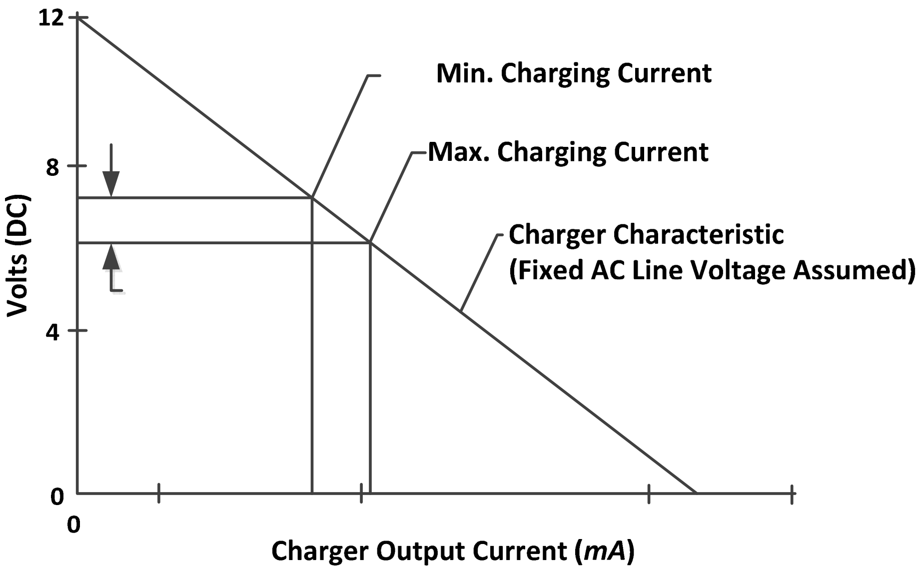


Figure 7-5 Typical Constant-current Charger Characteristics [66]

Also seen on in Figure 7-5 is the operating range of the battery during charging. A difference (75 mA minimum and 105 mA maximum) of 30 mA is seen. This difference means that it is not a constant-current, but according to the Rechargeable Batteries Application Handbook (RBAH) [66], this is acceptable for most applications.

Figure 7-6 below illustrates the cell charging voltage profile with time as a sealed lead-acid cell is being charged. The curves in Figure 7-6 are normalized to the percentage of capacity returned to the cell for ease of comparison of the various charge rates.

As the charge state nears the full charge state, the voltage of the cell increases severely and this can also be seen in Figure 7-6. This voltage increase occurs due to the overcharging of the plates. The voltage increase will also be seen when the cell is in a lower state of charge and the cell is being charged at a higher rate due to the reduced efficiency of at the higher charging rates [66].

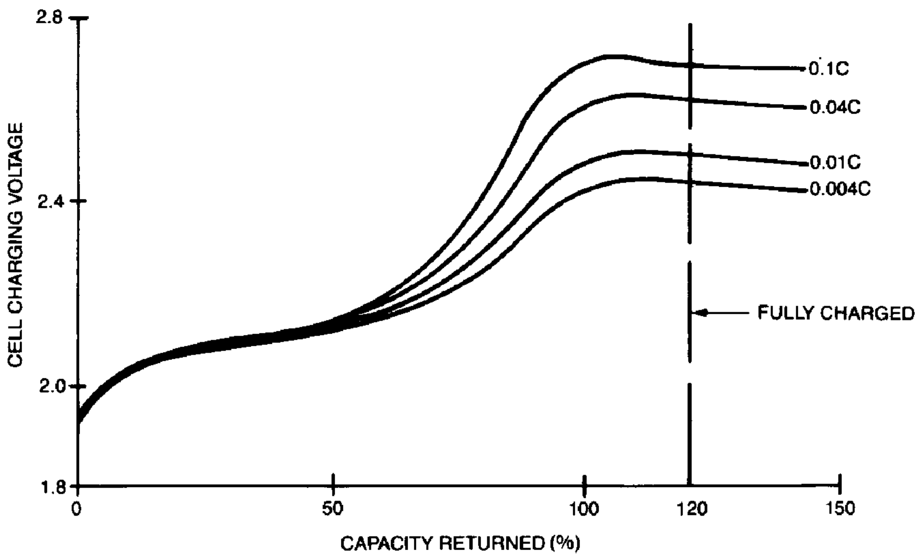


Figure 7-6 Typical Charging Voltages of Stabilized Sealed-Lead Cells at 25°C [66]

The overcharging of the sealed lead-acid battery using the constant-current charging method is of great concern as was said previously, the constant overcharging of a lead-acid cell increases oxidation of the positive grid and this effects the battery life and therefore a charge limit should be applied to prevent constant over-charging of the cell [66].

7.3.2.1 Single-rate Constant Current Charging

Single-rate constant current chargers are mostly simple in design and can easily be found from charging manufacturers or they can easily be designed into an end product. These chargers are mostly used in portable applications ranging from garden tools, flashlights to portable appliances. The main advantage of single-rate constant current chargers is their low cost [57], [66]. These chargers are generally made up out of a simple transformer and diode rectifiers and there is no need for switching or sensing circuits.

The charge rate selection of these chargers is very important as it is a function of both the product and application profile. As long as the state of charge is very low on sealed lead-batteries, the batteries can be charged at very high rates and a charge rate of 1C is possible for fully discharged batteries [66]. As the battery reaches its full charged state, the pressure will increase due to gassing and at this point the charge rate should be reduced to minimize the venting of excessive gasses. According to the RBAH [66], charge rates higher than 1C is not recommended for single-rate constant current chargers.

For low temperature there are two concerns that can act to limit the maximum charging rate that can be used[57], [66]:

- The concentration of the electrolyte solution becomes so low at low states of charge and very low temperatures that it is possible for the electrolyte solution to reach freezing point.
- At low temperatures and high states of charge as the cell approaches the overcharge state, the gassing must be limited to keep the internal pressure to an acceptable level.

The minimum charge rate can also be applied to a battery as the charge acceptance of a lead-acid battery is very good at low charge rates [57], [66]. According to the RBAH [66], the advantage of a very low charge rate is extended battery life, but this advantage is eliminated as soon as one realises that the charge time at this low charge rate will exceed 100 hours for a fully discharged battery.

It is more appropriate to use single-rate constant current chargers in cyclic operation applications where it is often required that a battery should be re-charge to the full state overnight or within 24 hours. To achieve this, a charge rate in the 0.05C to 0.1C range should be used, but it should also be noted that at these chare rates some venting of gases will occur as well as oxidation of the positive grid that will have a negative effect on the battery life at elevated temperatures and/or extended overcharge times [66].

7.3.2.2 Split-rate Constant Current Charging

According to the RBAH [66], the concept of split-rate constant current charging is accepted as one of the best methods of charging sealed lead-acid batteries. During the first part of charging while the battery is in a low state of charge a medium to high charge rate is applied. As the battery nears it full charge state, the charging current is switched to a very low trickle charge rate and thereafter the battery can be left connected to the charger indefinitely.

The voltage/current versus time profile for one form of a split-rate constant current charger based on a combination of voltage and time can be seen in Figure 7-7 below.

From Figure 7-7 one can also see when the charger switches from the high charging rate to the low charging rate, as the state of charge reaches approximately 110% [66].

The switch point and switching method selection will be affected by the relative priority of minimising venting by switching early versus maintaining a good cell balance by switching later. Some forms of split-rate chargers exist that can alternate between the high and low rate of charging when the battery is in the state of charge range of between 90% and 120% with the amount of time spent in the low charge rate increasing as the battery approaches the full charged state [66].

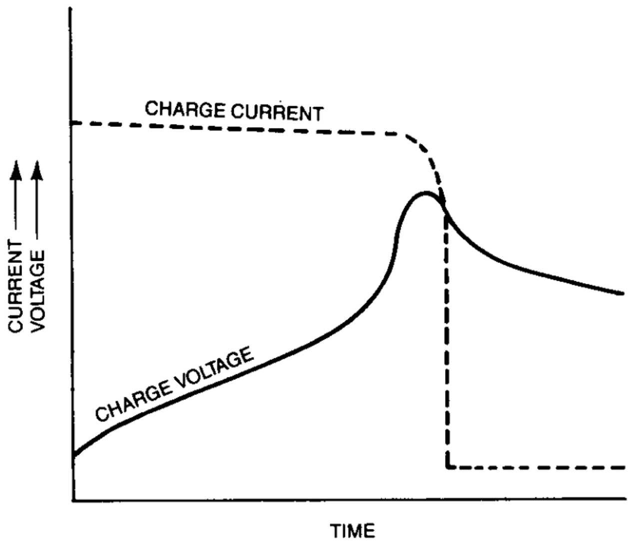


Figure 7-7 Voltage/Current versus Time Profile for a Split-rate Constant-current Charger[66]

According to the RBAH [66], the benefits of improved battery performance and battery life outweigh the increased cost and complexity of the split-rate constant current charger.

The following are advantages of split-rate constant current chargers [57], [66]:

- Very rapid charging of the battery can be done.
- The oxidation on the positive plate is minimal due to the limited overcharge from the very low charge rate when the charger is switched to the trickle charge state.
- Throughout the life of the battery it is possible to keep a very long series string of cells reasonably well balanced.

7.4 Summary

As mentioned, lead-acid batteries are used as the main storage elements in off-grid wind generator systems. It is important to prolong the battery life and to maximize its use. To accomplish this, the charging methods of lead-acid batteries were looked at as this is integral to the prolonging of the battery's life. A four stage charging algorithm was discussed and thereafter a description of some of the battery chargers available was given. Table 7-3 shows a short summary of a few secondary battery types and their characteristics. This section is now concluded with an example of a circuit that is able to implement all the special requirements for charging a lead-acid battery effectively.

Table 7-3 Summary of Secondary Battery Types and Characteristics [60]

Battery Type	Cost	Deep Cycle Performance	Maintenance
Nickel-Cadmium			
Sealed Sintered-Plate	High	Good	None
Flooded Pocket-Plate	High	Good	Medium
Flooded Lead-Acid			
Lead-Antimony	Low	Good	High
Lead-Calcium Open Vent	Low	Poor	Medium
Lead-Calcium Sealed Vent	Low	Poor	Low
Lead-Antimony/Calcium Hybrid	Medium	Good	Medium
Captive Electrolyte Lead-Acid			
Gelled	Medium	Good	None
Absorbed Glass Mat	Medium	Good	Medium

Like this circuit in Figure B-1 Appendix B, there are more available and can be seen in more detail by referring to the following sources [67], [68]. These circuits all implement lead-acid battery charging by using a switch-mode configuration to maintain the different modes of charging. These converters all have high charging efficiency's, ranging from 80%-95% [67], [68]. Although the charging efficiency of these chargers are very high, most of the energy is lost through the chemical to electrical conversion process that takes place in the lead-acid battery itself during charging [60].

During the conversion process, heat is generated and this is where the most energy is lost. According to RBAH [66] the losses can be as high as 20% and in a study done by G.A. Keen [69] on a domestic application of a photo voltaic system, it was found that the most energy was lost during the charging process and that during off-grid use, an efficiency of 55% was possible, but during stand-by use the efficiency dropped to less than 25%.

8 Generator System Cost

In this chapter a wind generator system will be assembled from the various components discussed throughout the dissertation. The wind generator system will be sized accordingly and this will also be discussed. The cost of the system will be calculated consisting of component cost, installation cost and maintenance cost. This cost of sourcing the same energy requirements from the utility or a carbon fuel generator for the same period will be calculated and will then be compared to the wind generator system cost to determine if it is viable to use a wind generator system for energy sourcing.

8.1 Wind Generator System Specifications

To make decisions in context in terms of components sizing, a WGS specification is required. The goal of this dissertation is to see if wind energy is viable for a small sized energy efficient home in South Africa, by identifying the components of the WGS, then to optimise the output of the WGS by selecting the most efficient, cost effective and low maintenance components to make up a viable WGS.

The location is a theoretical best case scenario location. This is to give one an idea of what a best case scenario location would produce and cost to setup, as well as maintain. This can be used as a basis to compare other areas to.

WGS Specification:

- **Location** - The site is situated on an outlaying area of Johannesburg, South Africa. The off-grid house is situated in an open area with a flat land profile. No high objects are within 150 m of the house. The site has a 4.0 m/s average wind speed at a height of 15 m.
- **Energy Requirement -** The house, with no efficient energy usage methods employed, uses 900 kWh per month. This is a total of 30 kWh per day. In Section 2.2 it was determined that a 60% energy reduction is possible. Thus, the energy usage of the house can be brought down to 540 kWh per month or 18 kWh per day. To ensure the components are sized sufficiently, and to cover for some inefficiencies when converting from wind energy to electrical energy, an overhead of 15% is added to the energy usage bill. This will bring the energy to be generated by the wind generator system to 20.7 kWh per day. The peak power drawn at any time by simultaneously running appliances will never be larger than 5 kW.
- **Tower -** The tower needs to be at least 15 m high as this is the height where the 4.0 m/s average wind speed is found.

- **Blades and Generator -** The blades will be paired with the correct generator to have an energy production capability of at least 20.7 kWh per day.
- **AC-DC-AC -** The power electronics will have to handle the load and have a maximum input voltage of 230 VAC. The output voltage for battery charging will have to be determined from the battery requirements below. The inverter must be able to generate a sine wave output at a frequency of 50 Hz and at a voltage of 230 VAC for use on home appliances.
- **Battery -** The battery bank must be able to supply the house with 20.7 kWh of energy for 2 days.
- **Battery Charger -** The charger must be able to charge the batteries and must not over-charge the batteries nor let them be discharged to a depth of discharge (DOD) level of more than 50%.
- **Backup Generator -** In case of lack of wind for more than 2 days, the backup generator must be able to re-charge the batteries and be able to supply high priority loads (5 kW peak load) of the house for 2 days.
- **WGS -** The WGS specified above must also have a useful running life period of 20 years and must therefore be maintained for this period of time.

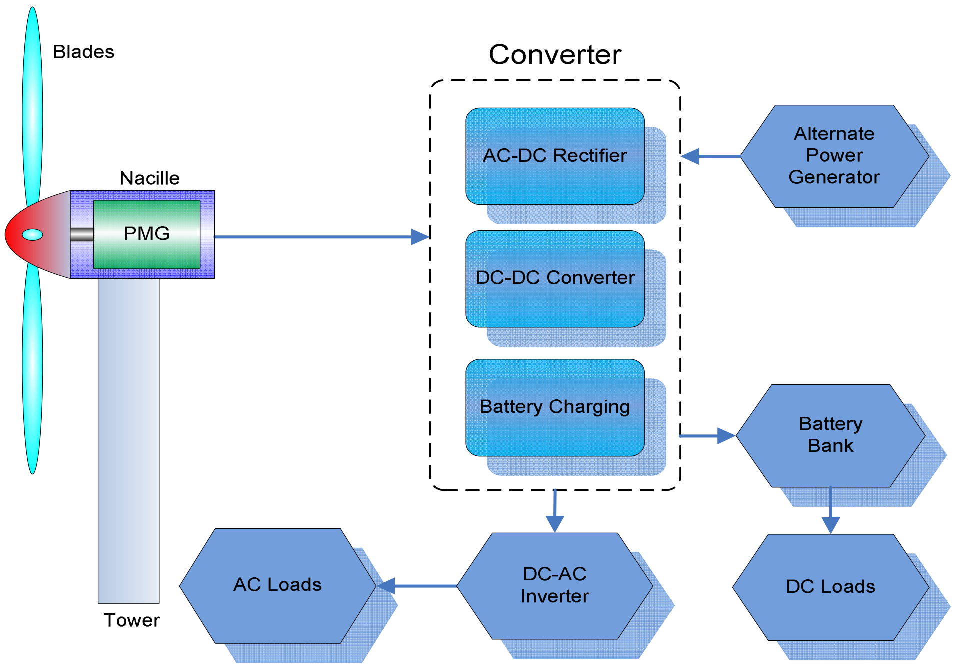


Figure 8-1 Wind Generator System (WGS)

8.2 Wind Generator System Cost

The following sections are the last step of an iterative process followed to calculate the required sizing for the various components of this wind generator system. An iterative process was necessary as some of the underlying components have an effect on upper level components. The cost of the complete WGS system will be taken into consideration, but not every component of the WGS will be sized and discussed, only the major components seen in the following sections will be sized and discussed in terms of installation and maintenance requirements.

8.2.1 Tower

The average wind speed of the site was given as 4 m/s at a height of 15 m. The tower height could simply be used as 15 m, but keep in mind that from Section 4.2, the wind speed has a cube-three factor on the energy output and the higher one goes up with the tower the higher the wind speed will be. The tower height will be determined in Section 8.2.3 as the generator, blade diameter and tower height are all interlinked.

The Danish Wind Site [19] has a wind shear (the rate of wind speed increase as one goes further up from the ground) calculator that can be used to determine the wind speed at different heights. The wind shear calculator also determines the wind speed according to roughness class.

8.2.2

Some of the classes are define below:

- Class 0: Water surface
- Class 1: Farm areas without fences and hedgerows. Only soft rounded hills.
- Class 2: Agricultural areas with some houses and hedgerows.
- Class 3: Villages, small towns, forests and very rough and uneven terrain.
- Class 4: Large cities with tall buildings and skyscrapers.

For a full list of the class definitions please refer to the Danish Wind Industry Association's (DWIA) website [19]. For the specified WGS, a wind class of 2 was chosen. The output of the wind shear calculator can be seen below (Table 8-1) in the first column, the second column shows the cube-three effect of the wind speed as it increases with height.

Table 8-1 Tower Height vs. Wind Speed [19]

Tower Height (m)	Wind Speed (m/s)	Wind Speed $(m/s)^3$
20	4.37	83.5
30	4.71	104.5
40	4.94	120.6
50	5.13	135
60	5.28	147.2
70	5.41	158.3
80	5.52	168.2

One has to keep in mind that the tower cost will increase dramatically as the height increases as was seen in Section 4.2. A horizontal axis tower was chosen, as this is the most common type of tower generator configuration found. See Section 4.2 for more advantages and disadvantages of the different types of towers. An upwind configuration was also chosen, although it might cost a bit more than a downwind configuration because of the tail. The tail will help to pull the generator out of high winds and also forms part of the furling system.

A fixed guy-wired tower type was chosen as it is also more readily available and doesn't have the high cost of a free standing tower, and one can easily find this configuration in various heights. Installing the tower one will need to do some excavation work for the base and anchors for the guy ropes. A crane might also be required to lift the tower. This will add to the cost, but will still not be as expensive as a free standing tower. The only disadvantage might be the footprint of the fixed guy tower type, but this is not a major factor in this case.

The tower requires annual maintenance that includes checking the guy ropes for tension and making sure they are all still secure. The tower also has to be checked for corrosion and structural damage. Because the tower is a fixed tower type, it is also possible to climb the tower easily to do maintenance work on the generator or blades.

8.2.3 Blades and Generator

The sizing of the blades and the generator are rarely done separate as most manufacturers already have paired the correct blades with a generator. Therefore, one does not really have a choice on selecting the blades separately from the generator. It is possible though to order the blades and generator separate, but it is not recommended as the manufacturer's best knows what blades to pair with which generator.

A rotor with three blades was chosen, as from Section 4.3, more bladed machines have reduced flicker and also provides more stability than two bladed rotors. This means that there are less vibrations and thus less chance for failure.

There is no definite way of calculating what size of blades and what size of generator is required, but two wind generator experts Hugh Piggot [70] and Michael Klemen [71], have through years of experience with wind turbines, come up with two methods to roughly determine the blade and generator size. For more information on how these methods were derived, refer to the respective references.

Hugh Piggot uses the following formula:

$$P_{AVG} = \frac{2.24V^3 \times 3.28D^2}{k} \qquad \text{(Eq. 8-1)}$$

where, V is the wind speed in m/s, and D is the diameter of the blades in m. k is based on various factors, like turbine efficiency, which differs from manufacturer to manufactures. Hugh Piggot [70] recommends in his article "Estimating Wind Energy" that $\mathrm{k} = 600$ be selected to get the best overall results.

Michael Klemen [71] uses a pre-calculated table seen in Table 8-2 below. The values for perfect turbines that could theoretically work at the Betz Limit have first been calculated. The second column shows the values for good real life turbines. The values are shown in meter squared and in feet squared.

Table 8-2 Michael Klemen's Estimated Energy Output [71]

Energy Per Month (kWh)				
Wind Speed Mph-[m/s]	**Betz Limit per m^2**	**Good Turbine per m^2**	**Betz Limit per ft^2**	**Good Turbine per ft^2**
5-[2.24]	4.47	2.65	0.415	0.246
6-[2.68]	7.99	4.74	0.742	0.440
7-[3.13]	12.98	7.70	1.206	0.715
8-[3.58]	19.66	11.66	1.826	1.083
9-[4.02]	28.02	16.63	2.604	1.545
10-[4.47]	37.70	22.36	3.502	2.078
11-[4.92]	47.95	28.45	4.455	2.643
12-[5.36]	57.96	34.38	5.384	3.194
13-[5.81]	67.01	39.75	6.226	3.693
14-[6.26]	74.68	44.30	9.938	4.116

Table 8-2 is used as follows; a wind speed at which the generator will operate is looked up in the table. The corresponding meter squared value of the good turbine column is then multiplied by the blades diameter to arrive at the estimated kWh per month for the selected blades and turbine. This can then be compared to manufacturer's specifications. The energy production of a turbine at a specific average wind speed and with a specific blade diameter can never be better than the theoretical Betz Limit [17].

Both Hugh and Michael's methods was used to calculate the blade and generator sizes required to supply the home with 20.7 kWh energy per day. Both methods do not give one the exact same energy output value, but they are close to each other. The calculation process was repeated until it was found that the method that calculates the least output energy at least satisfied the requirement of 20.7 kWh per day. As was mentioned before, there is no single method for calculating the exact correct size for the turbine and blades required, but by using the wind expert's methods, one can at least get a rough idea of what is required.

Hugh Piggot [70]:

$$P_{AVG} = \frac{(2.24 \times 4\ m/s)^3 \times (3.28 \times 7\ m)^2}{600} \qquad \textit{(Eq. 8-2)}$$

$$P_{AVG} \cong 632\ Watts$$

$\mathrm{P_{AVG}}$ is the average power and should be multiplied by 24 hours to get to the daily energy production potential of the generator and blades at the selected wind speed. Thus, the estimated production for this generator and blade configuration was calculated to be 15.2 kWh per day at a 4 m/s average wind speed with 7 m diameter blades. This was still below the required 20.7 kWh per day.

Michael Klemen [71]:

For a 4 m/s average wind speed, from the Michaels table seen in Table 8-2, a corresponding value (16.63) for the good wind turbine is found from the table. The swept area (38.5 m^2) of the 7 m blades is then multiplied by the 16.63 value. This gives us the energy per month value of 640 kWh thus, 21 kWh per day.

To show the effect of increasing the tower height to 30 m, therefore increasing the wind speed (to 4.71 m/s) by using the wind shear value from Table 8-1, the estimated output energy for Hugh's method was found to be 24.8 kWh per day, and for Michael's method, it was found to be 28.7 kWh per day.

A 20 m tower can also be considered, and the estimated energy output for Hugh's method was calculated as 19.78 kWh per day, and for Michael's method it was calculated as 28.2 kWh per day. For this WGS a 15 m tower will be used as the generator discussed below can according to the specifications produce the amount of required energy at 15 m and 4 m/s wind speed.

If the wind blows at a constant speed of 4 m/s for 1 hour, the generator should be able to produce 1 kWh. This is 24 kWh per day and is higher than the required energy output also very close to Hugh's estimated kWh's per day. For 21 kWh per day, a much larger turbine-generator set is required than the average of 1 kW times 24 h. Typically, the average output is 10% to 15% of the rated capacity of the turbine set. Therefore, a 10 kW set was selected.

A 10 kW generator was found locally that can produce 1 kWh energy output at a constant wind speed of 4 m/s. The power curve for the particular generator can be seen in Figure B-2, Appendix B. For an average wind speed of 4.71 m/s (if a 30 m high tower is used) the generator is able to produce 1250 Wh of energy which equates to 30 kWh per day. The power curve for the particular generator can be seen in Figure B-2, Appendix B. The generator is a PMG type generator and the specifications can be found in Table B-9, Appendix B.

The generator will be attached to the top part of the tower at ground level. The blades will then be attached to the generator via the hub also at ground level. This is the safest method as compared to lifting the tower into the air and then attaching it to the tower in the air.

The reason is if the wind starts to pick up, it could push the generator or blades into the guy-wires of the tower or even into the tower itself. The tower will require a concrete base that will form the foundation of the tower.

The blades have to be checked annually to make sure they are still tightly bolted to the hub, and that no cracks or wear are appearing. The blades should also be checked for crud build-up that should be removed. One should also make sure the blades are still balanced. The generator is a direct driven generator, thus there is less energy losses in the system and also lower maintenance requirements as described in Section 3.1.

Maintenance is still required though and it is important to check that all hardware is tightened to manufacturer specification, and that all the moving parts are properly greased. It is also important to check the wiring and connections at the generator as the connections could come loose from a vibrating blade or machine. The furling system, yaw bearings and main bearing should also be inspected.

8.2.4 Controller

The controller will include the AC-DC, DC-DC, and DC-AC converters and battery charger all in one (see Figure 8-1). The input voltage should be 250 VAC maximum, as this is the output of the generator. The output voltage of the charge control part will be determined by the battery requirements discussed later in this chapter. The final output voltage for the inverting part of the controller should be 230 VAC. This is required to operate everyday appliances.

The controller will divert the energy away from the batteries to the house if the batteries are fully charged. The controller will keep a float charge on the batteries to make sure they are full and ready to be used in case of low wind periods.

The controller must at least be able to handle the peak output power of the generator, thus 10 kW. The controller must also be able to handle the maximum power that the house could draw at any time. This is the total power drawn by all simultaneous running devices at any instance and can in some cases be higher than the generators peak output power, but in this case it is 5 kW as was given in the specification. Therefore the controller’s peak power rating will have to be 10 kW at least.

The controller must be situated close to the tower as to minimise cable lengths and costs. The controller must be installed in a safe dry environment. The controller will also need to be programmed with the battery charge parameters.

The controller itself will not necessarily require maintenance, unless struck by lightning or overloaded and blown. The connections should be checked to make sure they are secure. The controller must be checked to see if it is working properly.

The settings must be recorded with the commissioning of the system, and should then be checked often to make sure they have not changed. Modern controllers have monitoring systems built in that also has data logging capabilities. This will help one to keep track of energy generated and energy used. It will also give information on battery charging and battery voltage. This information will help one to identify problems even before they become critical.

8.2.5 Batteries

The batteries are required to supply the appliances in the home with energy through the controller for periods where there are not enough wind to charge the batteries and supply the house of energy. The battery of choice is the (flooded or sealed) deep-cycle lead-acid battery and was also discussed in Section 7.1. The batteries are sized as follows:

$$Battery\ capacity\ in\ Ah = \frac{kWh_{required} \times Days \times 2_{DOD}}{V_{battery}} \qquad \textit{(Eq. 8-3)}$$

where, $\mathrm{kWh_{required}}$ is the house's required energy per day. Days are the days the system is required to run from the batteries. 2_{DOD} is the required depth of discharge for the batteries to prolong their life.

This value is multiplied by two in this case the make provision for the 50% DOD. $\mathrm{V_{battery}}$ is the selected nominal battery voltage and it can be from 6 V to 48 V. 48 V is more and more becoming an industry standard as all the controllers work on 48 V. Therefore 48 V is also selected for this WGS. The ampere hour requirement for the batteries was calculated as 1725 Ah.

The 48 V cell will be made up out of four 12 V cells, connected in series multiplied by four. Each 12 V battery has an Ah rating of 125 Ah and the battery specifications is seen in Figure B-3, Appendix B. Thus, the total number of batteries used to form the battery bank is 16 (R2250 per battery from Current Automation [72]). The total Ah of the battery system is 16 times each battery's Ah rating, thus 2000 Ah.

$$Battery\ capacity\ in\ Ah = \frac{20.7\ kWh \times 2\ days \times 2\ DOD}{48V} = 1725\ Ah \qquad \textit{(Eq. 8-4)}$$

The batteries will require a cool installed environment as the temperature [61] greatly effects the battery life as was seen in Section 7.1. The batteries will also have to be placed in a dry safe ventilated environment. All the terminals and cable ends should also be protected. Regular maintenance is required in terms of making sure flooded cells are still flooded, and that the terminals are clean and that there are no corrosion occurring. The connections should be checked for tightness. It is very important to make sure that the charge controller does not allow the batteries to discharge past the depth of discharge (DOD) point and if the batteries are discharged, that they are quickly charged to full capacity.

8.2.6 Backup Fuel Generator

The generator should be able to handle the charging of the batteries and the high priority loads that will run from the backup generator in case the batteries are discharged and the wind is low. The peak output power for the generator is equal to the batteries maximum required charge current added to the peak power that will be drawn by the house or high priority loads in low wind periods. The maximum charge for the specified batteries is 50 A per battery and can be seen in Figure B-3, Appendix B.

The batteries required charge current is suggested by [73], [74], [75] as C/8. C is the defined as the 20-hour-ampere-hour-rating of the batteries. This is 125 Ah. Thus the required charge current is 15.6 A. But one has to remember to multiply this by the four parallel coupled cells to get the total required charge current, which is 62.5 A. The peak power drawn for the battery charging is simply the total required charge current multiplied by the battery voltage, which results in a rating of 3 kW. By adding the 5 kW of peak power required by the high priority loads in low wind periods, the fuel generator's size is calculated as 8 kW minimum.

A 10 kVA generator (R20 000 from The Generator King [76]) was chosen as this will enable the house to run the required loads comfortably while charging the batteries. The generator specifications can be seen in Figure B-4, Appendix B. The fuel generator will have to be installed in a dry place. It will also require a silencer to dampen the noise or should be installed far away enough not to cause a disturbance to neighbours and one self. The oil level of the generator should be checked regularly. The connections should be checked for tightness, and the mechanical part of the generator should be checked for wear.

8.3 Total Wind Generator System Cost

The maintenance requirements discussed with each component in the above Section 8.2 could be done by one self, but it is recommended for a system of this size that a maintenance contract is invested in. Maintenance is very important to prolong the life of one's investment. Ian Woofenden [9] recommends that one spend 1% of the cost of the wind generator system after installation on maintenance per year. The installation cost is an estimate value based on findings by Ian Woofenden [9].

The batteries have to be replaced four times throughout the 20 year life cycle, which should counteract for a worst case scenario. The fuel price calculated for the fuel generator was as follows; the fuel generator can run for 8 hours on a 25 litre tank. Thus, running the generator for a day would require 75 litres of fuel.

For a 20 year period, with the generator only running 2 days of each month, the total fuel consumption was calculated as 36000 litres. The total cost of the fuel was then calculated on a 5.3% inflation rate (August 2011) for South Africa [77] and a current diesel price of R9.35 per litre (September 2011) [78] for the 20 year period. The price of the LP gas to be used by the stove is currently R21.26 per kg (October 2011) [79].

The following assumptions were made:

- That asset based finance for the setup cost of the wind turbine can be obtained over a 10 year period and is repayable on 120 equal payments.
- The interest rate for the loan used is 12%.
- The R20 000 setup cost is seen as a deposit value and is not part of the load value.
- To simplify the calculations, only the first set of batteries is financed by the loan. The second, third and fourth sets are added as cash components and it is the responsibility of the owner to either finance these extra sets through a loan or buy them cash.

The following was done to determine the kWh cost for this wind turbine. All future and current cash flows associated with the setup and maintenance of the wind turbine was projected. Where applicable, inflation was applied to determine the future value of certain commodities. The net cost of each future month was discounted back to a present value to make the kWh cost comparable to the present kWh cost of the local utility Eskom. The total net present value of the wind turbine over a 20 year operating period was divided by the total projected 20 year kWh output to determine a per unit kWh cost.

The current cost per kWh for the WGS was calculated to be R6.15 per kWh. This amounts to R3872.19 per month at 20.7 kWh per day. Table 8-3 shows a snapshot taken from the worksheet used to calculate the WGS cost up to the first required battery replacement.

Table 8-3 Total WGS Cost (Case 1)

Loan		Date	#months	Deposit	Loan	Batteries	Fuel	Gas	Maintenance	Total Cost	Discounted Value
Tower (15 m Guy Tower)	R 33,184.75	01-Jan-12	0	20,000.00	3,936.37	-	1,500.00	77.95	228.64	25,742.96	25,742.96
Generator, Hub and Blades (10 kW)	R 124,320.61	01-Feb-12	1	-	3,936.37	-	1,506.63	78.30	229.65	5,750.94	5,725.65
Controller (10 kW)	R 30,861.66	01-Mar-12	2	-	3,936.37	-	1,513.28	78.64	230.66	5,758.96	5,708.42
Batteries (16x 125Ah)	R 36,000.00	01-Apr-12	3	-	3,936.37	-	1,519.96	78.99	231.68	5,767.01	5,691.26
Fuel Generator (10 kVA)	R 25,000.00	01-May-12	4		3,936.37	-	1,526.68	79.34	232.71	5,775.09	5,674.18
Solar Geyser	R 20,000.00	01-Jun-12	5	-	3,936.37	-	1,533.42	79.69	233.73	5,783.21	5,657.17
Gas stove	R 5,000.00	01-Jul-12	6	-	3,936.37	-	1,540.19	80.04	234.77	5,791.37	5,640.24
	R 274,367.02	01-Aug-12	7	-	3,936.37	-	1,546.99	80.40	235.80	5,799.56	5,623.38
		01-Sep-12	8	-	3,936.37	-	1,553.83	80.75	236.84	5,807.79	5,606.60
Interest Rate	12%	01-Oct-12	9	-	3,936.37	-	1,560.69	81.11	237.89	5,816.06	5,589.89
Term (Years)	10	01-Nov-12	10	-	3,936.37	-	1,567.58	81.47	238.94	5,824.36	5,573.26
PMT	R 3,936.37	01-Dec-12	11	-	3,936.37	-	1,574.51	81.83	240.00	5,832.70	5,556.69
		01-Jan-13	12	-	3,936.37	-	1,581.46	82.19	241.06	5,841.07	5,540.20
Inflation	5.3%	01-Feb-13	13	-	3,936.37	-	1,588.44	82.55	242.12	5,849.48	5,523.78
Deposit	R 20,000.00	01-Mar-13	14	-	3,936.37	-	1,595.46	82.91	243.19	5,857.93	5,507.44
Maintenance	1%	01-Apr-13	15	-	3,936.37	-	1,602.51	83.28	244.26	5,866.42	5,491.17
Petrol	R 10.00	01-May-13	16	-	3,936.37	-	1,609.58	83.65	245.34	5,874.95	5,474.96
Fuel per month (liter)	150	01-Jun-13	17	-	3,936.37	-	1,616.69	84.02	246.43	5,883.51	5,458.83
Gas per Kg	R 21.26	01-Jul-13	18	-	3,936.37	-	1,623.83	84.39	247.51	5,892.11	5,442.77
Gas per month (kg)	3.67	01-Aug-13	19	-	3,936.37	-	1,631.01	84.76	248.61	5,900.75	5,426.78
		01-Sep-13	20	-	3,936.37	-	1,638.21	85.14	249.71	5,909.42	5,410.87
kWh output per day	20.7	01-Oct-13	21	-	3,936.37	-	1,645.45	85.51	250.81	5,918.14	5,395.02
Total kWh used (20 Years)	151,213.50	01-Nov-13	22	-	3,936.37	-	1,652.71	85.89	251.92	5,926.89	5,379.24
Total Discounted Value	R 929,243.62	01-Dec-13	23	-	3,936.37	-	1,660.01	86.27	253.03	5,935.68	5,363.53
Cost per kWh	**R 6.15**	01-Jan-14	24	-	3,936.37	-	1,667.34	86.65	254.15	5,944.51	5,347.89
		01-Feb-14	25	-	3,936.37	-	1,674.71	87.03	255.27	5,953.38	5,332.31
		01-Mar-14	26	-	3,936.37	-	1,682.10	87.42	256.40	5,962.29	5,316.81
		01-Apr-14	27	-	3,936.37	-	1,689.53	87.80	257.53	5,971.24	5,301.38
		01-May-14	28	-	3,936.37	-	1,697.00	88.19	258.67	5,980.22	5,286.01
		01-Jun-14	29	-	3,936.37	-	1,704.49	88.58	259.81	5,989.25	5,270.71
		01-Jul-14	30	-	3,936.37	-	1,712.02	88.97	260.96	5,998.32	5,255.48
		01-Aug-14	31	-	3,936.37	-	1,719.58	89.36	262.11	6,007.42	5,240.31
		01-Sep-14	32	-	3,936.37	-	1,727.18	89.76	263.27	6,016.57	5,225.21
		01-Oct-14	33	-	3,936.37	-	1,734.80	90.16	264.43	6,025.76	5,210.18
		01-Nov-14	34	-	3,936.37	-	1,742.47	90.55	265.60	6,034.99	5,195.21
		01-Dec-14	35	-	3,936.37	-	1,750.16	90.95	266.77	6,044.26	5,180.31
		01-Jan-15	36	-	3,936.37	-	1,757.89	91.36	267.95	6,053.57	5,165.48
		01-Feb-15	37	-	3,936.37	-	1,765.66	91.76	269.13	6,062.92	5,150.71
		01-Mar-15	38	-	3,936.37	-	1,773.45	92.16	270.32	6,072.31	5,136.00
		01-Apr-15	39	-	3,936.37	-	1,781.29	92.57	271.51	6,081.74	5,121.36
		01-May-15	40	-	3,936.37	-	1,789.15	92.98	272.71	6,091.22	5,106.79
		01-Jun-15	41	-	3,936.37	-	1,797.06	93.39	273.92	6,100.73	5,092.27
		01-Jul-15	42	-	3,936.37	-	1,804.99	93.80	275.13	6,110.29	5,077.83
		01-Aug-15	43	-	3,936.37	-	1,812.96	94.22	276.34	6,119.90	5,063.44
		01-Sep-15	44	-	3,936.37	-	1,820.97	94.63	277.56	6,129.54	5,049.12
		01-Oct-15	45	-	3,936.37	-	1,829.01	95.05	278.79	6,139.23	5,034.86
		01-Nov-15	46	-	3,936.37	-	1,837.09	95.47	280.02	6,148.96	5,020.67
		01-Dec-15	47	-	3,936.37	-	1,845.21	95.89	281.26	6,158.73	5,006.53
		01-Jan-16	48	-	3,936.37	-	1,853.36	96.32	282.50	6,168.54	4,992.46
		01-Feb-16	49	-	3,936.37	-	1,861.54	96.74	283.75	6,178.40	4,978.45
		01-Mar-16	50	-	3,936.37	-	1,869.76	97.17	285.00	6,188.30	4,964.51
		01-Apr-16	51	-	3,936.37	-	1,878.02	97.60	286.26	6,198.25	4,950.62
		01-May-16	52	-	3,936.37	-	1,886.32	98.03	287.52	6,208.24	4,936.80
		01-Jun-16	53	-	3,936.37	-	1,894.65	98.46	288.79	6,218.27	4,923.03
		01-Jul-16	54	-	3,936.37	-	1,903.02	98.90	290.07	6,228.35	4,909.33
		01-Aug-16	55	-	3,936.37	-	1,911.42	99.33	291.35	6,238.48	4,895.68
		01-Sep-16	56	-	3,936.37	-	1,919.86	99.77	292.64	6,248.64	4,882.10
		01-Oct-16	57	-	3,936.37	-	1,928.34	100.21	293.93	6,258.86	4,868.58
		01-Nov-16	58	-	3,936.37	-	1,936.86	100.66	295.23	6,269.11	4,855.11
		01-Dec-16	59	-	3,936.37	46,689.93	1,945.41	101.10	296.53	52,969.35	40,841.71
		01-Jan-17	60	-	3,936.37	-	1,954.01	101.55	297.84	6,289.76	4,828.36

The wind turbine generator, blades, hub, tower and controller is sourced from GW Store [80] and the prices can be seen in Table 8-3. The price for the solar geyser and stove can also be seen in Table 8-3 and is an average price obtained by looking at various supplier prices.

A few more cases will now be shown to give one a feeling of the effect the various parameters will have on the cost per kWh of the WGS. In the cases below the tower height is varied, this will have a direct effect on output power and also on the number of batteries required to store the extra energy. The days per month for the backup generator (thus the fuel required) was also reduced to see what effect this will have on the cost per kWh.

The snapshots of worksheets for case 2 to case 4 can be seen in Appendix B by referring to the relevant table seen in Table 8-4 below. Table 8-4 below shows a summary of the parameters changed for each case. A 3-D column chart can also be seen in Figure 8-2 in the summary of this section, which clearly shows the difference in price per kWh as the various parameters are changed.

For case 7 to case 9 it might happen that there is not enough wind available to recharge the batteries. The batteries cannot be run completely down as this will damage the batteries. Therefore, the user might have 2-3 days that there is no electrical energy available. This is a risk that could be taken in these cases and the user should be aware of this.

Table 8-4 Total WGS Cost Case Summary

Case	Tower Height (m)	Batteries	Backup Generator (Days)	Energy Output (kWh/Day)	R/kWh	Table
1	15	16	2	20.7	R 6.15	Table 8-3
2	20	18	2	25	R 5.26	Table B-1
3	25	20	2	28	R 4.83	Table B-2
4	15	16	1	20.7	R 4.95	Table B-3
5	20	18	1	25	R 4.27	Table B-4
6	25	20	1	28	R 3.95	Table B-5
7	15	16	0	20.7	R 3.51	Table B-6
8	20	18	0	25	R 3.08	Table B-7
9	25	20	0	28	R 2.88	Table B-8

As the tower height increases, the energy available increases and is required to be stored by including more batteries. Note that the energy required by the user stays the same throughout, and it is only the output energy that increases with tower height. One can see from Table 8-4 that the cost of the fuel is so high that even with a longer tower and more batteries the cost per kWh comes down. This is most apparent from the last three cases as there is no fuel needed.

8.4 WGS vs. Fuel Generator vs. Utility Cost

8.4.1 Total Fuel Generator Cost

The total cost for the fuel generator was calculated in the same way WGS's cost was calculated, except this time the generator would be running continuously for 20 years. The generator is a 6.5 kVA single-phase generator (R10 000 from Power Solutions [81]) with a 230 VAC output. It consumes 20 litres of fuel in 9.5 hours. This means the generator will consume 50.5 litres per day and 368842.1 litres of diesel in the 20 year period. The maintenance cost per year was calculated on 10% of the generator and installation cost as the generator is now running permanently and will require more maintenance. The cost per kWh for the fuel generator is calculated as R34.82 per kWh. Table 8-5 shows a snapshot taken from the worksheet used to calculate the generator's cost.

Table 8-5 Fuel Generator Cost

Loan				Date	#months	Deposit	Loan	Fuel	Gas	Maintenance	Total Cost	Discounted Value
Fuel Generator Single-phase (6.5 kVA)	R	10,000.00		01-Jan-12	0	10,000.00	502.15	21,329.69	77.95	291.67	32,201.46	32,201.46
Solar Geyser	R	20,000.00		01-Feb-12	1	-	502.15	21,423.89	78.30	292.95	22,297.29	22,199.25
Gas stove	R	5,000.00		01-Mar-12	2	-	502.15	21,518.52	78.64	294.25	22,393.56	22,197.05
	R	-		01-Apr-12	3	-	502.15	21,613.56	78.99	295.55	22,490.24	22,194.86
	R	-		01-May-12	4		502.15	21,709.02	79.34	296.85	22,587.36	22,192.68
	R	-		01-Jun-12	5	-	502.15	21,804.90	79.69	298.16	22,684.90	22,190.51
	R	-		01-Jul-12	6	-	502.15	21,901.20	80.04	299.48	22,782.87	22,188.35
	R	35,000.00		01-Aug-12	7	-	502.15	21,997.93	80.40	300.80	22,881.28	22,186.20
				01-Sep-12	8	-	502.15	22,095.09	80.75	302.13	22,980.12	22,184.06
Interest Rate		12%		01-Oct-12	9	-	502.15	22,192.68	81.11	303.47	23,079.40	22,181.93
Term (Years)		10		01-Nov-12	10	-	502.15	22,290.69	81.47	304.81	23,179.12	22,179.81
PMT	R	502.15		01-Dec-12	11	-	502.15	22,389.14	81.83	306.15	23,279.27	22,177.69
				01-Jan-13	12	-	502.15	22,488.03	82.19	307.51	23,379.87	22,175.59
Inflation		5.3%		01-Feb-13	13	-	502.15	22,587.35	82.55	308.86	23,480.91	22,173.50
Deposit	R	10,000.00		01-Mar-13	14	-	502.15	22,687.11	82.91	310.23	23,582.40	22,171.41
Maintenance		10%		01-Apr-13	15	-	502.15	22,787.31	83.28	311.60	23,684.34	22,169.34
Diesel	R	9.35		01-May-13	16	-	502.15	22,887.96	83.65	312.97	23,786.73	22,167.27
Fuel per month (liter)		2281.25		01-Jun-13	17	-	502.15	22,989.05	84.02	314.36	23,889.57	22,165.21
Gas per Kg	R	21.26		01-Jul-13	18	-	502.15	23,090.58	84.39	315.75	23,992.86	22,163.16
Gas per month (kg)		3.67		01-Aug-13	19	-	502.15	23,192.57	84.76	317.14	24,096.62	22,161.12
				01-Sep-13	20	-	502.15	23,295.00	85.14	318.54	24,200.82	22,159.09
kWh output per day		20.7		01-Oct-13	21	-	502.15	23,397.89	85.51	319.95	24,305.49	22,157.07
Total kWh used (20 Years)		151,213.50		01-Nov-13	22	-	502.15	23,501.23	85.89	321.36	24,410.62	22,155.06
Total Discounted Value	R	5,264,735.02		01-Dec-13	23	-	502.15	23,605.02	86.27	322.78	24,516.22	22,153.05
Cost per kWh	**R**	**34.82**		01-Jan-14	24	-	502.15	23,709.28	86.65	324.21	24,622.28	22,151.06
				01-Feb-14	25	-	502.15	23,813.99	87.03	325.64	24,728.81	22,149.07

8.4.2 Total Utility Cost

The current utility cost is R1.20 per kWh (2011/2012 Eskom [82] Tariffs and Charges Booklet). This cost can now be directly compared to the kWh cost of the WGS and the fuel generator system because these values where calculated by discounting the amounts to present values and is shown in the summary section that follows.

8.5 Summary

In this Chapter a WGS was specified and assembled. A cost assessment was done for a 20 year running period. Various cases were considered by varying the parameters of the WGS and the effect on the cost per kWh can be seen in Figure 8-2 below. The cost of the WGS was then compared to the cost of running the same home from a fuel generator and also to the cost of running the home from the utility. The cost per kWh for each type of energy source can be seen in Table 8-6 below.

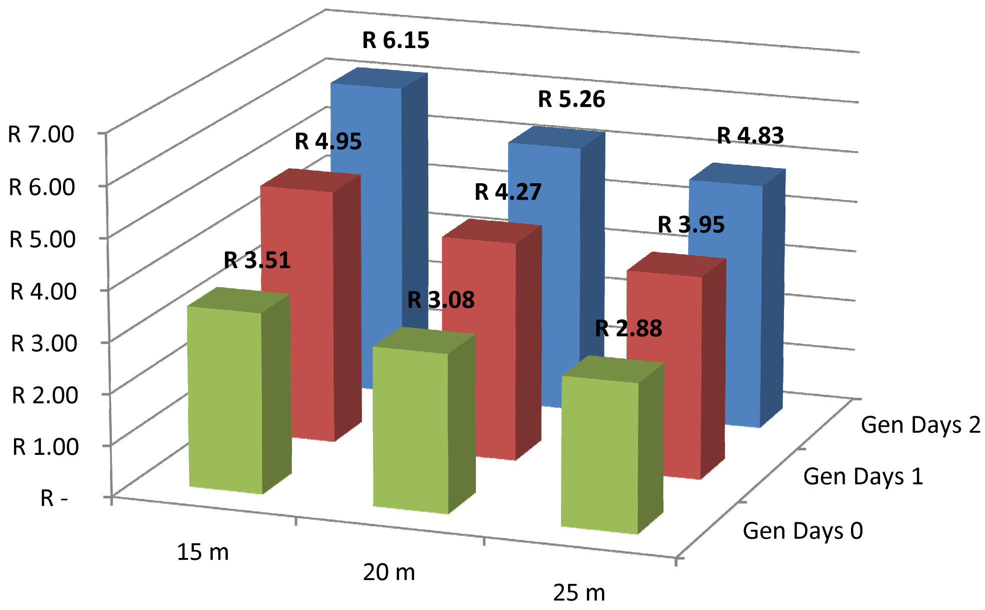


Figure 8-2 WGS Cost Summary

Table 8-6 Energy Source Cost Comparison

Energy Source	**R/kWh**
Wind Generator	R2.88 – R6.16
Fuel Generator	R 34.82
Utility	R 1.20

9 Conclusion

This chapter contains the conclusion to this dissertation. The objectives achieved in this dissertation are discussed, which is then followed with a short discussion on recommended future research. The chapter and dissertation is then concluded with a final thought on wind generator systems.

The world is currently in a state of energy usage awareness as the rate at which the world is currently generating environmentally unfriendly energy is alarming and the effects are starting to show through global warming, which has finally attracted the attention to inefficient energy usage that was long overdue. In South Africa, global warming has not yet had a direct effect on the population and there has generally been a delayed reaction to do something about the inefficient energy usage habits of the South African population. This delayed reaction has been shortened somewhat by problems for the local utility Eskom to supply the population with enough electrical energy.

The load shedding from 2003 onwards by Eskom made it apparent that there is a need to be independent of the local utility. The cost increases imposed by Eskom is another factor that further encouraged the need to do research on the viability of living off-grid in South Africa with a renewable energy source, which in this case was selected to be wind energy.

The primary concern of this document is to identify the components of the WGS that will make off-grid living possible. A WGS is a complex system, by breaking the WGS system down into smaller components, it helped to identify where there is place for improvement within the system, and this allowed optimising the conversion process from kinetic wind energy to electrical energy.

The research is started off by looking at how the efficient use of energy could initially lower the cost of the WGS to be installed. The energy usage of a small house with no energy efficiency strategy implemented, were analysed. The energy wasting appliances were identified and replaced by energy efficient appliances, or appliances that do not require electrical energy at all. The use time of energy hungry devices was shortened, and “phantom” loads were identified and removed by switching them off at the source, and not allowing them to go into standby mode, where they still consume energy although they appear switched off. It was concluded that by implementing a relatively simple efficient energy usage strategy, the cost of the required WGS could be greatly brought down.

The various components of the WGS are then sub-divided and each discussed in more detail. For the first component, the site, it is important to quantify the amount of wind power that is available. A site with no wind will not generate any energy even if the largest, most expensive WGS is used. The average wind speed is the most important parameter for the wind site as it contains historical data. The instantaneous wind speed does not contain any historical data, therefore, a site with a high wind speed, does not make it a good wind site if it only occurs three or four times a year. The profile of the site is also important, as tall structures close to the wind generator will disrupt the flow of the wind, directly impacting the quality of wind that the blades experience.

The tower is maybe one of the most overlooked, but important, components of the WGS. By increasing the tower height it is easily possible to increase the energy output of the WGS. The wind speeds are higher and more continuous. There are a few different tower types, each with their own advantages and disadvantages, but the main contribution to increase the wind generator output power is, the height above the ground and not what configuration of tower is selected. The configuration and height has a direct impact on the cost though.

The blades are the main energy collectors and are therefore responsible for converting the kinetic wind energy to mechanical energy that is required to turn the generator. The maximum energy that can be extracted by the blades from the wind is limited to physical laws of aerodynamics. Betz Law states that the maximum energy that can be taken from the wind without stalling the blades is 59%. The number of blades on a generator is determined by efficiency, cost and flicker. The cost and losses increase with more blades being added, but the flicker does decrease. The efficiency is decreased because the more blades that are added, the more the drag is introduced that creates turbulent air.

The generator is found in various different sizes and topologies. The generator topology that should be used depends largely on the required output power of the WGS. The permanent magnet generator (PMG) is mostly used in small WGS's that has power output requirements of up to 10 kW. This does not mean that the PMG cannot be used for larger WGS's. As better magnet technologies become available and the cost decreases, PMG might be used in larger WGS's. For larger WGS's, the induction machine is recommended as PMG of 10 kW and up becomes very expensive.

The generator has an AC voltage output that is variable in magnitude and frequency. The magnitude and frequency depends on the speed at which the generator is rotating, which is of course dependant on the wind.

The “wild” AC voltage is not suitable for battery charging, neither is it suitable to be used on home appliances because of it variability factor. Therefore the “wild” AC voltage must be converted to a DC voltage via a rectifier. Various rectifiers exist and are found in singe-phase and three-phase configurations. Two major groups of rectifiers, namely, uncontrolled and controlled exist. Controlled rectifiers are simple devices with a small component count. Controlled rectifiers are more complex and expensive and have a higher component count.

The DC voltage output from the rectifier is still variable in magnitude and depending on the generator design, this DC voltage could still be too high for battery charging or use on DC loads. A DC-DC converter, also known as a switch mode power supply (SMPS) is required to convert the high DC voltage to a lower DC voltage suitable for battery charging and use on DC loads. SMPS are more efficient than the linear type of voltage regulator but are also more complex and has a higher component count and cost. The efficiency factor outweighs the linear regulators by far, and even though the SMPS has a high cost and component count, it is the preferred device to use. It allows for optimal energy conversion in WGS.

The DC output voltage of the DC-DC converter is now suitable for battery charging, but to be able to use it on home appliances, it is required to be converted back to an AC voltage with a magnitude of 230V and a frequency of 50 Hz. This is accomplished by using a DC-AC converter (inverter) that is usually not directly connected to the DC-DC converter output, but rather to the batteries output as it serves as a buffer when the wind is low; therefore it is a continuous DC source to the DC-AC converter. Various types of inverter technologies exist and are described in terms of the output wave form. The first inverters called square wave inverters had a square wave output and not the required smooth square wave output. This was adequate at the time, but was very inefficient. The square wave inverter was then modified to be smoother, and so the modified square wave inverter came into existence. It is more efficient than a square wave inverter, but the waveform output is still not the correct sine waveform required by today’s home appliances. A sine wave inverter or pure sine wave inverter is the latest inverter technology available today and is also the recommended one to use. The output waveform is near sinusoidal and in some cases better than the waveform output by the local utility.

As was said, the batteries serve as a buffer and a backup to the variable supply from the wind generator. The batteries are one of the more expensive components of the WGS, and must therefore be correctly charged and well maintained to prolong their usable life. Various types of battery technologies exist today, but the battery best suited for WGS’s is deep-cycle lead-acid batteries. Correctly charging these batteries is very important as it will prolong the batteries life.

A four stage charge algorithm, which is widely used for lead-acid battery charging, is recommended. The battery charger itself is a very important component as it has to make sure the battery is not under or overcharged as this will drastically shorten the batteries life.

The main focus of this document is to determine if it is viable for a home to be supplied of electrical energy by an off-grid WGS. A WGS is assembled according to a theoretical specification (based on real world parameters) for a site in Johannesburg, South Africa. A typical house with no energy efficiency strategy is specified. The house’s energy usage was brought down by making use of the findings on efficient energy usage in Section 2.2. This was done to reduce the size and therefore the cost of the WGS. The major components of the WGS, the tower, the wind generator, the controller (AC-DC-AC),the batteries and backup fuel generator are then sized for this specific off-grid WGS. The components are selected based on their performance characteristics in terms of cost, efficiency and maintenance requirements.

A long term cost analysis of a period of 20 years is done on the off-grid WGS that is assembled. The WGS included a maintenance contract for the 20 year period that is very important to increase the life of the WGS. The cost of the WGS per kWh is then compared to the cost per kWh for supplying the same home with electrical energy from a fuel generator, and is also compared to the cost per kWh for supplying the same home with electrical energy directly from the utility for the same period of 20 years.

9.1 Objectives Achieved

The primary objective was to determine the viability of living off-grid with a sole supply of energy being self-generated via a WGS. During the course of the research the various components that make up the off-grid WGS were identified and each component had to be viewed in terms of available technology and performance to enable one to identify areas where the energy output of the WGS could be optimised. This was also done to, in the end, correctly size and select the required components for an efficient, maintainable and possibly viable off-grid WGS solution.

It was found that supplying a off-grid home with wind energy for a period of 20 years is 140% - 413% more expensive than supplying the home from the local utility, but it is by far not as expensive as supplying the home from a fuel generator for the same period.

9.2 Future Research

It is proposed that more research should be done on the energy use and efficient energy use of an average home. The research on increasing the efficiency of the inverters, batteries and the battery charger of a WGS could be increased as these components were only shortly discussed in this dissertation. Each of these components can be a research field of its own and should possibly be done as separate research projects.

Finally, in this dissertation there was looked at the viability of living off-grid with a WGS only. The research could be expanded to include a combination of wind and solar energy off-grid living. The solar energy will help to decrease the size of the WGS, and therefore the cost of the WGS. Solar energy is also not as maintenance intense as WGS.

9.3 Final thoughts on WGS

Although the WGS might not seem like a viable option when compared to a home being supplied of electrical energy from the utility, one has to remember that there is a hidden cost from the utility. This cost will be the price we, as humans, will have to pay to try and repair the damage that has already been done, and will most definitely continue to be done, to the environment unless drastic measures are taken to change the inefficient use of energy. It is ultimately one's "green" conscious that will determine if living off-grid with a WGS is viable or not and what the price is that one is willing to pay for the damage being done to the environment.

APPENDIX

Appendix A

Table A-1 Energy usage of small sized home (Home A-No Efficiency)

QTY	Appliance	Use(hours)	Rated Power (W)	Total Power(W)	Energy Usage(Wh)
			Main Bedroom		
QTY	**Appliance**	**Use(hours)**	**Rated Power (W)**	**Total Power(W)**	**Energy Usage(Wh)**
1	Hair Dryer	4	1800	1800	7200
1	Straighter	2	250	250	500
2	Bed Side Lamp	4	15	30	120
2	Cell phone Charger	8	6	12	96
4	Spot Light	10	50	200	2000
				Total Energy Usage/Month	**9916**
			Second Bedroom		
QTY	**Appliance**	**Use(hours)**	**Rated Power (W)**	**Total Power(W)**	**Energy Usage(Wh)**
1	Bed Side Lamp	2	15	15	30
1	PC (Normal)	10	500	500	5000
1	PC (Standby)	710	5	5	3550
2	19" LCD Monitor (Normal)	10	50	100	1000
2	19" LCD Monitor (Standby)	710	2	4	2840
1	Laser Printer (Normal)	8	345	345	2760
1	Laser Printer (Standby)	712	6	6	4272
1	Inkjet Printer (Normal)	8	100	100	800
1	Inkjet Printer (Standby)	712	5	5	3560
1	ADSL Router	720	20	20	14400
1	Clothing Iron	8	1000	1000	8000
1	Spot Light	5	50	50	250
				Total Energy Usage/Month	**46462**
			Main & Second Bathroom		
QTY	**Appliance**	**Use(hours)**	**Rated Power (W)**	**Total Power(W)**	**Energy Usage(Wh)**
1	Electrical Geyser	150	2000	2000	300000
2	Spot Light	10	50	100	1000
2	Light	10	60	120	1200
				Total Energy Usage/Month	**302200**
			TV Room		
QTY	**Appliance**	**Use(hours)**	**Rated Power (W)**	**Total Power(W)**	**Energy Usage(Wh)**
3	Floor Standing Lights	20	50	150	3000
1	Aquarium Heater	200	200	200	40000
2	Aquarium Lights	480	28	56	26880
1	Aquarium Pump	744	50	50	37200
1	MC-PC(Normal)	120	600	600	72000
1	MC-PC(Standby)	600	10	10	6000
1	Home Theatre System (Normal)	124	60	60	7440
1	Home Theatre System (Standby)	596	15	15	8940
1	40" LCD TV (Normal)	124	200	200	24800
1	40" LCD TV (Standby)	596	10	10	5960
1	DVD/HDD Recorder (Normal)	8	200	200	1600
1	DVD/HDD Recorder (Standby)	712	10	10	7120
1	DSTV HD PVR (Normal)	124	200	200	24800
1	DSTV HD PVR (Standby)	596	20	20	11920
1	DSTV SD (Normal)	2	100	100	200
1	DSTV SD (Standby)	718	5	5	3590
4	Spot Light	5	50	200	1000
				Total Energy Usage/Month	**282450**

Dining Room					
QTY	Appliance	Use(hours)	Rated Power (W)	Total Power(W)	Energy Usage(Wh)
1	Cordless Phone	720	10	10	7200
1	Tumble Dryer	20	2000	2000	40000
2	Spot Light	5	50	100	500
				Total Energy Usage/Month	**47700**
Kitchen					
QTY	Appliance	Use(hours)	Rated Power (W)	Total Power(W)	Energy Usage(Wh)
1	Fridge/Freezer Combo	360	300	300	108000
1	Stove/Oven	30	2000	2000	60000
1	Kettle	15	2000	2000	30000
1	Steamer	5	600	600	3000
1	Microwave (Normal)	10	1500	1500	15000
1	Microwave (Standby)	710	10	10	7100
1	Dishwasher (Normal)	30	500	500	15000
1	Dishwasher (Standby)	690	10	10	6900
3	Spot Light	10	50	150	1500
				Total Energy Usage/Month	**246500**
Garage with Automated Double Door					
QTY	Appliance	Use(hours)	Rated Power (W)	Total Power(W)	Energy Usage(Wh)
1	Fluorescent Light	2	50	50	100
1	Garage Door Motor	2	500	500	1000
4	Outside Light	20	60	240	4800
				Total Energy Usage/Month	**5900**
				Total Energy Usage/Month	**941128**
				kWh	**941.128**

Table A-2 Energy usage of small sized home (Home A-No Efficiency)

Nr	Date	Energy Usage (kWh)
1	2009/03/25	705.11
2	2009/04/25	758.69
3	2009/05/25	854.96
4	2009/06/25	928.34
5	2009/07/25	924.13
6	2009/08/25	915.36
7	2009/09/25	865.55
8	2009/10/25	755.63
9	2009/11/25	723.21
10	2009/12/25	711.32
11	2010/01/25	691.87
12	2010/02/25	656.85
	Average	**790.92**

Table A-3 Energy usage of small sized home (Home B-Efficient)

Main Bedroom					
QTY	**Appliance**	**Use(hours)**	**Rated Power (W)**	**Total Power(W)**	**Energy Usage(Wh)**
1	Hair Dryer	2	1000	1000	2000
1	Straighter	2	125	125	250
2	Bed Side Lamp	4	15	30	120
2	Cell phone Charger	8	6	12	96
4	LED Spot Light	10	3	12	120
				Total Energy Usage/Month	**2586**
Second Bedroom					
QTY	**Appliance**	**Use(hours)**	**Rated Power (W)**	**Total Power(W)**	**Energy Usage(Wh)**
1	Bed Side Lamp	2	15	15	30
1	PC (Normal)	10	500	500	5000
1	PC (Standby)	0	5	5	0
2	19" LCD Monitor (Normal)	10	26	52	520
2	19" LCD Monitor (Standby)	0	2	4	0
1	Laser Printer (Normal)	2	345	345	690
1	Laser Printer (Standby)		5	5	0
1	Inkjet Printer (Normal)	2	20	20	40
1	Inkjet Printer (Standby)	0	5	5	0
1	ADSL Router	10	20	20	200
1	Clothing Iron	2	1000	1000	2000
1	LED Spot Light	5	3	3	15
				Total Energy Usage/Month	**8495**
Main & Second Bathroom					
QTY	**Appliance**	**Use(hours)**	**Rated Power (W)**	**Total Power(W)**	**Energy Usage(Wh)**
1	Gas Geyser	10	0	0	0
2	LED Spot Light	10	3	6	60
2	Light	10	15	30	300
				Total Energy Usage/Month	**360**
TV Room					
QTY	**Appliance**	**Use(hours)**	**Rated Power (W)**	**Total Power(W)**	**Energy Usage(Wh)**
3	Floor Standing Lights	20	10	30	600
1	Aquarium Heater	360	100	100	36000
2	Aquarium Lights	480	28	56	26880
1	Aquarium Pump	744	25	25	18600
1	MC-PC(Normal)	32	600	600	19200
1	MC-PC(Standby)	0	10	10	0
1	Home Theatre System (Normal)	124	60	60	7440
1	Home Theatre System (Standby)	0	15	15	0
1	40" LCD TV (Normal)	60	150	150	9000
1	40" LCD TV (Standby)	0	10	10	0
1	DVD/HDD Recorder (Normal)	8	200	200	1600
1	DVD/HDD Recorder (Standby)	0	10	10	0
1	DSTV HD PVR (Normal)	60	200	200	12000
1	DSTV HD PVR (Standby)	0	20	20	0
1	DSTV SD (Normal)	2	100	100	200
1	DSTV SD (Standby)	0	5	5	0
4	Spot Light	5	3	12	60
				Total Energy Usage/Month	**131580**
Dining Room					
QTY	**Appliance**	**Use(hours)**	**Rated Power (W)**	**Total Power(W)**	**Energy Usage(Wh)**
1	Cordless Phone	720	10	10	7200
1	Air Dry Outside(Tumble Dryer)	20	0	0	0
2	Spot Light	5	3	6	30
				Total Energy Usage/Month	**7230**

Kitchen					
QTY	**Appliance**	**Use(hours)**	**Rated Power (W)**	**Total Power(W)**	**Energy Usage(Wh)**
1	Gas Fridge/Freezer Combo	720	0	0	0
1	Gas Stove/Oven	30	0	0	0
1	Gas Kettle	15	0	0	0
1	Steamer	5	0	0	0
1	Microwave (Normal)	5	1500	1500	7500
1	Microwave (Standby)	0	10	10	0
1	Dishwasher (Normal)	16	500	500	8000
1	Dishwasher (Standby)	0	10	10	0
3	LED Spotlight	10	3	9	90
				Total Energy Usage/Month	**15590**
Garage with Automated Double Door					
QTY	**Appliance**	**Use(hours)**	**Rated Power (W)**	**Total Power(W)**	**Energy Usage(Wh)**
1	Fluorescent Light	2	50	50	100
1	Garage Door Motor	2	500	500	1000
4	Outside Light	20	15	60	1200
				Total Energy Usage/Month	**2300**
				Total Energy Usage/Month	**168141**
				kWh	**168.141**

Appendix B

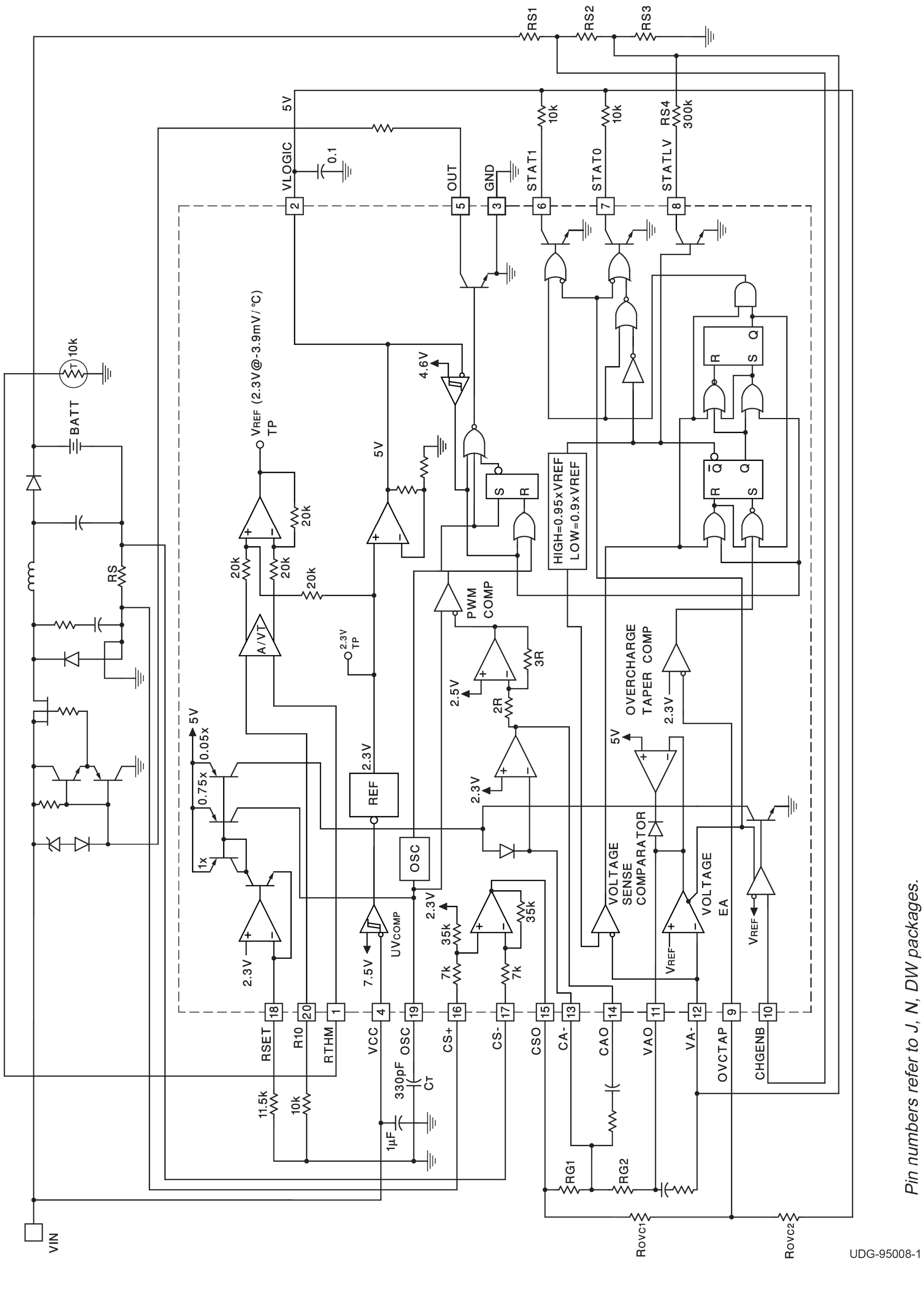


Figure B-1 Typical Application Circuit for a Lead-acid Battery Charger [67]

Table B-1 Total WGS Cost (Case 2)

Loan			Date	#months	Deposit	Loan	Batteries	Fuel	Gas	Maintenance	Total Cost	Discounted Value
Tower (20 m Guy Tower)	R	40,000.00	01-Jan-12	0	20,000.00	4,098.71	-	1,500.00	77.95	238.07	25,914.73	25,914.73
Generator, Hub and Blades (10 kW)	R	124,320.61	01-Feb-12	1	-	4,098.71	-	1,506.63	78.30	239.12	5,922.75	5,896.71
Controller (10 kW)	R	30,861.66	01-Mar-12	2	-	4,098.71	-	1,513.28	78.64	240.18	5,930.81	5,878.77
Batteries (18x 125Ah)	R	40,500.00	01-Apr-12	3	-	4,098.71	-	1,519.96	78.99	241.24	5,938.90	5,860.90
Fuel Generator (10 kVA)	R	25,000.00	01-May-12	4		4,098.71	-	1,526.68	79.34	242.30	5,947.03	5,843.11
Solar Geyser	R	20,000.00	01-Jun-12	5	-	4,098.71	-	1,533.42	79.69	243.37	5,955.19	5,825.41
Gas stove	R	5,000.00	01-Jul-12	6	-	4,098.71	-	1,540.19	80.04	244.45	5,963.39	5,807.78
	R	285,682.27	01-Aug-12	7	-	4,098.71	-	1,546.99	80.40	245.53	5,971.63	5,790.22
			01-Sep-12	8	-	4,098.71	-	1,553.83	80.75	246.61	5,979.90	5,772.75
Interest Rate		12%	01-Oct-12	9	-	4,098.71	-	1,560.69	81.11	247.70	5,988.21	5,755.35
Term (Years)		10	01-Nov-12	10	-	4,098.71	-	1,567.58	81.47	248.79	5,996.55	5,738.03
PMT	R	4,098.71	01-Dec-12	11	-	4,098.71	-	1,574.51	81.83	249.89	6,004.94	5,720.78
			01-Jan-13	12	-	4,098.71	-	1,581.46	82.19	251.00	6,013.35	5,703.61
Inflation		5.3%	01-Feb-13	13	-	4,098.71	-	1,588.44	82.55	252.11	6,021.81	5,686.52
Deposit	R	20,000.00	01-Mar-13	14	-	4,098.71	-	1,595.46	82.91	253.22	6,030.30	5,669.50
Maintenance		1%	01-Apr-13	15	-	4,098.71	-	1,602.51	83.28	254.34	6,038.84	5,652.55
Petrol	R	10.00	01-May-13	16	-	4,098.71	-	1,609.58	83.65	255.46	6,047.40	5,635.68
Fuel per month (liter)		150	01-Jun-13	17	-	4,098.71	-	1,616.69	84.02	256.59	6,056.01	5,618.89
Gas per Kg	R	21.26	01-Jul-13	18	-	4,098.71	-	1,623.83	84.39	257.72	6,064.66	5,602.16
Gas per month (kg)		3.67	01-Aug-13	19	-	4,098.71	-	1,631.01	84.76	258.86	6,073.34	5,585.52
			01-Sep-13	20	-	4,098.71	-	1,638.21	85.14	260.00	6,082.06	5,568.94
kWh output per day		25	01-Oct-13	21	-	4,098.71	-	1,645.45	85.51	261.15	6,090.82	5,552.44
Total kWh used (20 Years)		182,625.00	01-Nov-13	22	-	4,098.71	-	1,652.71	85.89	262.31	6,099.62	5,536.01
Total Discounted Value	R	960,169.50	01-Dec-13	23	-	4,098.71	-	1,660.01	86.27	263.46	6,108.46	5,519.65
Cost per kWh	**R**	**5.26**	01-Jan-14	24	-	4,098.71	-	1,667.34	86.65	264.63	6,117.33	5,503.36
			01-Feb-14	25	-	4,098.71	-	1,674.71	87.03	265.80	6,126.25	5,487.15

Table B-2 Total WGS Cost (Case 3)

Loan			Date	#months	Deposit	Loan	Batteries	Fuel	Gas	Maintenance	Total Cost	Discounted Value
Tower (25 m Guy Tower)	R	45,000.00	01-Jan-12	0	20,000.00	4,235.01	-	1,500.00	77.95	245.99	26,058.95	26,058.95
Generator, Hub and Blades (10 kW)	R	124,320.61	01-Feb-12	1	-	4,235.01	-	1,506.63	78.30	247.07	6,067.00	6,040.32
Controller (10 kW)	R	30,861.66	01-Mar-12	2	-	4,235.01	-	1,513.28	78.64	248.16	6,075.09	6,021.78
Batteries (20x 125Ah)	R	45,000.00	01-Apr-12	3	-	4,235.01	-	1,519.96	78.99	249.26	6,083.22	6,003.32
Fuel Generator (10 kVA)	R	25,000.00	01-May-12	4		4,235.01	-	1,526.68	79.34	250.36	6,091.38	5,984.95
Solar Geyser	R	20,000.00	01-Jun-12	5	-	4,235.01	-	1,533.42	79.69	251.47	6,099.58	5,966.65
Gas stove	R	5,000.00	01-Jul-12	6	-	4,235.01	-	1,540.19	80.04	252.58	6,107.82	5,948.43
	R	295,182.27	01-Aug-12	7	-	4,235.01	-	1,546.99	80.40	253.69	6,116.09	5,930.30
			01-Sep-12	8	-	4,235.01	-	1,553.83	80.75	254.81	6,124.40	5,912.24
Interest Rate		12%	01-Oct-12	9	-	4,235.01	-	1,560.69	81.11	255.94	6,132.74	5,894.26
Term (Years)		10	01-Nov-12	10	-	4,235.01	-	1,567.58	81.47	257.07	6,141.12	5,876.36
PMT	R	4,235.01	01-Dec-12	11	-	4,235.01	-	1,574.51	81.83	258.20	6,149.54	5,858.55
			01-Jan-13	12	-	4,235.01	-	1,581.46	82.19	259.34	6,158.00	5,840.80
Inflation		5.3%	01-Feb-13	13	-	4,235.01	-	1,588.44	82.55	260.49	6,166.49	5,823.14
Deposit	R	20,000.00	01-Mar-13	14	-	4,235.01	-	1,595.46	82.91	261.64	6,175.02	5,805.56
Maintenance		1%	01-Apr-13	15	-	4,235.01	-	1,602.51	83.28	262.80	6,183.59	5,788.05
Petrol	R	10.00	01-May-13	16	-	4,235.01	-	1,609.58	83.65	263.96	6,192.20	5,770.62
Fuel per month (liter)		150	01-Jun-13	17	-	4,235.01	-	1,616.69	84.02	265.12	6,200.84	5,753.26
Gas per Kg	R	21.26	01-Jul-13	18	-	4,235.01	-	1,623.83	84.39	266.29	6,209.52	5,735.98
Gas per month (kg)		3.67	01-Aug-13	19	-	4,235.01	-	1,631.01	84.76	267.47	6,218.24	5,718.78
			01-Sep-13	20	-	4,235.01	-	1,638.21	85.14	268.65	6,227.00	5,701.65
kWh output per day		28	01-Oct-13	21	-	4,235.01	-	1,645.45	85.51	269.84	6,235.80	5,684.60
Total kWh used (20 Years)		204,540.00	01-Nov-13	22	-	4,235.01	-	1,652.71	85.89	271.03	6,244.64	5,667.63
Total Discounted Value	R	988,299.83	01-Dec-13	23	-	4,235.01	-	1,660.01	86.27	272.23	6,253.51	5,650.73
Cost per kWh	**R**	**4.83**	01-Jan-14	24	-	4,235.01	-	1,667.34	86.65	273.43	6,262.43	5,633.90
			01-Feb-14	25	-	4,235.01	-	1,674.71	87.03	274.64	6,271.38	5,617.14

Table B-3 Total WGS Cost (Case 4)

Loan			Date	#months	Deposit	Loan	Batteries	Fuel	Gas	Maintenance	Total Cost	Discounted Value
Tower (15 m Guy Tower)	R 33,184.75		01-Jan-12	0	20,000.00	3,936.37	-	750.00	77.95	228.64	24,992.96	24,992.96
Generator, Hub and Blades (10 kW)	R 124,320.61		01-Feb-12	1	-	3,936.37	-	753.31	78.30	229.65	4,997.63	4,975.65
Controller (10 kW)	R 30,861.66		01-Mar-12	2	-	3,936.37	-	756.64	78.64	230.66	5,002.32	4,958.42
Batteries (16x 125Ah)	R 36,000.00		01-Apr-12	3	-	3,936.37	-	759.98	78.99	231.68	5,007.02	4,941.26
Fuel Generator (10 kVA)	R 25,000.00		01-May-12	4		3,936.37	-	763.34	79.34	232.71	5,011.75	4,924.18
Solar Geyser	R 20,000.00		01-Jun-12	5	-	3,936.37	-	766.71	79.69	233.73	5,016.50	4,907.17
Gas stove	R 5,000.00		01-Jul-12	6	-	3,936.37	-	770.10	80.04	234.77	5,021.27	4,890.24
	R 274,367.02		01-Aug-12	7	-	3,936.37	-	773.50	80.40	235.80	5,026.06	4,873.38
			01-Sep-12	8	-	3,936.37	-	776.91	80.75	236.84	5,030.88	4,856.60
Interest Rate	12%		01-Oct-12	9	-	3,936.37	-	780.34	81.11	237.89	5,035.71	4,839.89
Term (Years)	10		01-Nov-12	10	-	3,936.37	-	783.79	81.47	238.94	5,040.57	4,823.26
PMT	R 3,936.37		01-Dec-12	11	-	3,936.37	-	787.25	81.83	240.00	5,045.44	4,806.69
			01-Jan-13	12	-	3,936.37	-	790.73	82.19	241.06	5,050.34	4,790.20
Inflation	5.3%		01-Feb-13	13	-	3,936.37	-	794.22	82.55	242.12	5,055.26	4,773.78
Deposit	R 20,000.00		01-Mar-13	14	-	3,936.37	-	797.73	82.91	243.19	5,060.20	4,757.44
Maintenance	1%		01-Apr-13	15	-	3,936.37	-	801.25	83.28	244.26	5,065.17	4,741.17
Petrol	R 10.00		01-May-13	16	-	3,936.37	-	804.79	83.65	245.34	5,070.15	4,724.96
Fuel per month (liter)	75		01-Jun-13	17	-	3,936.37	-	808.35	84.02	246.43	5,075.16	4,708.83
Gas per Kg	R 21.26		01-Jul-13	18	-	3,936.37	-	811.92	84.39	247.51	5,080.19	4,692.77
Gas per month (kg)	3.67		01-Aug-13	19	-	3,936.37	-	815.50	84.76	248.61	5,085.24	4,676.78
			01-Sep-13	20	-	3,936.37	-	819.10	85.14	249.71	5,090.32	4,660.87
kWh output per day	20.7		01-Oct-13	21	-	3,936.37	-	822.72	85.51	250.81	5,095.41	4,645.02
Total kWh used (20 Years)	151,213.50		01-Nov-13	22	-	3,936.37	-	826.36	85.89	251.92	5,100.53	4,629.24
Total Discounted Value	R 749,243.62		01-Dec-13	23	-	3,936.37	-	830.01	86.27	253.03	5,105.67	4,613.53
Cost per kWh	**R 4.95**		01-Jan-14	24	-	3,936.37	-	833.67	86.65	254.15	5,110.84	4,597.89
			01-Feb-14	25	-	3,936.37	-	837.35	87.03	255.27	5,116.03	4,582.31

Table B-4 Total WGS Cost (Case 5)

Loan			Date	#months	Deposit	Loan	Batteries	Fuel	Gas	Maintenance	Total Cost	Discounted Value
Tower (20 m Guy Tower)	R 40,000.00		01-Jan-12	0	20,000.00	4,098.71	-	750.00	77.95	238.07	25,164.73	25,164.73
Generator, Hub and Blades (10 kW)	R 124,320.61		01-Feb-12	1	-	4,098.71	-	753.31	78.30	239.12	5,169.44	5,146.71
Controller (10 kW)	R 30,861.66		01-Mar-12	2	-	4,098.71	-	756.64	78.64	240.18	5,174.17	5,128.77
Batteries (18x 125Ah)	R 40,500.00		01-Apr-12	3	-	4,098.71	-	759.98	78.99	241.24	5,178.92	5,110.90
Fuel Generator (10 kVA)	R 25,000.00		01-May-12	4		4,098.71	-	763.34	79.34	242.30	5,183.69	5,093.11
Solar Geyser	R 20,000.00		01-Jun-12	5	-	4,098.71	-	766.71	79.69	243.37	5,188.48	5,075.41
Gas stove	R 5,000.00		01-Jul-12	6	-	4,098.71	-	770.10	80.04	244.45	5,193.30	5,057.78
	R 285,682.27		01-Aug-12	7	-	4,098.71	-	773.50	80.40	245.53	5,198.13	5,040.22
			01-Sep-12	8	-	4,098.71	-	776.91	80.75	246.61	5,202.99	5,022.75
Interest Rate	12%		01-Oct-12	9	-	4,098.71	-	780.34	81.11	247.70	5,207.86	5,005.35
Term (Years)	10		01-Nov-12	10	-	4,098.71	-	783.79	81.47	248.79	5,212.76	4,988.03
PMT	R 4,098.71		01-Dec-12	11	-	4,098.71	-	787.25	81.83	249.89	5,217.68	4,970.78
			01-Jan-13	12	-	4,098.71	-	790.73	82.19	251.00	5,222.62	4,953.61
Inflation	5.3%		01-Feb-13	13	-	4,098.71	-	794.22	82.55	252.11	5,227.59	4,936.52
Deposit	R 20,000.00		01-Mar-13	14	-	4,098.71	-	797.73	82.91	253.22	5,232.57	4,919.50
Maintenance	1%		01-Apr-13	15	-	4,098.71	-	801.25	83.28	254.34	5,237.58	4,902.55
Petrol	R 10.00		01-May-13	16	-	4,098.71	-	804.79	83.65	255.46	5,242.61	4,885.68
Fuel per month (liter)	75		01-Jun-13	17	-	4,098.71	-	808.35	84.02	256.59	5,247.66	4,868.89
Gas per Kg	R 21.26		01-Jul-13	18	-	4,098.71	-	811.92	84.39	257.72	5,252.74	4,852.16
Gas per month (kg)	3.67		01-Aug-13	19	-	4,098.71	-	815.50	84.76	258.86	5,257.84	4,835.52
			01-Sep-13	20	-	4,098.71	-	819.10	85.14	260.00	5,262.96	4,818.94
kWh output per day	25		01-Oct-13	21	-	4,098.71	-	822.72	85.51	261.15	5,268.10	4,802.44
Total kWh used (20 Years)	182,625.00		01-Nov-13	22	-	4,098.71	-	826.36	85.89	262.31	5,273.26	4,786.01
Total Discounted Value	R 780,169.50		01-Dec-13	23	-	4,098.71	-	830.01	86.27	263.46	5,278.45	4,769.65
Cost per kWh	**R 4.27**		01-Jan-14	24	-	4,098.71	-	833.67	86.65	264.63	5,283.66	4,753.36
			01-Feb-14	25	-	4,098.71	-	837.35	87.03	265.80	5,288.89	4,737.15

Table B-5 Total WGS Cost (Case 6)

Loan			Date	#months	Deposit	Loan	Batteries	Fuel	Gas	Maintenance	Total Cost	Discounted Value
Tower (25 m Guy Tower)	R 45,000.00		01-Jan-12	0	20,000.00	4,235.01	-	750.00	77.95	245.99	25,308.95	25,308.95
Generator, Hub and Blades (10 kW)	R 124,320.61		01-Feb-12	1	-	4,235.01	-	753.31	78.30	247.07	5,313.69	5,290.32
Controller (10 kW)	R 30,861.66		01-Mar-12	2	-	4,235.01	-	756.64	78.64	248.16	5,318.45	5,271.78
Batteries (20x 125Ah)	R 45,000.00		01-Apr-12	3	-	4,235.01	-	759.98	78.99	249.26	5,323.24	5,253.32
Fuel Generator (10 kVA)	R 25,000.00		01-May-12	4		4,235.01	-	763.34	79.34	250.36	5,328.05	5,234.95
Solar Geyser	R 20,000.00		01-Jun-12	5	-	4,235.01	-	766.71	79.69	251.47	5,332.87	5,216.65
Gas stove	R 5,000.00		01-Jul-12	6	-	4,235.01	-	770.10	80.04	252.58	5,337.72	5,198.43
	R 295,182.27		01-Aug-12	7	-	4,235.01	-	773.50	80.40	253.69	5,342.59	5,180.30
			01-Sep-12	8	-	4,235.01	-	776.91	80.75	254.81	5,347.48	5,162.24
Interest Rate	12%		01-Oct-12	9	-	4,235.01	-	780.34	81.11	255.94	5,352.40	5,144.26
Term (Years)	10		01-Nov-12	10	-	4,235.01	-	783.79	81.47	257.07	5,357.33	5,126.36
PMT	R 4,235.01		01-Dec-12	11	-	4,235.01	-	787.25	81.83	258.20	5,362.29	5,108.55
			01-Jan-13	12	-	4,235.01	-	790.73	82.19	259.34	5,367.27	5,090.80
Inflation	5.3%		01-Feb-13	13	-	4,235.01	-	794.22	82.55	260.49	5,372.27	5,073.14
Deposit	R 20,000.00		01-Mar-13	14	-	4,235.01	-	797.73	82.91	261.64	5,377.29	5,055.56
Maintenance	1%		01-Apr-13	15	-	4,235.01	-	801.25	83.28	262.80	5,382.34	5,038.05
Petrol	R 10.00		01-May-13	16	-	4,235.01	-	804.79	83.65	263.96	5,387.40	5,020.62
Fuel per month (liter)	75		01-Jun-13	17	-	4,235.01	-	808.35	84.02	265.12	5,392.49	5,003.26
Gas per Kg	R 21.26		01-Jul-13	18	-	4,235.01	-	811.92	84.39	266.29	5,397.61	4,985.98
Gas per month (kg)	3.67		01-Aug-13	19	-	4,235.01	-	815.50	84.76	267.47	5,402.74	4,968.78
			01-Sep-13	20	-	4,235.01	-	819.10	85.14	268.65	5,407.90	4,951.65
kWh output per day	28		01-Oct-13	21	-	4,235.01	-	822.72	85.51	269.84	5,413.08	4,934.60
Total kWh used (20 Years)	204,540.00		01-Nov-13	22	-	4,235.01	-	826.36	85.89	271.03	5,418.28	4,917.63
Total Discounted Value	R 808,299.83		01-Dec-13	23	-	4,235.01	-	830.01	86.27	272.23	5,423.51	4,900.73
Cost per kWh	**R 3.95**		01-Jan-14	24	-	4,235.01	-	833.67	86.65	273.43	5,428.76	4,883.90
			01-Feb-14	25	-	4,235.01	-	837.35	87.03	274.64	5,434.03	4,867.14

Table B-6 Total WGS Cost (Case 7)

Loan			Date	#months	Deposit	Loan	Batteries	Fuel	Gas	Maintenance	Total Cost	Discounted Value
Tower (15 m Guy Tower)	R 33,184.75		01-Jan-12	0	20,000.00	3,577.69	-	-	77.95	207.81	23,863.45	23,863.45
Generator, Hub and Blades (10 kW)	R 124,320.61		01-Feb-12	1	-	3,577.69	-	-	78.30	208.72	3,864.71	3,847.72
Controller (10 kW)	R 30,861.66		01-Mar-12	2	-	3,577.69	-	-	78.64	209.65	3,865.98	3,832.06
Batteries (16x 125Ah)	R 36,000.00		01-Apr-12	3	-	3,577.69	-	-	78.99	210.57	3,867.25	3,816.46
Fuel Generator (10 kVA)	R -		01-May-12	4		3,577.69	-	-	79.34	211.50	3,868.53	3,800.94
Solar Geyser	R 20,000.00		01-Jun-12	5	-	3,577.69	-	-	79.69	212.44	3,869.82	3,785.48
Gas stove	R 5,000.00		01-Jul-12	6	-	3,577.69	-	-	80.04	213.37	3,871.11	3,770.09
	R 249,367.02		01-Aug-12	7	-	3,577.69	-	-	80.40	214.32	3,872.40	3,754.77
			01-Sep-12	8	-	3,577.69	-	-	80.75	215.26	3,873.71	3,739.52
Interest Rate	12%		01-Oct-12	9	-	3,577.69	-	-	81.11	216.21	3,875.01	3,724.33
Term (Years)	10		01-Nov-12	10	-	3,577.69	-	-	81.47	217.17	3,876.33	3,709.21
PMT	R 3,577.69		01-Dec-12	11	-	3,577.69	-	-	81.83	218.13	3,877.65	3,694.15
			01-Jan-13	12	-	3,577.69	-	-	82.19	219.09	3,878.97	3,679.17
Inflation	5.3%		01-Feb-13	13	-	3,577.69	-	-	82.55	220.06	3,880.30	3,664.25
Deposit	R 20,000.00		01-Mar-13	14	-	3,577.69	-	-	82.91	221.03	3,881.64	3,649.39
Maintenance	1%		01-Apr-13	15	-	3,577.69	-	-	83.28	222.01	3,882.98	3,634.60
Petrol	R 10.00		01-May-13	16	-	3,577.69	-	-	83.65	222.99	3,884.33	3,619.87
Fuel per month (liter)	0		01-Jun-13	17	-	3,577.69	-	-	84.02	223.97	3,885.68	3,605.21
Gas per Kg	R 21.26		01-Jul-13	18	-	3,577.69	-	-	84.39	224.96	3,887.04	3,590.62
Gas per month (kg)	3.67		01-Aug-13	19	-	3,577.69	-	-	84.76	225.96	3,888.41	3,576.08
			01-Sep-13	20	-	3,577.69	-	-	85.14	226.95	3,889.78	3,561.61
kWh output per day	20.7		01-Oct-13	21	-	3,577.69	-	-	85.51	227.96	3,891.16	3,547.21
Total kWh used (20 Years)	151,213.50		01-Nov-13	22	-	3,577.69	-	-	85.89	228.96	3,892.54	3,532.87
Total Discounted Value	R 530,742.74		01-Dec-13	23	-	3,577.69	-	-	86.27	229.97	3,893.93	3,518.59
Cost per kWh	**R 3.51**		01-Jan-14	24	-	3,577.69	-	-	86.65	230.99	3,895.33	3,504.37
			01-Feb-14	25	-	3,577.69	-	-	87.03	232.01	3,896.73	3,490.22

Table B-7 Total WGS Cost (Case 8)

Loan		Date	#months	Deposit	Loan	Batteries	Fuel	Gas	Maintenance	Total Cost	Discounted Value
Tower (20 m Guy Tower)	R 40,000.00	01-Jan-12	0	20,000.00	3,740.03	-	-	77.95	217.24	24,035.22	24,035.22
Generator, Hub and Blades (10 kW)	R 124,320.61	01-Feb-12	1	-	3,740.03	-	-	78.30	218.19	4,036.53	4,018.78
Controller (10 kW)	R 30,861.66	01-Mar-12	2	-	3,740.03	-	-	78.64	219.16	4,037.84	4,002.40
Batteries (18x 125Ah)	R 40,500.00	01-Apr-12	3	-	3,740.03	-	-	78.99	220.13	4,039.15	3,986.10
Fuel Generator (10 kVA)	R -	01-May-12	4		3,740.03	-	-	79.34	221.10	4,040.47	3,969.87
Solar Geyser	R 20,000.00	01-Jun-12	5	-	3,740.03	-	-	79.69	222.08	4,041.80	3,953.71
Gas stove	R 5,000.00	01-Jul-12	6	-	3,740.03	-	-	80.04	223.06	4,043.13	3,937.63
	R 260,682.27	01-Aug-12	7	-	3,740.03	-	-	80.40	224.04	4,044.47	3,921.61
		01-Sep-12	8	-	3,740.03	-	-	80.75	225.03	4,045.81	3,905.66
Interest Rate	12%	01-Oct-12	9	-	3,740.03	-	-	81.11	226.02	4,047.17	3,889.79
Term (Years)	10	01-Nov-12	10	-	3,740.03	-	-	81.47	227.02	4,048.52	3,873.98
PMT	R 3,740.03	01-Dec-12	11	-	3,740.03	-	-	81.83	228.03	4,049.88	3,858.24
		01-Jan-13	12	-	3,740.03	-	-	82.19	229.03	4,051.25	3,842.58
Inflation	5.3%	01-Feb-13	13	-	3,740.03	-	-	82.55	230.04	4,052.63	3,826.98
Deposit	R 20,000.00	01-Mar-13	14	-	3,740.03	-	-	82.91	231.06	4,054.01	3,811.45
Maintenance	1%	01-Apr-13	15	-	3,740.03	-	-	83.28	232.08	4,055.39	3,795.98
Petrol	R 10.00	01-May-13	16	-	3,740.03	-	-	83.65	233.11	4,056.79	3,780.59
Fuel per month (liter)	0	01-Jun-13	17	-	3,740.03	-	-	84.02	234.14	4,058.19	3,765.26
Gas per Kg	R 21.26	01-Jul-13	18	-	3,740.03	-	-	84.39	235.17	4,059.59	3,750.01
Gas per month (kg)	3.67	01-Aug-13	19	-	3,740.03	-	-	84.76	236.21	4,061.00	3,734.81
		01-Sep-13	20	-	3,740.03	-	-	85.14	237.25	4,062.42	3,719.69
kWh output per day	25	01-Oct-13	21	-	3,740.03	-	-	85.51	238.30	4,063.84	3,704.63
Total kWh used (20 Years)	182,625.00	01-Nov-13	22	-	3,740.03	-	-	85.89	239.35	4,065.27	3,689.64
Total Discounted Value	R 561,668.62	01-Dec-13	23	-	3,740.03	-	-	86.27	240.41	4,066.71	3,674.71
Cost per kWh	**R 3.08**	01-Jan-14	24	-	3,740.03	-	-	86.65	241.47	4,068.15	3,659.85
		01-Feb-14	25	-	3,740.03	-	-	87.03	242.54	4,069.60	3,645.06

Table B-8 Total WGS Cost (Case 9)

Loan		Date	#months	Deposit	Loan	Batteries	Fuel	Gas	Maintenance	Total Cost	Discounted Value
Tower (25 m Guy Tower)	R 45,000.00	01-Jan-12	0	20,000.00	3,876.33	-	-	77.95	225.15	24,179.44	24,179.44
Generator, Hub and Blades (10 kW)	R 124,320.61	01-Feb-12	1	-	3,876.33	-	-	78.30	226.15	4,180.77	4,162.39
Controller (10 kW)	R 30,861.66	01-Mar-12	2	-	3,876.33	-	-	78.64	227.15	4,182.12	4,145.42
Batteries (20x 125Ah)	R 45,000.00	01-Apr-12	3	-	3,876.33	-	-	78.99	228.15	4,183.47	4,128.52
Fuel Generator (10 kVA)	R -	01-May-12	4		3,876.33	-	-	79.34	229.16	4,184.83	4,111.70
Solar Geyser	R 20,000.00	01-Jun-12	5	-	3,876.33	-	-	79.69	230.17	4,186.19	4,094.96
Gas stove	R 5,000.00	01-Jul-12	6	-	3,876.33	-	-	80.04	231.18	4,187.56	4,078.28
	R 270,182.27	01-Aug-12	7	-	3,876.33	-	-	80.40	232.21	4,188.93	4,061.68
		01-Sep-12	8	-	3,876.33	-	-	80.75	233.23	4,190.31	4,045.15
Interest Rate	12%	01-Oct-12	9	-	3,876.33	-	-	81.11	234.26	4,191.70	4,028.70
Term (Years)	10	01-Nov-12	10	-	3,876.33	-	-	81.47	235.30	4,193.09	4,012.32
PMT	R 3,876.33	01-Dec-12	11	-	3,876.33	-	-	81.83	236.34	4,194.49	3,996.01
		01-Jan-13	12	-	3,876.33	-	-	82.19	237.38	4,195.90	3,979.77
Inflation	5.3%	01-Feb-13	13	-	3,876.33	-	-	82.55	238.43	4,197.31	3,963.60
Deposit	R 20,000.00	01-Mar-13	14	-	3,876.33	-	-	82.91	239.48	4,198.73	3,947.51
Maintenance	1%	01-Apr-13	15	-	3,876.33	-	-	83.28	240.54	4,200.15	3,931.48
Petrol	R 10.00	01-May-13	16	-	3,876.33	-	-	83.65	241.60	4,201.58	3,915.53
Fuel per month (liter)	0	01-Jun-13	17	-	3,876.33	-	-	84.02	242.67	4,203.02	3,899.64
Gas per Kg	R 21.26	01-Jul-13	18	-	3,876.33	-	-	84.39	243.74	4,204.46	3,883.83
Gas per month (kg)	3.67	01-Aug-13	19	-	3,876.33	-	-	84.76	244.82	4,205.91	3,868.08
		01-Sep-13	20	-	3,876.33	-	-	85.14	245.90	4,207.36	3,852.40
kWh output per day	28	01-Oct-13	21	-	3,876.33	-	-	85.51	246.98	4,208.83	3,836.80
Total kWh used (20 Years)	204,540.00	01-Nov-13	22	-	3,876.33	-	-	85.89	248.07	4,210.29	3,821.26
Total Discounted Value	R 589,798.96	01-Dec-13	23	-	3,876.33	-	-	86.27	249.17	4,211.77	3,805.79
Cost per kWh	**R 2.88**	01-Jan-14	24	-	3,876.33	-	-	86.65	250.27	4,213.25	3,790.39
		01-Feb-14	25	-	3,876.33	-	-	87.03	251.38	4,214.74	3,775.05

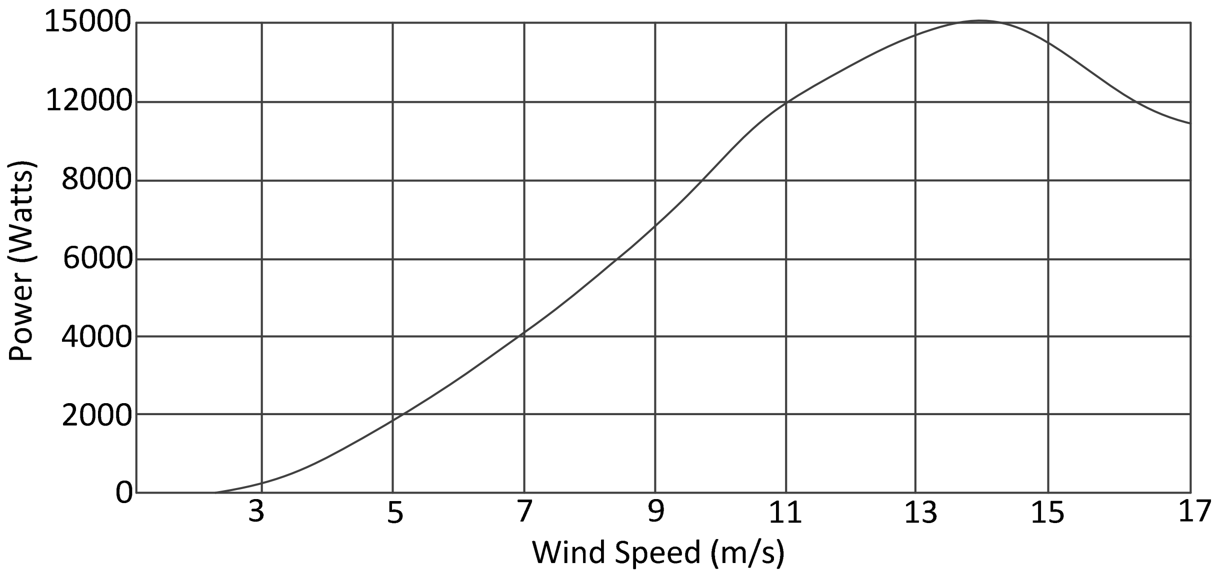


Figure B-2 Wind Generator Power Curve (HM7.0 – 10 kW 240 Volt Wind Turbine Kit) [80]

Table B-9 Wind Generator Specifications (HM7.0 – 10 kW 240 Volt Wind Turbine Kit) [80]

Rotor Diameter (m)	7.0
Material and number of the blades	FRB*3pcs
Rated power/maximum power	10/12 kW
Rated wind speed (m/s)	11
Start-up wind speed (m/s)	2.5
Working wind speed (m/s)	3–25
Survived wind speed	50
Rated rotate speed(r/min)	220
Working voltage	DC 240 V/300 V/360 V/480 V
Generator style	Three phase, permanent magnet
Charging method	Constant voltage current saving
Speed regulation method	Yaw+ Auto brake
Tower height (m)	15
Life time	15 Years

Model	Nominal Voltage	Nominal Capacity (20hr/Ah)	Weight (Approx. kg)	Internal Resistance Approx. (m Ω)	Dimension Height (h) mm	Dimension Length (l) mm	Dimension Width (w) mm	Max. Charging Current (A)
HR1221W	12	5.2	1.9	25	102	90	70	2.1
HR1224W	12	6.5	2.06	21	94	151	51	2.4
HR1234W	12	9	2.26	20	94	151	65	3.4
HRL1280W	12	20	6.5	9	159	181	76.2	8
HRL12110W	12	28	9.9	9	167	165	125	11
HRL12150W	12	38	11.75	7	172	195	130	15
HRL12200W	12	50	17.6	5.9	208	228	139	20
HRL12280W	12	70	25.8	4	215	257	168	28
HRL12330W	12	83	29.6	4	215	309	170	33
HRL12390W	12	98	33	4	218	343	170	39
HRL12500W	12	125	45.7	3.7	278	343	170	50

Figure B-3 Battery Specifications [72]

KIPOR The power keeper

DIESEL POWERED GENERATING SETS

9.5 KVA

the GENERATOR KING

Standby Power	9.5kVA	
Prime Power	8.5kVA	
Voltage	V	220
Phase	1	

STANDARD GENSET SPECIFICATIONS

PERFORMANCE

Alternator Specifications	
Alternator Model	KTS12
Rated Frequency (Hz)	50
Rated Voltage (V)	230
Rated Current (A) Per Phase	36.9
Rated Output/Prime Power (kVA)	8.5
Max Output/Standby Power (kVA)	9.5
Rated Rotation Speed	3000
Power Factor cosØ	0.8
Pole Number	2
Phase Number	Single Phase
Diesel Engine Specifications	
Model Type	KM2V80
Type	engine
Starting System	12 Volt Electric Starter
Auto-Decompression for easy starting	Yes
Displacement (L)	0.794 (794)
Compression Ratio	0.959027778
Rated Power (kW / rpm)	12 / 3000
Fuel Type	Diesel
Lube Oil	L-ECD grade or 15W40
Low Pressure alert System	Yes
Low fuel cut out protection	Yes
General Specifications	
Fuel Tank Capacity (L)	25
Continuous Running time @ full load (Hr)	8 @ full load
Dimensions: unpacked (L x W x H)	1360*560*760 (mm)
Dimensions: packed (L x W x H)	1460*760*900 (mm)
Dry Weight Unpacked / Packed (Kg)	300 / 350
Structure Type	Silent (Not Weatherproof)
Noise Level (dBA @ 7m)	70 - 74
AVR	Constant voltage AVR
Excitation Mode	Self Excitation
Panel Type	Digital Control Panel
ISO9001 & CE certified	Yes

"Life goes on even when the power goes out"

Extreme weather, construction, and many other unforeseen complications can interrupt the electrical service which you and your family depend on to continue your daily activities. With a KIPOR HOME standby power system, life goes on day or night - you can be assured that your home will have comfort and convenience you depend on.

Low noise operation

The KIPOR super silent generator series offer unparalleled low noise levels. KIPOR employs an unique double air inlet and outlet design. The generator is equipped with a built-in large attenuating muffler and additional sound insulation liners to limit noise.

High quality power output

The improved AVR (Automatic Voltage Regulator) limits fluctuation to a very low level ensuring a smooth and steady output. Additionally, the AVR features built-in overload protection and will automatically shut off the output at 110 % of rated load.

ATS (Automatic Transfer Switch)

The ATS continually monitors utility power and if voltage or frequency fall below acceptable levels, it commands the generator to start automatically and connect generator power to the intended load. Once proper utility power is restored, the ATS stops the generator and reconnects utility power. The ATS has been designed to be installed either inside or outside the generator set.

Unique & Compact Structure

The generator set has a compact and unique design. The exhaust is ducted out the top cover facilitation installation. The layout of the oil and coolant inlet has been redesigned to permit easier access for services.

Digital control panel

The digital control panel makes operating and maintaining the set easier and safer. Real-time data such as amperage, voltage, and frequency levels give immediate information to the operator. Additionally, warning lamps immediately alert the operator of any extraordinary running condition.

Competitive economic advantage

The large capacity fuel tank provides extended running time. The high efficiency combustion system is designed to reduce fuel consumption and operating costs.

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Figure B-4 Generator Specifications [76]

REFERENCES

[1] Department of Minerals and Energy. (2009, Mar.) Department of Minerals and Energy. [Online]. http://www.dme.gov.za/pdfs/energy/efficiency/ee_strategy_05.pdf

[2] Department of Minerals and Energy. (2009, Jun.) Department of Minerals and Energy.

[3] A. J. Bredekamp, E. A. Uken, and L. Borril, "Standby Power Consumption of Domestic Appliances in South Africa," Cape Peninsula University of Technology, Apr. 2006.

[4] D. M. Altman, P. R. Davies, A. Mather, D. Flemming, and H. Harris. (2008, Jul.) Human Sciences Research Council. [Online]. http://www.hsrc.ac.za/research/output/outputDocuments/5687_Altman_Theimpactofelectricitypriceincreases.pdf

[5] D. C. Kallis and W. L. O. Fritz. (2009, Mar.) Cape Town University of Technology. [Online]. http://active.cput.ac.za/energy/web/DUE/DOCS/405/Paper%20-%20Fritz%20W.pdf

[6] Environmental Management Department. (2010, Jan.) ECOServ. [Online]. http://www.ecoserv.info/news/Energy.pdf

[7] Strike Technologies, *"EnermaxOne Single-Phase Pilot Project"*. Johannesburg, Gauteng, South-Africa, 2011, www.strike.co.za, Tel: +2711 315 0815.

[8] F. Blaabjerg and Z. Chen, *Power Electronics for Modern Wind Turbines*. U.S.A.: Morgan & Claypool, 2006.

[9] I. Woofenden, *Wind Power for Dummies*. Hoboken: Wiley Publishing, Inc., 2009.

[10] M. R. Patel, *Wind and Solar Power Systems*. Florida: CRC Press LLC, 1999.

[11] J. F. Manwell, J. G. McGowan, and A. L. Rogers, *Wind Energy Explained: Theory, Design and Application*. Chichester: John Wiley & Sons Ltd, 2002.

[12] F. D. Bianchi, H. De Battista, and R. J. Mantz, *Wind Turbine Control Systems: principles, modelling and gain scheduling design*. Germany: Springer-Verlag London Limited 2007, 2007.

[13] Bohlweki-SSI Environmental, "Environmental Scoping Report for the Proposed Construction of the Johannesburg East Electricity Supply Strengthening Project," Bohlweki-SSI Environmental, Gauteng Province, Environmental Scoping Report, 2009.

[14] Conserve Energy Future. (2011, Oct.) Conserve Energy Future. [Online]. http://www.conserve-energy-future.com/WindTurbines.php

[15] Wikipedia. (2008, Dec.) Wikipedia. [Online]. http://en.wikipedia.org/wiki/Wind_turbine#Horizontal_axis

[16] Danish Wind Industry Assosiation. (2009, Jan.) Danish Wind Industry Assosiation. [Online]. http://www.talentfactory.dk/en/tour/design/concepts.htm

[17] Danish Wind Energy Association. (2009, Feb.) Danish Wind Energy Association. [Online]. http://guidedtour.windpower.org/en/tour/wres/betz.htm

[18] M. O. L. Hansen, *Aerodynamics of Wind Turbines, Second Edition*. Sterling: Earthscan, 2008.

[19] Danish Wind Industry Association. (2010, Jul.) Danish Wind Industry Association. [Online]. http://www.windpower.org/en/

[20] S. T. Scowby, R. T. Dobson, and M. J. Kamper, "Thermal modelling of an axial flux permanent magnet machine," *Apllied Thermal Engineering*, vol. 24, no. 2-3, pp. 192-207, Feb. 2004.

[21] B. J. Chalmers, "Developments in electrical machines using permanent magnets," *Journal of Magnetism and Magnetic Materials*, vol. 157-158, pp. 131-132, May 1996.

[22] H. Piggot. (2001, Jun.) The Permanent Magnet Generator (PMG): A manual for manufacturers and developers. Document - pmg_manual.pdf.

[23] ITDG - Practical answers to poverty. (2009, Jun.) Practical Action. [Online]. http://www.practicalactionpublishing.org/energy/docs/energy/EnergyBooklet6.pdf

[24] A. Hirzel. (2009, Feb.) Ansoft. [Online]. http://www.ansoft.com/workshops/altpoweree/Andy_Hirzel_Light_Engrg.pdf

[25] S. E. Skaar, O. Krovel, and H. Erstad. (2003, Mar.) The University of Queensland Australia. [Online]. http://www.itee.uq.edu.au/~aupec/aupec03/papers/119%20Skaar%20full%20paper.pdf

[26] A. Binder. (2005) Technische Universität Darmstadt. [Online]. http://www.ecpe.org/download/presentations/tu_darmstadt_sept08.pdf

[27] G. Kalokiris and A. Kladas, "New magnetic material impact in electric machine design: high speed operation and reduction of losses," vol. 106, no. 1-3, pp. 292-297, Sep. 2003.

[28] S. Kiartzis and A. Kladas, "Deterministic and artificial intelligence approaches in optimizing permanent magnet generators for wind power applications," *Journal of Materials Processing*

Technology, vol. 108, no. 2, pp. 232-236, Jan. 2001.

[29] T. Kefalas, G. Kalokiris, A. Kladas, and J. Tegopoulos, "Design of skewed mounted permanent magnet synchronous generators based on 2D and 3D finite element techniques," *Journal of Materials Processing Technology*, vol. 161, no. 1-2, pp. 288-293, Apr. 2005.

[30] J. G. M. a. A. L. R. J.F. Manwell, *Wind Energy Explained: Theory, Design and Application*. Chichester: John Wiley & Sons Ltd, 2002.

[31] M. S. Sarma, *Electric Machines: Steady-State Theory and Dynamic Performance*. Boston: PWS Publishing Company, 1994.

[32] V. Cohen, "Induction Motors - Protection and Starting," Circuit Breaker Industries, 2000.

[33] A. H. Samra and K. M. Islam, "HARMONIC EFFECTS ON SYNCHRONOUS GENERATORS VOLTAGE REGULATION," Florida International University Department of Electrical & Computer Engineering Paper, 1995.

[34] H. Nicky, K. Tan, and S. Islam, "Mitigation of Harmonics in Wind Turbine Driven Variable Speed Permanent Magnet Synchronous Generators," Curtin University of Technology Paper, 2006.

[35] C. X. Pang and M. Z. Tarnawecky, "GENERATOR WINDING IZR LOSSES AND HARMONIC INTERFERENCE UNDER VARIABLE FREQUENCY OPERATION OF AN HVDC UNIT-CONNECTION SCHEME," *IEEE Transactions on Energy Conversion*, vol. 10, no. 1, pp. 133-139, Mar. 1995.

[36] H. Fujita, T. Yamasaki, and H. Akagi, "A Hybrid Active Filter for Damping of Harmonic Resonance in Industrial Power Systems," *IEEE TRANSACTIONS ON POWER ELECTRONICS*, vol. 15, no. 2, pp. 215-222, Mar. 2000.

[37] R. J. Smith and R. C. Dorf, *Circuits, Devices and Systems - 5th Ed.* United States: John Wiley & Sons, Inc., 1992.

[38] D. F. Warne, *Newnes Electrical Engineer's Handbook*. Woburn: Newnes, 2000.

[39] R. C. Dorf, *The Electrical Engineering Handbook: Electronics, power electronics, optoelectronics, microwaves, electromagnetics, and radar*, 3rd ed. California: CRC Press, 2006.

[40] A. I. Pressman, *Switching Power Supply Design*, 2nd ed. Waban, Massachusetts: McGraw-Hill, 1998.

[41] fke. (2009, Apr.) Universiti Teknologi Malaysia. [Online].
http://encon.fke.utm.my/nikd/SEM4413/AnalysisConverter-buck.pdf;
http://encon.fke.utm.my/nikd/SEM4413/AnalysisConverter-boost.pdf;
http://encon.fke.utm.my/nikd/SEM4413/AnalysisConverter-buck-boost.pdf

[42] Bguru. (2006, Feb.) Kettering University. [Online]. http://www.kettering.edu/~bguru/PEDC2DC/Buck.pdf; http://www.kettering.edu/~bguru/PEDC2DC/Boost.pdf

[43] B. D. Moore, "Step-up / Step-down Converters Power Small Portable Systems," *EDN*, pp. 79-84, Feb. 1994.

[44] N. Kularatna, *Power Electronics Design Handbook - Low-Power Components and Applications*, 1st ed. BOSTON: Newnes - Butterworth-Heinemann, 1998.

[45] M. Brown, *Power Supply Cookbook*, 2nd ed. United States of America: Newnes - Butterworth-Heinemann, 2001.

[46] ON Semiconductor, "SWITCHMODE™ Power Supply Reference Manual," ON Semiconductor Formerly a Devision of Motorola Reference Manual SMPSRM/D, September,1999.

[47] Onsemi. (2007, Mar.) Onsemi. [Online]. http://www.onsemi.com/pub_link/Collateral/AND8039-D.PDF

[48] H. Schmidt-Walter. (2009, Mar.) Hochschule Darmstadt University of Applied Sciences. [Online]. http://schmidt-walter.eit.h-da.de/snt/snt_eng/snteng4.pdf

[49] R. H. Muhammad, *POWER ELECTRONICS HANDBOOK*, 1st ed. Canada: Academic Press, 2001.

[50] Fairchildsemiconductor. (2007, Mar.) Fairchildsemiconductor. [Online]. http://www.fairchildsemi.com/an/AN/AN-4140.pdf

[51] K. H. Billings, *Switchmode Power Supply Handbook*, 1st ed., A. Daniel, G. Thomas, and S. Thomas, Eds. New York, Unites States of America: McGraw-Hill, Inc, 1989.

[52] E. L. Owen, "Origins of the Inverter," *Industry Applications Magazine, IEEE*, vol. 2, no. 1, pp. 64-66, Jan. 1996.

[53] N. Mohan, T. M. Undeland, and W. P. Robbins, *Power Electronics - Converters, Applications and Design*, Second Edition ed. New York: John Wiley & Sons, Inc., 1995.

[54] D. Fewson, *Introduction to Power Electronics*, First Edition ed. London, Great Brittian: Arnold, Member of Hodder Headline Group, 1998.

[55] Wilmore Electronics Co., Inc. (2008, Mar.) DC-to-AC Power Inverters. Series 1400 DC to AC Inverter Specification Document Bulletin no. 3031.

[56] K. H. Edelmoser and F. A. Himmelstoss, "Analysis of a New High-Efficiency DC-to-AC Inverter," *IEEE*

TRANSACTIONS ON POWER ELECTRONICS, vol. 14, no. 3, pp. 454-460, May 1999.

[57] T. R. Crompton, *Battery Reference Book*, Third Edition ed. Oxford: Newnes, 2000.

[58] M. Stiebler, *Wind Energy Systems for Electric Power Generation*. Berlin, Germany: Springer, 2008.

[59] H. A. Kiehne, *Battery Technology Handbook*, 2nd ed., H. A. Kiehne, Ed. New York, U.S.A.: Expert Verlag GmbH, 2003.

[60] P. James and P. E. Dunlop, "Batteries and Charge Control in Stand-Alone Photovoltaic Systems - Fundamentals and Application," Sandia National Laboratories - Photovoltaic Systems Applications Dept., Albuquerque, Fundamentals and Application Report, 1997.

[61] First National Battery. (2008, Nov.) First National Battery. [Online]. http://www.battery.co.za/download/dl/Batteries%20and%20Inverters.pdf

[62] GAIAM. (2010, Mar.) Pure Energy Systems. [Online]. http://www.pureenergysystems.com/PESWiki/Directory/Bedini_SG/files/Short_Primer_on_Lead-Acid_Battery_Types.pdf

[63] First National Battery. (2009, Sep.) First National Battery. [Online]. http://www.battery.co.za/download/dl/IndustrialBatteriesTypes%26Selection.pdf

[64] J. A. O'Connor. (1999) Texas Instruments. [Online]. http://focus.ti.com/lit/an/slua055/slua055.pdf

[65] Woodbank Communications. (2010, Nov.) Electropedia. [Online]. http://www.mpoweruk.com/chargers.htm

[66] EDN Series for Design Engineers, *Rechargeable Batteries - Applications Handbook*. Boston, Unsited States of America: Newnes,Butterworth-Heinemann, 1998.

[67] Unitrode, "Switchmode Lead-Acid Battery Charger," Unitrode Application Note UC2909, UC3903, 2010.

[68] Unitrode, "Simple Switchmode Lead-Acid Battery Charger," Unitrode Application Note U-131, 1999.

[69] G. A. Keen, "Domestic Application of a PV system," *Vector*, pp. 64-67, Jul. 2011.

[70] H. Piggot, "Estimating Wind Energy," *Home Power*, no. 102, pp. 42-44, Aug. 2004.

[71] M. A. Klemen. (2001) Small Wind Energy Systems. [Online]. http://www.ndsu.nodak.edu/ndsu/klemen/Perfect_Turbine.htm

[72] Current Automation. (2010, Oct.) Current Automation. [Online]. http://www.rectifier.co.za/Catalogue/Batteries/CSB/CSB%20Batteries%20Internet.pdf

[73] Solar Navigator. (2010, Nov.) Solar Navigator. [Online]. http://www.solarnavigator.net/battery_charging.htm

[74] Jaycar Electronics. (2010, Nov.) Jaycar Electronics. [Online]. http://www.jaycar.com.au/images_uploaded/slabatts.pdf

[75] C. von Wentzel. (2010, Nov.) von Wentzel. [Online]. http://www.vonwentzel.net/Battery/00.Glossary/

[76] The Generator King. (2010, Oct.) The Generator King. [Online]. http://www.genking.co.za/19sta.pdf

[77] The Labour Research Service. (2011, Aug.) The Labour Research Service. [Online]. http://www.lrs.org.za/docs/Inflation%20Monitor%20August%202011.pdf

[78] Shell South Africa. (2010, Nov.) Shell South Africa. [Online]. http://www.shell.co.za/vpower/pprice.htm

[79] Department Energy: Republic of South Africa. (2011, Oct.) Department Energy: Republic of South Africa. [Online]. http://www.energy.gov.za/files/esources/petroleum/Oct%202011/Maximum%20Retail%20Price%20for%20LPGAS%20Gauteng.pdf

[80] GW Store, *GW Store - Centurion*. Gauteng, South Africa, 2011, www.gwstore.co.za, Tel: +2712 664 1771.

[81] Prelec Power Solutions. (2011, Nov.) Prelec Power Solutions. [Online]. http://www.erakiprelec.co.za/diesel-generator.html

[82] Eskom, "Eskom Tariffs and Charges Booklet 2011/2012," Eskom Booklet, 2011.

[83] H. H. Goh, M. S. Looi, and B. C. Kok, "Comparison between Direct-On-Line, Star-Delta and Auto-transformer Induction Motor Starting Method in terms of Power Quality," in *Proceedings of the International MultiConference of Engineers and Computer Scientists 2009 Vol II,*, Hong Kong, 2009.

[84] J. Larabee, B. Pellegrino, and B. Flick, "Induction motor starting methods and issues," Siemens Energy & Automation, Inc. Paper, 2005.

[85] J. A. Kay, R. H. Paes, G. J. Seggewiss, and R. G. Ellis, "Methods for the Control of Large Medium-Voltage Motors: Application Considerations and Guidelines," *IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS*, vol. 36, no. 6, Nov. 2000.

[86] A. J. Wigington, "A Comparison of Induction MotorStarting Methods Being Powered by a Diesel-Generator Set," University of Nebraska Thesis, 2010.

[87] S. J. Chapman, *Electric machinery fundamentals*, 4th ed. New York: McGraw-Hill Higher Education, 2005, 2005.

[88] R. F. McElveen and M. K. Toney, "Starting High-Inertia Loads," *IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS*, vol. Vol 37, no. No.1, pp. 137-144, Jan. 2001.

[89] Rockewell Automation, "Basics for practical operation Motor starting - Traditional motor starting, Soft starters, frequency inverters," Rockwell Automation Publication, 1998.

[90] F. Blaabjerg, J. K. Pedersen, S. Rise, and H.-H. Hansen, "A Comparative Study of Energy Saving Benefits in Softstarters for Three-phase Induction Motors," Aalborg University, NESA A h , EGITEK Paper 0-7803-3008-0/95, 1995.