DEVELOPMENT OF A LOW COST DIRECT-DRIVE PERMANENT MAGNET GENERATOR FOR POWER GENERATION IN SMALL WIND TURBINES

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Development of a Low Cost Direct-Drive Permanent Magnet Generator for Power Generation in Small Wind Turbines

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other University.

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This thesis has been submitted for examination with our approval as the University supervisors.

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DEDICATION

This thesis is dedicated to my wife Peninah and children Priscillah, Patience and Prince for their endless love, support and encouragement throughout my studies.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF PLATES

LIST OF APPENDICES

LIST OF NOMENCLATURES

a	Number of parallel connected circuits
A	Cross-section of winding wire
A_m	Area of one magnet piece
A_s	Area swept by the blades
B_g	Air-gap flux density
B_m	Flux density in permanent magnet
B_p	Peak air-gap flux density
B_r	Remanent flux density of permanent magnet
C_F	Capacity Factor
C_f	Coefficient of friction
C_{om}	Operation and maintenance cost of WECS for the first year
$C_{om(esc)}$	Present worth of the annual cost throughout lifetime of WECS
C_p	Power coefficient
C_{ph}	Number of coils per phase
CRF	Capital recovery factor
d	Wire diameter
D	Generator diameter
D_r	Rotor diameter
e	Inflation escalation rate
e_a	Apparent escalation rate
e_{om}	Escalation of operation and maintenace
E_{gen}	Generator AC-voltage source
E_{ph}	RMS value of sinusoidal phase voltage of stator winding

E_w	Kinetic energy of wind energy
E_{WT}	Annual energy output of WECS in kilowatt hour
g	Air-gap length
g_e	Effective air-gap
h	Axial height of coil
h_m	Thickness of magnet
i	Inflation rate
i_r	Interest rate
I	Total capital/initial cost
I_{ac}	Current flowing out of generator
I_{ph}	RMS value of stator phase current
k	Any integer
k_d	Distribution factor
k_{fb}	Bearing friction coefficient
K_n	Nagaoka constant
k_p	Pitch factor of non-overlapping winding
k_w	Stator winding factor
l	Length of wire per stator coil
L	Self-inductance of stator winding
l_a	Active length of stator winding
l_e	End-winding length of stator coil
l_g	Axial length of air-gap
L_g	Axial length of generator
L_i	Internal inductance of generator
l_m	Length of magnet
L_r	Rotor axial length
L_s	Stator axial length

m	Number of magnets per phase
m_b	Mass of bearing
m_r	Mass of rotor disks
n	Number of coils per stator phase
N	Generator speed at a given open circuit AC voltage
N_c	Number of turns per coil
n_o	Useful lifetime of the WECS
N_{br}	Bridge rectifier efficiency
N_g	Generator efficiency
N_{ph}	Number of turns of stator phase
N_r	Generator rated speed
n_s	Generator speed in runs per second
N_s	Generator speed in runs per minute
p	Number of poles
P_a	Available power for a wind turbine
P_{cu}	Copper losses per phase
P_{eddy}	Stator eddy current losses
P_{eR}	Rated output of WECS
P_{fr}	Frictional losses in the bearing
Ph	Phase number
P_{in}	Generator power input
P_{loss}	Generator power loss
P_{max}	Maximum power of a wind turbine
P_{mech}	Mechanical losses
P_{out}	Generator power output
P_{ph}	Generator power output per phase
P_r	Generator rated power

P_{wind}	Windage losses
q	Number of stator coils per phase
Q	Total number of stator coils
r	Discount rate
r_b	Outer diameter of bearing
r_e	Average radius of stator winding
R_e	Reynolds number
R_{eddy}	Eddy current losses as depicted in the equivalent circuit
r_i	Inner rotor radius
R_i	Internal resistance of generator
r_o	Outer rotor radius
R_{ph}	Generator phase resistance
r_{si}	Inner stator radius
r_{so}	Outer stator radius
t_r	Rotor disk thickness
t_w	Winding thickness
V_a	Volume of air interacting with wind turbine
V_{avg}	Average phase voltage
V_{gen}	Voltage across generator terminals
V_{oc}	Open circuit voltage
V_r	Rated voltage
V_w	Velocity of wind
w	Width of stator coil

Greek Symbols

ρ_a	Density of air at sea level
ω	Generator rotating speed

θ_{re}	Coil-width-angle at radius r_e
ρ_{cu}	Resistivity of copper wire
θ_m	Power angle
ρ_r	Density of rotating part
μ	Kinematic viscosity of air
η	Electromechanical efficiency of generator
Φ_{ph}	Total flux per phase
λ	Ratio of inner to outer rotor radii

LIST OF ABBREVIATIONS

AC	Alternating Current
AFPM	Axial-Flux Permanent Magnet
ASAL	Arid and Semi-arid Land
BHEL	Bob Harris Engineering Ltd
CAD	Computer Aided Design
CRF	Capacity Recovery Factor
DC	Direct Current
DFIG	Doubly Fed Induction Generator
EAWEL	East African Wind Energy Ltd
EMF	Electromotive Force
FEA	Finite Element Analysis
FEMM	Finite Element Method Magnetism
FiTs	Feed-in-Tariffs
FSIG	Fixed Speed Induction Generator
HAWT	Horizontal Axis Wind Turbine
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IEET	Institute of Energy and Environmental Technology
IRENA	International Renewable Energy Agency
ITDG	Intermediate Technology Development Group
JKUAT	Jomo Kenyatta University of Agriculture and Technology
KPLC	Kenya Power and Lighting Company
KENGEN	Kenya Electricity Generation Company
kW	Kilowatt
LCOE	Levelised Cost of Electricity
NACOSTI	National Commission for Science, Technology and Innovation

NdFeB	Neodymium Iron Boron
PM	Permanent Magnet
PMG	Permanent Magnet Generator
PMSG	Permanent Magnet Synchronous Generator
PV	Photovoltaic
R & D	Research and Development
RE	Renewable Energy
RFPM	Radial-Flux Permanent Magnet
DTU	Technical University of Denmark
RIWIK	Rural Investment Wind Power in Kenya
RMS	Root Mean Square
RPM	Runs per Minute
SCIG	Squirrel Cage Induction Generator
SG	Synchronous Generator
SME	Small and Medium micro Enterprise
SWT	Small Wind Turbine
TFPM	Transverse-Flux Permanent Magnet
VAWT	Vertical Axis Wind Turbine
VSD	Variable Speed Drive
WECS	Wind Energy Conversation Systems
WEO	World Energy Outlook
WRSG	Wound Rotor Synchronous Generator
WTG	Wind Turbine Generator
2-D	Two-dimensional
3-D	Three-dimensional

ABSTRACT

There is low penetration of Small Wind Turbines (SWTs) in Kenya mainly caused by high cost of the technology particularly the drive train (gearbox and/or generator). The gearbox is the main course of downtime in locally manufactured wind turbines. Imported SWTs are also expensive (including their spare parts) and the skill required for their maintenance is locally inadequate. This study presents the design and development of a low cost direct-drive Axial Flux Permanent Magnet (AFPM) generator that utilizes locally available materials and eliminates the use of gearbox. It is designed for ease of manufacture in small workshops using basic tools and with limited electro-mechanical engineering knowledge. The main objective of the study was to design, fabricate and analyse the performance of the AFPM generator for SWT power generation. The machine configuration consists of two rotor disks, permanent magnets, stator support, windings, and car hub bearing. The methodology used involved stratified random sampling, questionnaires and face to face interviews of SWT manufacturers; computational electro-mechanical design using FEMM 4.2 software; and prototype development and testing. Performance equations and Finite Element Analysis (FEA) were used to analyse generator performance, while the Levelised Cost of Electricity (LCOE) was used for economic analysis. While the AFPM generator configuration presented is not new, the generator assembly is however reinforced using a strong T-frame to improve generator stability and provide a flexible mounting support for use in both Horizontal Axis Wind Turbines (HAWTs) and Vertical Axis Wind Turbines (VAWTs) rotor blades. The generator costs Kshs 58,228 which is 35 – 41% cheaper than the existing SWT transmission systems in the market with similar power rating. The generator attains a maximum efficiency of 89% which is reasonably high as the maximum efficiency of a typical AFPM generator is in the range of 90 to 97%.

CHAPTER ONE

INTRODUCTION

1.1 Background

Availability of energy services and appropriate energy technologies are vital for the social and economic development of Kenya. However, according to the World Energy Outlook (WEO) report of 2012, Kenya is among the ten electricity poorest countries in the world. The WEO report of 2014 further estimated that only about 7% of Kenya's rural inhabitants have access to any kind of electricity. In these regions, energy needs are met by polluting and unhealthy energy sources such as traditional biomass (wood fuel and charcoal) and fossil fuels (mainly kerosene). Besides, where electricity is available, it is most commonly delivered to the grid, which suffers from power cuts and growing cost (Kiplagat *et al*., 2011). Small Wind Turbines (SWTs) are a viable option to electrifying rural areas with sufficient wind resources especially for regions where the grid is not present. The technology is available in a whole range of sizes and can fulfil rural energy needs at all levels of society. Smaller wind systems (<1kW) are suitable for household usage, small businesses and farmers whereas larger systems (>1kW) are more appropriate for electrifying institutions and village mini grids (Berges, 2007).

However, despite the fact that SWTs have been available in Kenya for more than 10 years and the urgent need for rural electricity, the SWT sector is still limited to a few companies and pilot projects. As a result, there are only a limited number of SWTs installed in Kenya. Besides the technical barriers, there are various social, institutional, cultural and economic issues that are at the root of the slow coming and difficult adoption of small wind systems in Kenya (Vanheule, 2012). These include limited access to information on available technologies, insufficient institutional support framework and financial constraints.

1.1.1 Energy from the Wind

The increase in energy demands, high cost of non-renewable energy resources like fossil fuels, and global warming, caused by increasing environmental pollution, call for the use of renewable energy resources. Among them, wind energy is currently assumed as the lowest risk, with proven technology and no greenhouse-gas emissions or waste products (Ferreira *et al.*, 2007). Wind energy has been used since the earliest civilization to grind grain, pump water from deep wells and power sailboats. From as early as the thirteenth century, horizontal-axis windmills were an integral part of the rural economy and only fell into disuse with the advent of cheap fossil-fuelled engines (Kolachana, 2012). The wind carries some energy with it, and only a part of this is harnessed by the wind turbine. A wind turbine is a machine that converts the wind's kinetic energy into rotary mechanical energy, which is then used to do work. The kinetic energy of wind moving at a velocity can be expressed mathematically as:

$$\boldsymbol{E_w = \frac{1}{2}\rho_a V_a^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 1.1$$

where ρ_a is the density of air at sea level and V_a is the volume of air interacting with the turbine. The available power, P_a, that can be absorbed by a wind turbine is expressed as:

$$\boldsymbol{P_a = \frac{1}{2}\rho_a A_s v_w^3} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 1.2$$

where A_s is the area swept by the blades and v_w is the velocity of wind. However, the wind turbine cannot extract all of the available power from the wind. Some of the kinetic energy is lost as the wind passes through the turbine. Therefore, the maximum power, P_{max} that a turbine can extract from wind is calculated as follows:

$$\boldsymbol{P_{max} = \frac{1}{2}C_p\rho_a A_s v_w^3 N_g} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 1.3$$

where N_g is the wind generator efficiency, C_p is the power coefficient, and it defines the efficient conversion of wind power to electricity by the wind turbine. The theoretical maximum value of C_P is 16/27 ≈ 0.59, and is called the Betz limit. In practice however, obtainable values of the power coefficient center around 45 percent. This value below the theoretical limit is caused by the inefficiencies and losses attributed to different configurations, rotor blades profiles, finite wings, friction, and turbine designs (Ragheb & Ragheb, 2011). Since the power in the wind is proportional to wind speed cubed, the amount of power available for a wind turbine is therefore highly variable.

1.1.2 Wind Turbines

Wind Turbines are wind energy converters that harness the kinetic energy contained in air masses (Kolachana, 2012). Wind turbines are classified as Horizontal Axis Wind Turbine (HAWT) and Vertical Axis Wind Turbine (VAWT) based upon the axis of rotation. HAWTs are turbines where the axis of rotation is parallel to the ground while for VAWTs, the axis of rotation is perpendicular to the ground. HAWTs have been known since the 10th century (Krag & Vernersen, 2010). Today HAWT is the most cost-effective means of capturing wind energy. They are positioned on land or at sea in a proven windy area. Most horizontal axis turbines are built with two or three blades. Figures 1.1 and 1.2 shows historical horizontal axis wind mills and a modern three-blade HAWT respectively.

Figure 1.1: Historical wind mills:

(a) Dutch windmill (b) American wind pump (c) Thai wind pump (Hau, 2000).

Figure 1.2: A modern horizontal axis wind turbine

(Rodriguez, 2010)

VAWTs, on the other hand, are known to be simpler and cheaper to build (see Figure 1.3 for several configurations of VAWTs). In addition, VAWTs have the following advantages (Rodriguez, 2010): They are not affected by the direction of the wind which is useful in areas where the wind changes direction frequently or quickly; they are able to harvest turbulent air flow found around buildings and other obstacles, a situation that is more common in areas where people live; they are also ideal for both rural and urban applications including roof top installations; they can also be installed at the ground level, making it simpler to install or maintain; and finally, they can be significantly less expensive to build, produce less noise compared with horizontal ones and are more aesthetically pleasing.

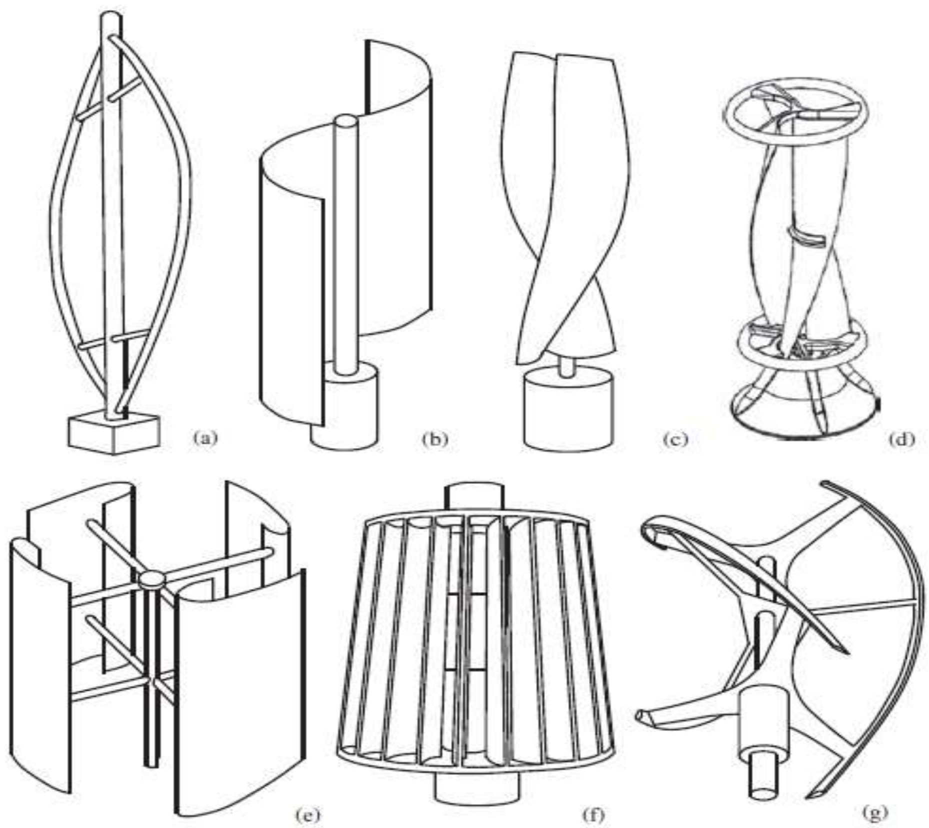


Figure 1.3: Different configurations of vertical-axis wind turbines:

(a) Darrieus; (b) Savonius; (c) Solarwind™; (d) Helical; (e) Noguchi; (f) Maglev;

(g) Cochrane (Tong, 2006).

1.1.3 Wind Generators

The interest in producing electricity from wind puts certain demands on the electrical machines and drives (Madani, 2011). This challenge is what has led to much technological advancement in the development of innovative, direct driven, variable speed generators for wind turbines. The generator is an important component in a wind turbine, since it converts the mechanical energy in the rotating wind turbine to electricity. Small scale wind power applications require a cost effective and mechanically simple generator in order to be a reliable energy source. Direct-drive generators fulfill this requirement by eliminating the need of gearbox in wind turbines since the gearbox is the part in a wind turbine responsible for most downtime due to failures (Ribrant & Bertling, 2007).

For direct drive, the popular machine option is the permanent magnet (PM) synchronous machines (Wenping *et al*., 2012). PM machines are electromagnetic energy conversion devices in which the magnetic excitation is supplied by a permanent magnet. They are rapidly finding numerous applications as alternators, automotive applications, small appliances, computer and robotics applications among others (Rizk & Nagrial, 2010). The stator of the machine is identical to the stator of a multiphase AC machine. The new component is the rotor which relies on permanent magnets as the source of excitation rather than an electric current in windings of conventional rotors (Rizk & Nagrial, 2010).

1.2 Problem Statement

SWTs have been available in Kenya for more than 10 years. However, despite the huge potential for SWTs alongside the stringent need for rural electricity, the pace of adoption in many rural areas is still low. The major reason for the continued low penetration of SWTs in Kenya is the high cost of the technology particularly the drive train (gearbox and/or generator). The gearbox is also responsible for major downtime in wind turbines. A solution to this drivetrain challenge is the use of direct drive generator that eliminates the gear box. However, imported manufactured direct drive generators available in the Kenyan market are not only expensive but also the local skill required for their maintenance is inadequate. At the same time, locally manufactured SWT generators are equally expensive and have stability problems. Using locally available materials, this study focused on the development of direct drive generator that is cost efficient to improve its adoption and easy to manufacture so that it can be made in small workshops using basic tools with limited electrical engineering knowledge. This can make it attractive as a source of employment for the youth. The study also focused on improving the generator stability by reinforcing the generator assembly using an innovative frame that also offers a flexible mounting support to the turbine blades so that the generator can easily be mounted both on a HAWT as well as a VAWT.

1.3 Objectives

1.3.1 Main Objective

This study is part of a major research on "Development of low cost, locally manufactured small wind turbines for use in Kenya," organised with funding from the National Council of Science, Technology and Innovation (NACOSTI) and carried out by a Wind Research Group of three Masters students each with a specific area of study. The main objective of this study was to develop a low cost direct-drive permanent magnet generator for power generation in SWTs in low wind speed sites.

1.3.2 Specific Objectives

The specific objectives of the study were to:

1. Review and document the opportunities and challenges of small wind turbine penetration and power generation technologies in Kenya.
2. Design and fabricate, using locally available materials and components, a low cost direct-drive permanent magnet generator for power generation in small wind turbines.
3. Test and analyse the performance of the direct-drive permanent magnet generator.

4. Design and integrate power transmission and control system for the direct-drive permanent magnet generator.
5. Determine and analyse the cost of the small wind turbine permanent magnet generator.

1.4 Justification

Most SWTs are directly connected to the generator in order to avoid the failures associated with the use of a gearbox transmission system. A case study has shown that the gearbox is the part in a wind turbine responsible for most downtime due to failures (Ribrant & Bertling, 2007). Other setbacks associated with gearboxes are that the addition of a gearbox increases the initial and maintenance costs of the turbine; the frictional torque in a gearbox leads to starting problems; gearboxes are a source of heat losses due to friction which reduces system efficiency; and that gearboxes require oil and regular maintenance which reduces overall system reliability, especially in autonomous off grid applications where a SWT is sited in a remote area.

Besides the gearbox challenges, the SWTs in Kenya are still expensive and as such, the majority of rural households that need SWTs most cannot afford them. This study came up with a generator design that does not only eliminate the gearbox, but one that also makes use of locally available materials in an attempt to reduce by a significant margin the cost of a single unit of SWT.

Kenya is amongst the countries with the highest energy prices which hinder the development and sustainability of Small and Medium micro Enterprises (SMEs). The SMEs play a greater role in alleviating poverty in the country, with a majority of the population still living below the poverty line. The poor need energy that is not only affordable but also environmentally sustainable. Utilizing a wind turbine is a green mini-grid option that many communities can greatly benefit making it an attractive decision not only for energy conservation but for substantial potential savings on energy costs. Employment opportunities in the manufacturing of the generator and SWT as a whole may also be created, in addition to jobs created from the use of the affordable electricity.

The other justification is that in recent years, the performance of PMs has been improving and that the cost of PM is decreasing. Additionally the cost of power electronics is decreasing roughly by a factor 10 over the past 10 years (Polinder *et al*, 2006). Therefore these trends, alongside other advantages of PM as already discussed make PM machines more attractive for the direct-drive wind generators.

Finally, the cost of wind turbines and components is relatively high in Kenya and out of reach of many rural inhabitants who need the technology most. A study on the cost of small wind turbines by Lynn Vanheule observes that the price range for the smaller sizes (150W-300W) is between Kshs 100,000 – 200, 000. Wind turbines of capacity 1kW rated power are available for a total cost of Kshs 280,000– 350,000. For power outputs of around 3kW, which is the maximum size that can mostly be found installed, turbine prices rise up to Kshs 800,000 (Vanheule, 2012). Such high costs are a justification for carrying out this research study with the aim of providing a low cost solution.

1.5 Scope

This study describes a design concept for generating sufficient amounts of electrical energy from low wind speeds using a SWT. The design process combines analytic design and Finite Element Analysis (FEA) of a 1kW 3-phase Axial Flux Permanent Magnet (AFPM) machine. The analytic part is used to calculate the initial values of generator parameters before fabrication and to analyze its performance from sizing equations and measured results. The FEA part of design is used to verify the analytic solutions before making appropriate recommendations about modifications for future work. Before the design process starts, some basic theory about permanent magnet machines is presented. Variations of major generator topologies are compared to find the most suitable one for the given design requirements and research objectives. The study targets rural households that are far from the national grid and in areas recording average wind speeds of about 4m/s. This study will be of great interest to anyone, particularly those in the informal sector, who may be interested in manufacturing an efficient low cost SWT generator in a small workshop with limited electrical engineering knowledge.

1.6 Limitations

A major limiting factor to this study is that while all the other materials used in the manufacture of the AFPM generator can easily be sourced locally, PMs must however be imported. This has a direct implication on the overall cost of the generator. The cost of the generator is therefore limited to a large extent by the cost of PMs in the world market. Despite this limitation, it is worth noting that PMs are readily available in the international market and that the costs of rare earth magnets are generally on a reducing trend globally (Polinder *et al*, 2006).

Another limiting factor is workmanship. Good workmanship is vital for generator stability and proper sizing especially in setting the air-gap as this greatly enhances generator performance. While the study leaves room for improvement in terms of better workmanship, the generator attains a maximum efficiency of 89% which is sufficient for a non-optimized prototype (Ferreira *et al*., 2007) and considerably high in comparison to the maximum efficiency of a typical AFPM generator which ranges between 90 and 97% (Auinger 2001; Hey *et. al*., 2010).

CHAPTER TWO

LITERATURE REVIEW

2.1 History of Small Wind Turbines in Kenya

According to the International Electrotechnical Commission (IEC) Standard, a Small Wind Turbine (SWT) can be defined as a system of $200m^2$ rotor swept area or less that converts kinetic energy in the wind into electrical energy (IEC 61400-2, 2006). Wind energy has a long history in Kenya. Wind pumps were first used over 100 years ago. Back then, it was the European settlers who imported the turbines. During 1960s, when oil became available, most windmills were replaced by diesel engines (Vanheule, 2012). However, the oil crisis in the seventies created a renewed interest in wind pumps. Over the years, there have been numerous feasibility studies, pilot projects and wind system ventures to demonstrate and increase uptake of wind energy in Kenya. Nevertheless, lack of proper coordination, inaccurate data, low income levels, small market share and low technical knowledge inhibited the establishment of a small wind energy sector. However, the feasibility studies did lead to some awareness of wind energy potential and wind energy technology in Kenya (Ogana, 1987).

The first wind turbine projects were carried out in the beginning of the eighties and these consisted of medium wind turbines for powering two off-grid communities. These projects both failed due to lack of attention and maintenance (Vanheule, 2012). In 1993, a third off-grid project was established through funding by development partners (KenGen, 2012). It took until the end of the nineties for the SWT sector to take off as established importers of energy systems started extending their product range to small wind turbines (Vanheule, 2012). The first SWT local manufacturer, Craftskills, was established in 1999, while WinAfrique entered the field in 2001, as the first dealer solely focusing on SWTs. Over the years, the numbers of SWT dealers have significantly increased. In 2005, the installed capacity was estimated at 80-100 SWTs (total of 50kW), a total of 750kW large wind turbines and 300-350 windmills (Mutimba, 2005). Two kinds of wind turbines exist in Kenya: the horizontal axis turbines and the vertical axis turbines. The vast majority of wind turbines in the country are however, horizontal wind turbines. This includes both locally manufactured and imported turbines (Vanheule, 2012).

The rise in cost of oil, surging energy demand and the need to address global warming have led to a steady increase in government awareness and interest in wind energy. Consequently, the Ministry of Energy developed wind maps in 2003 and 2007 to increase commercial grid wind energy interest (Kirai & Shah, 2009). Several other incentives such as feed-in tariffs have since followed. Since 2009, the number of experiments, research programs and overall attention for small wind turbines went up, partly due to the positive wind energy attention for the wind farm projects. Universities have increased their wind research, non-profit organisations are running support programs and more and more companies are getting involved (Vanheule, 2012). In 2009, Kenya held its first conference for SWTs, with a majority of attendants from Kenyan Research and Development (R&D) institutes and NGOs (Riso DTU, 2009). At the moment, the exact number of pilots, wind turbines installed or technology suppliers is unknown, since there is no central registration and hence no database (Vanheule, 2012).

The SWT manufacturers in Kenya are mainly local companies, especially Craftskills. Craftskills design, manufacture and sell consumer scale wind turbines to businesses, households and institutions throughout Kenya. It operates from the capital Nairobi, and their wind systems are especially designed for the Kenyan market while making use of locally available materials. WindGen, a foreign owned company established in 2011, also came into the market as a manufacturer of SWTs. However, at the moment, they mainly sell imported turbines.

Other foreign owned companies, Access Energy and RIWIK, have also been established. Access Energy was initially based in Kisumu but relocated to Nairobi in 2013. They entered the market as wind turbine manufacturers but also deal in solar energy technologies. RIWIK was started in 2012 and is based in Thika. They also manufacture SWTs for the local market in addition to supplying solar energy technologies. At the moment, there are two other Kenyan firms that have a strong focus on imported SWTs alongside WindGen; WinAfrique, established in 2001 and EAWEL established in 2011 (EAWEL, 2011). It is clear that most of these SWT dealers in Kenya primarily import solar systems and only complement their energy products with wind turbines. Less attention and promotion is paid to the SWT promotion and sales. It must be noted that the SWT activity strongly depends on the dealer. Despite their secondary focus, some of these enterprises have been able to sell up to 70 wind systems, whereas others just mention the turbines on their website but hardly make any sales (Vanheule, 2012).

Table 2.1 below provides an overview of the characteristics of the different SWT types on the Kenyan market (Vanheule, 2012).

Table 2.1: Characteristics of SWTs in Kenya

Aspect	Informal manufacturing	Local manufacturing	Imported turbines
Production	(Very) small scale Local scrap/ spare parts	Small scale local (quality) materials	Mass scale
Power	20-300W	200W – 10kW	200W-10kW
Efficiency	Very low	Medium	High
Cost	Very low – low	Medium	High
Quality	Low	Medium	Reliable and well-tested
Repair and maintenance	Can be locally repaired (spare parts available)	Can be locally repaired Spare parts available	Local skills and spare parts may not be available

Source: Vanheule, 2012

2.2 Generator Systems for Small Wind Energy Applications

Initial research on the subject of electrical generators revealed a huge variety in the type of electrical machines available for power generation. There is generally no consensus among academics and industry on the best wind turbine generator technology (Wenping *et al.,* 2012). Traditionally, there are three main types of wind turbine generators (WTGs) which can be considered for the various wind turbine systems:

a) Direct Current (DC) Generators
b) Alternating Current (AC) Asynchronous Generators
c) Alternating Current (AC) Synchronous Generators

In principle, each can be run at fixed or variable speed. Due to the fluctuating nature of wind power, it is advantageous to operate the WTG at variable speed which reduces the physical stress on the turbine blades and drive train, and which improves system aerodynamic efficiency and torque transient behaviours.

2.2.1 DC Generators

The application of DC generator in wind energy systems is not widely spread, mainly because of the high maintenance requirement of brushes and commutator. Furthermore a full scale inverter is required in order to get connected to the Alternative Current (AC) grid (Madani, 2011). Additionally, although this research utilizes a DC battery charging system, the use of a DC generator is also deemed unsuitable due to its poor efficiency in comparison to AC generators and the need for mechanically inferior brushes and components. In particular, removing the need for a commutator results in an AC generator showing improved economics compared to a DC generator (Johnson & Gary, 2001). For these reasons, DC generators were not considered in this study.

2.2.2 AC Asynchronous Generators

The most historically common generator type in larger wind turbines are AC Asynchronous Generators, which are also referred to as Induction generators. Induction fed generators are of two types; fixed speed induction generators (FSIGs) with squirrel cage rotors (sometimes called squirrel cage induction generators-SCIGs) and doubly fed induction generators (DFIGs) with wound rotors. DFIGs are the most commonly used generators. They use electro magnets, by driving a current through a rotor coil, to generate a magnetic field which allows the generation of power. They are still the predominant technology in wind turbine applications for a number of reasons (Murphie 2013);

a) Frequency of electricity generated may be held constant with respect to changing wind speeds by modulating the current input.
b) They are economically a good option in comparison to singly fed induction generators.
c) They allow for the use of advanced power controls, which is an important concern on larger systems.

This type of generator was considered a strong option in this study; however they have a number of setbacks, namely the requirement for a gearbox to generate suitable rotational speeds. In addition, the conventional DFIG with gearbox has several drawbacks (Hau, 2000):

a) High maintenance due to the slip rings.
b) Limited capability of supplying reactive power.
c) High torques in the machine during faulty conditions.
d) Additional measures are required to limit the start-up current.

Moreover, the most complex control, especially regarding converters in wind systems are related to DFIG, which makes them essentially more economical for large wind systems rather than small systems (Madani, 2011). Induction generators were therefore not an option in this research.

2.2.3 AC Synchronous Generators

The synchronous machines have many advantages over induction machines. One of them is a higher efficiency because the magnetizing current is not a part of the stator current. Accordingly, synchronous generators (SGs) have better efficiency and better power factor. SGs can be sub-divided into two major groups; Wounded Rotor Synchronous Generator (WRSG) and Permanent Magnet Synchronous Generator (PMSG). The main advantage of WRSG over PMSG is that it intrinsically can produce reactive power and subsequently regulate the voltage (Madani, 2011). Nonetheless the WRSG has not gained popularity among the wind turbine manufacturers mainly because the brushes for DC excitation in WRSG require maintenance. Mechanical vulnerability of rotor windings arising from rotation leads to winding insulation damage. PMGs on the other hand, are increasingly becoming popular in the wind energy industry, particularly with the increased availability of rare earth metal magnets. The advantages of PM machines over electrically excited machines can be summarized as follows according to literature (Polinder *et al*., 2006):

a) higher efficiency and energy yield
b) no additional power supply for the magnet field excitation
c) improvement in the thermal characteristics of the machine due to absence of the field losses
d) higher reliability due to the absence of mechanical components as slip rings
e) lighter and therefore higher power to weight ratio

The main disadvantages of PM machines are high cost of PM, difficulties in manufacturing and demagnetization of PM at high temperatures. By comparing the properties of the two generator types, it was evident that the PMG design was more suitable for our scope; particularly with consideration to the direct-drive arrangement. Therefore, it was apparent from the literature review, that to fulfill the design brief, the generator design work would focus on the design of a direct-drive PMSG.

2.2.4 Permanent Magnet Synchronous Generator (PMSG)

On the basis of direction of flux-path and the structure, the PMSGs can be categorized as follows (Bang *et al*., 2008):

a) Radial-flux permanent magnet machines (RFPM)
b) Axial-flux permanent magnet machines (AFPM)
c) Transverse-flux permanent magnet machines (TFPM)

2.2.4.1 Radial-flux Permanent Magnet Machines (RFPM)

The axial-flux permanent magnet (AFPM) machine is a machine producing magnetic flux in the axial direction with permanent magnets while radial-flux permanent magnet (RFPM) machines produce magnetic flux in radial direction with permanent magnets (Figure 2.1).

In comparison to AFPM machines, the RFPM machines have the advantages of higher torque/mass ratio, small outer diameter, small amount of PM, and easier to maintain air-gap in small diameter (Bang *et al*., 2008).

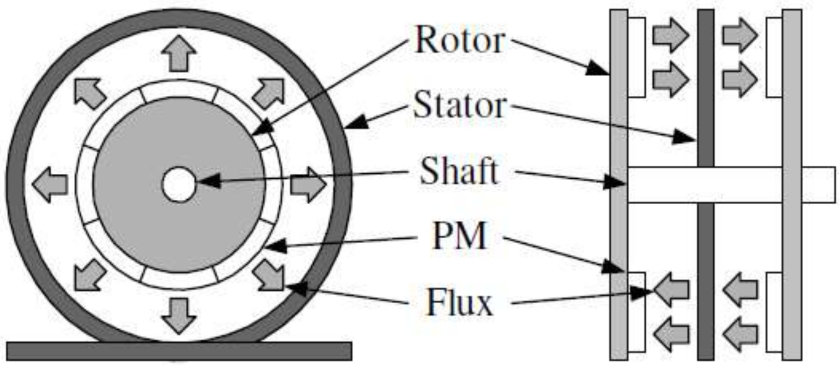


Figure 2.1: Radial-flux and Axial-flux Machines

(Rossouw, 2009).

2.2.4.2 Axial-flux Permanent Magnet Machines (AFPM)

In AFPM machines, the length of the machine is much smaller compared with radial flux machines. Their main advantage is high torque density, so they are recommended for applications with size constraints especially in axial direction. Unlike radial flux machines, any increase in length is accompanied by increase in air-gap diameter. Compared to the RFPM machines, the AFPM machines have the advantages of simple winding, low cogging torque and noise (in slotless machine), short axial length of the machine, and higher torque/volume ratio (Bang *et al.*, 2008).

2.2.4.3 Transverse-flux Permanent Magnet Machines (TFPM)

In transversal or longitudinal flux machines, the plane of flux path is perpendicular to the direction of rotor motion. Figure 2.2 shows a fraction of a typical transversal flux PMSG. One drawback of transverse PMSG is high leakage flux which results in poor power factor. Further- more the major drawback with rotational ones is relatively difficult manufacturing process. Yet another drawback is that, in rotating transverse PMSG, mechanical construction is weak due to large number of parts.

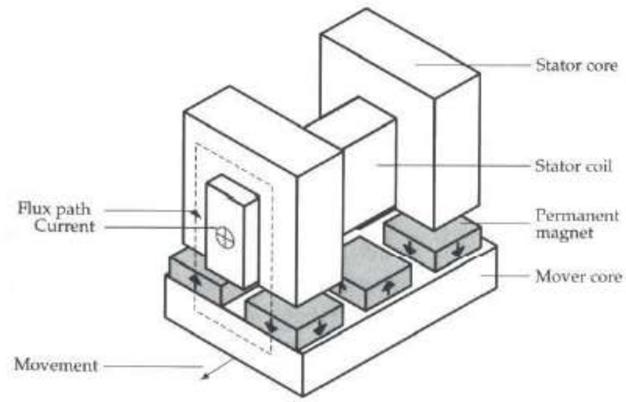


Figure 2.2: Fraction of a typical TFPM Synchronous Generator

(Svechkarenko, 2010)

Table 2.2 provides a summarized comparison of the different PMSG configurations in terms of their advantages and disadvantages. Following comparison and analysis, the generator choice was either to be AFPM or RFPM. From analysis of literature, radial-flux machines are considered to be more economical for high speed large direct-drive applications and offer better performance, though performance differences are minimal. The axial-flux machine is however more suitable for low speed small direct-drive applications. The manufacturing process of axial-flux in a small workshop is also relatively simple, resulting in a more flat packed design as opposed to a fairly long cylindrical design of the radial type (Figure 2.3). This makes the AFPM machine cheaper.

Table 2.2 Advantages and disadvantages of PMSG Configurations

Type of PMSG	Advantages	Disadvantages
AFPM	- simple winding - low cogging torque and noise (in slotless machine) - short axial length - higher torque/volume ratio	- lower torque/mass ratio - larger outer diameter - large amount of PM - structural instability (in slotless machine) - difficulty to maintain air gap in large diameter (in slotted machine) - difficult production of stator core (in slotted machine)
RFPM	- higher torque/mass ratio - small outer diameter - small amount of PM - easier to maintain air-gap in small diameter	- difficult winding - higher cogging torque and noise (in slotless machine) - long axial length - lower torque/volume ratio
TFPM	- higher force density - considerably low copper losses - simple winding	- high leakage flux which results in poor power factor - relatively difficult manufacturing process (rotational ones). - mechanical construction is weak due to large number of parts (rotational ones).

After considering the advantages and disadvantages of various generator topologies, the selected topology for this study was the Axial Flux Permanent Magnet (AFPM). Table 2.3 below contains comparison of relative advantages and disadvantages for seven most commonly used generator topologies in wind turbines.

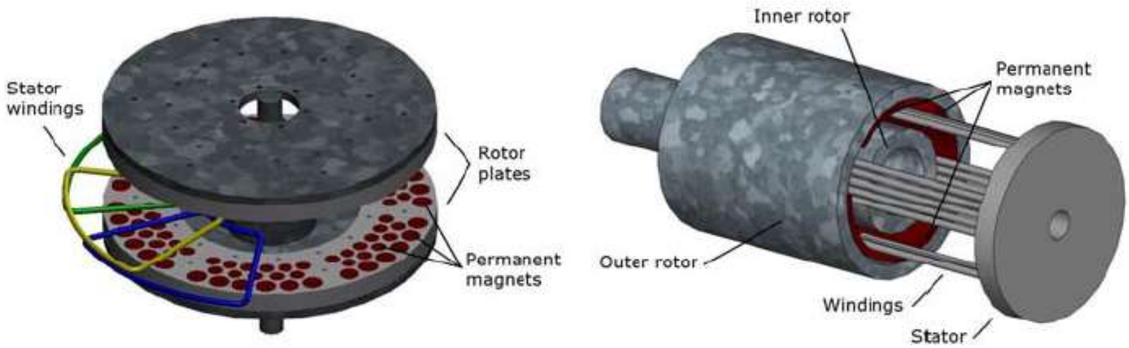


Figure 2.3: Ironless axial flux and radial flux machine schemes

(Santiago & Bernhoff, 2010).

2.3 AFPM Generator Topology

The next step was to determine the appropriate AFPM configuration that best suits our design requirements. There are several topologies of AFPM generators that exist today (Du-Bar, 2011; Mahmoudi *et al*., 2011):

a) Single-sided
b) Double-sided internal stator double rotor
c) Double-sided internal rotor double stator
d) Multi-disc

It is also possible to subdivide them further depending on such factors as winding configuration, slotted or slotless stator, iron core or coreless stator and so on. The main parameters to decide on include the number of rotor and stator disks and whether the stator should be slotted (cored) or not. Slotted stator configurations, such as the one shown in Figure 2.4, was not considered in this study because of additional cost implications in designing the stator slots. The slots are also difficult to construct. The absence of stator slots also eliminates cogging which makes it easier for the turbine to turn especially, at low wind speed. The AFPM generator with Toroidal stator, popularly referred to as TORUS (Figure 2.5), was equally left out in the selection process because it is also difficult to manufacture especially when it comes to placing windings on the stator ring. In order to minimize the stator construction costs, an air cored (coreless) stator configuration was chosen as the best option in this research.

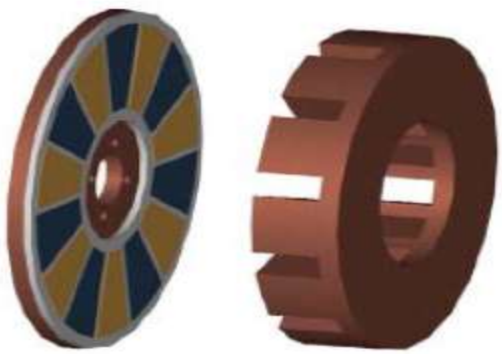
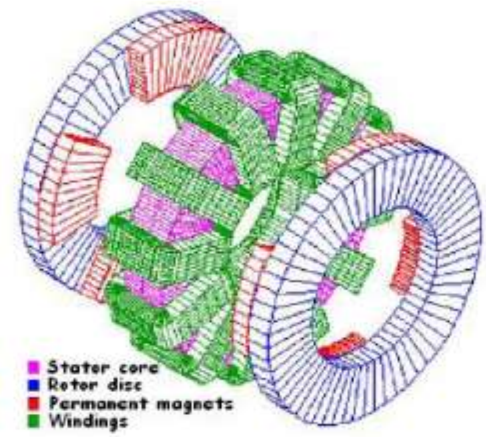


Figure 2.4: Single-sided axial flux machine with one PM rotor disk and slotted stator (Parviainen *et al*, 2005).

To reduce axial attraction forces between stator and rotor, it is advisable to have a double rotor configuration in which the stator is sandwiched between two rotors. This outer rotor configuration is also preferred because the outer rotor structure ensures easy coupling or assembling to the turbine. Another advantage is that the magnets are well supported despite the centrifugal force. Furthermore a better cooling of magnets is provided (Madani, 2011). A double-sided topology also has higher torque production capacity unlike the single-sided one. It is for these reasons that a double sided AFPM generator with air cored stator was selected for this research.

Table 2.3: Comparison of various generator topologies for wind turbines

Type of Generator	Advantages	Disadvantages
DC Generator	- Simple - Some good at low RPM - PM type easy to maintain as they lack brushes	- High maintenance of brushes and commutator - Need of a full scale inverter to connect to the AC grid. - Poor efficiency
SCIG	- Simple construction - Simple maintenance - Attenuated pulsations of turbine Torque - Low cost - Direct connection to the power grid	- Requires reactive power - Requires soft start device for initial connection to the grid - Applicable only for fixed turbine speed - Requires a gearbox - Cannot be used for large number of poles (>20)
DFIG	- Significantly reduced power rating and cost of the converter - Possible speed regulation for optimal utilization of energy (typically ±20 25%) - Reactive power for magnetization of the machine is provided by the power converter	- Slip rings and brushes, wear and tear, maintenance - Complex control of the entire unit - Direct connection to the grid is somewhat difficult
Direct Driven WRSG	- No gearbox - Higher efficiency	- Large dimensions an weight, - Problems with construction, transportation and installation
WRSG with Gearbox	- Small dimensions and weight - Standard construction can be used	- High cost, losses (2-3) % - Problematic maintenance of the gearbox
Direct Driven PMSG	- No gearbox - Higher efficiency - Simple maintenance	- Large dimensions and weight, problems with construction, transportation and installation
PMSG with Gearbox	- Small dimensions and weight - Standard construction can be used	- High cost, losses (2-3) % - Problematic maintenance of the gearbox



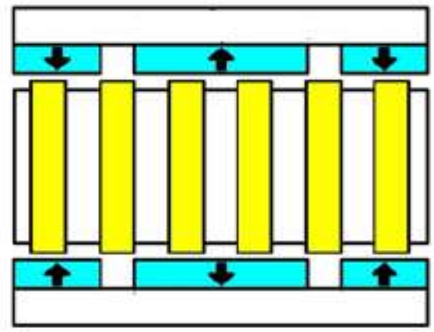


Figure 2.5: Double-sided AFPM machine with toroidal stator and two outer rotor disks

(Boccaletti *et al,* 2006).

However, the disadvantage of double-rotor topology is the huge attractive forces between the two opposing PM-rotor disks. These attractive forces cause a safety hazard during the machine's construction. This challenge was tackled in this study by having rotor disks of sufficient thickness (10mm) to avoid the bending of the disks which could lead to closing of the air-gap. Regardless of this disadvantage, and the fact that magnet volume is slightly higher than for single rotor configuration, the double-sided outer-rotor topology is the coreless AFPM machine of choice for small-scale wind generator applications (Rossouw, 2009).

In this research, a double-rotor AFPM generator with air cored (coreless) stator was developed for small wind energy applications in Kenya. The Structure of the double-rotor axial flux machine with air cored stator is illustrated in Figure 2.6. The machine configuration consists of the following components: two rotor disks, permanent magnets, stator support, windings, and bearing. The coreless stator is placed in between the two outer rotor disks. The axially magnetized permanent magnets are embedded onto the inner surfaces of the rotor disks using polyester casting, which supports them, and also protects them from corrosion, a potential problem with NdFeB magnets (Piggott, 2003). The magnets face each other N-S across the air-gap. In this way, the completed rotor disks attract each other.

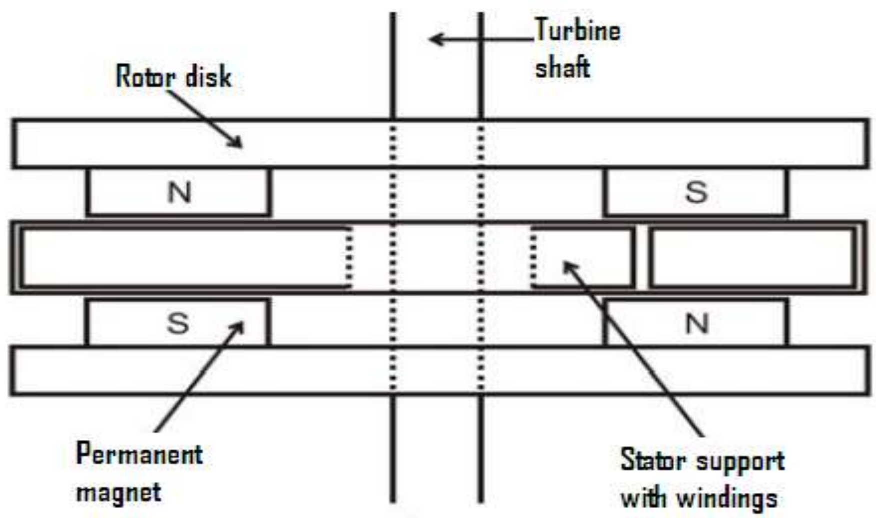


Figure 2.6: Structure of the double-rotor axial flux machine with air cored stator

(Ani, 2013).

The coils of wire are held steady, while the magnets spin past on the rotors. Because the magnets are arranged N-S-N-S, the direction of the field flips each time a magnet goes by. Each coil encounters a flipped magnetic field, and pulse of electricity is produced, according to Faraday's law of electromagnetic induction. The rotor poles with an opposite arrangement (N-S type) are shown in Figure. 2.7. The inner and outer radii of the disk are respectively represented by R_i and R_o. The stator winding of the machine has no iron core and the surface winding of the stator is perpendicular to the machine shaft.

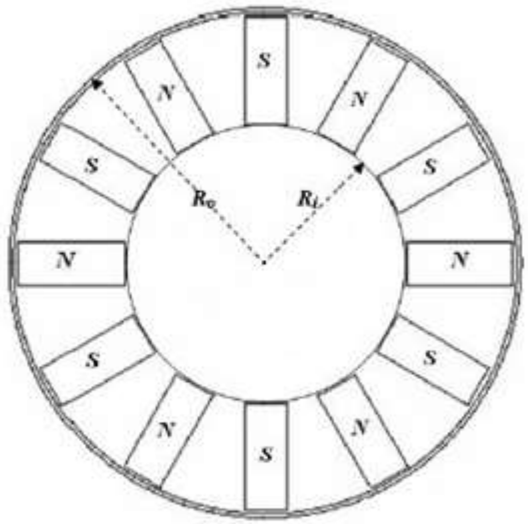


Figure 2.7: Rotor poles with an opposite magnets arrangement (N-S type)

(Hosseini *et al*, 2008)

2.4 Theoretical Analysis of the AFPM Generator with Coreless Stator

In this section, the chosen AFPM generator with coreless stator is analysed. In this type of machine, coil windings are kept in position using epoxy resin and not stator slots. With the absence of stator teeth there is no cogging torque or iron losses in the stator (Rossouw, 2009). At the same time, AFPM machines require high pole numbers in order to maintain frequency at low rotating speeds (Karim *et al.,* 2007). The high pole numbers will mean a larger machine diameter which in turn affects the material cost of the machine (Rossouw, 2009) and may disturb air-flow around the turbine hub and have a negative effect on cooling capabilities of the AFPM machine (Nilsson *et al.*, 2003).

2.4.1 Equivalent Circuit

The steady-state performance of AFPM generator is calculated with the use of an equivalent circuit in generator mode as shown in Figure 2.8 (Wang, 2003). The induced electro-motive force (EMF) is represented by generator ac-voltage source E_{gen}, connected in parallel with a resistor, R_{eddy}, which models the eddy current losses in the stator. These are in turn connected in series to a resistor, R_i and an inductor L_i, representing the internal impedance of the generator. The resultant current, I_{ac}, is chosen as flowing out of generator model, while voltage measured across generator terminals is V_{gen} (Rossouw, 2009).

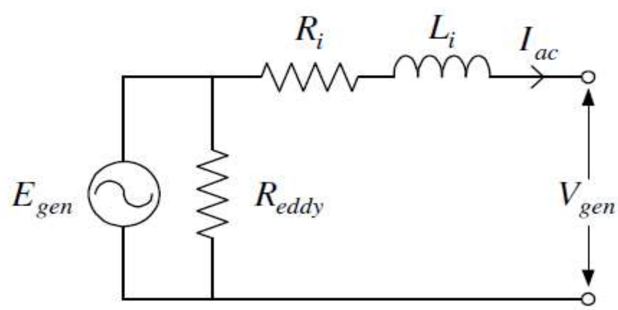


Figure 2.8: Equivalent circuit of an AFPM generator

(Rossouw, 2009)

2.4.2 Performance Equations

2.4.2.1 Induced Phase Voltage

The Root Mean Square (RMS) value of sinusoidal phase voltage of non-overlapping winding of AFPM generator is given by (Kamper *et al.*, 2008)

$$\boldsymbol{E_{ph} = \frac{q}{a}\frac{2\sqrt{2}}{p}\omega B_p N_c r_e l_a k_p\, k_d} \quad \text{.................................} \; 2.1$$

where q is the number of stator coils per phase, a is the number of parallel connected circuits, p is the number of poles, ω is the generator rotating speed (rad/s), B_p is the peak air-gap flux density, N_c is the number of turns per coil, r_e is average radius of stator winding, l_a is active length of stator winding, k_p is pitch factor of non-overlapping winding and k_d is the distribution factor. The peak value of air-gap flux density, B_p, can be calculated as (Rossouw, 2009)

$$\boldsymbol{B_p = \frac{2\sqrt{3}B_g}{\pi}} \quad \text{2.2}$$

where B_g is the air-gap flux density.

$$\boldsymbol{r_e = \frac{r_i + r_o}{2}} \quad \text{2.3}$$

where r_i and r_o are the inner and outer radii of the stator respectively.

$$\boldsymbol{l_a = r_o - r_i} \quad \text{2.4}$$

$$\boldsymbol{k_p = \frac{\sin(\theta_m[1-k]/2)\sin(k\theta_m/2)}{(k\theta_m/2)}} \quad \text{2.5}$$

$$\boldsymbol{\theta_m = \frac{\pi p}{Q}} \quad \text{2.6}$$

where Q is the total number of stator coils

$$\boldsymbol{k = \frac{\theta_{re}}{\theta_m}} \quad \text{2.7}$$

$$\boldsymbol{\theta_{re} = \frac{\pi}{3}\left(\frac{r_i - l_g}{r_e}\right)} \quad \text{2.8}$$

$$\boldsymbol{k_d = \frac{sin(n[\theta_m - \pi]/2)}{n\,sin([\theta_m - \pi]/2)}} \quad \text{2.9}$$

2.4.2.2 Stator Resistance

The per-phase resistance, R_{ph}, of stator windings is the sum of internal resistances, R_i, of each coil in a phase which can be obtained by:

$$\boldsymbol{R_i = \rho_{cu}\frac{l}{A}} \quad \text{……………………………………… 2.10}$$

where ρ_{cu} is the resistivity of copper wire used, L is the length of wire per coil and A is the cross-sectional area of the wire chosen. There are 3 coils in each phase, therefore,

$$\boldsymbol{R_{ph} = 3R_i} \quad \text{……………………..……………….. 2.11}$$

The generator power output per phase can be obtained from the following equation (Kellie *et al.*, 2010)

$$\boldsymbol{P_{ph} = \frac{V_o^2}{4R_{ph}}} \quad \text{……………………….…………….. 2.12}$$

where V_o is the open circuit phase voltage. The generator power output, P_{out} is the sum of power outputs from each phase. For a 3-phase generator,

$$\boldsymbol{P_{out} = 3P_{ph}} \quad \text{………………………………….. 2.13}$$

2.4.2.3 Stator Inductance

The AFPM generator utilizes a coreless stator which results in low internal inductance. The self-inductance of the stator winding can be calculated as follows (Rossouw, 2009)

$$\boldsymbol{L = \left[\frac{q(2l_a+l_e)^2N_c^2}{h}\right]10^{-7}K_n} \quad \text{…………..……….. 2.14}$$

where h is axial height of coil, l_e end winding length of coil and K_n Nagaoka constant. End-winding length of coil is obtained by (Kamper *et al.*, 2008)

$$l_e = 2\theta_m(r_o + r_i)\frac{1-0.6k}{p} \quad \text{……..……..…..…… 2.15}$$

Nagaoka constant, K_n is given by (Rossouw, 2009)

$$K_n = \frac{1}{1+0.9\left(\frac{2l_a+l_e}{2\pi h}\right)+0.32\left(\frac{2\pi w}{2l_a+l_e}\right)+0.84\left(\frac{w}{h}\right)} \quad \text{………… 2.16}$$

where *w* is width of coil side as indicated in Figure 2.9 below.

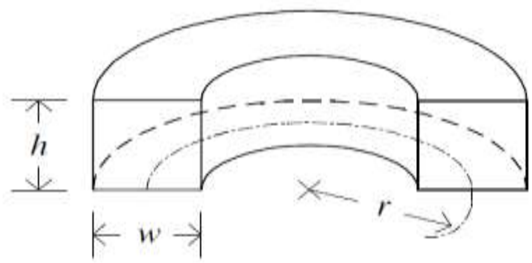


Figure 2.9: Cross-section of the round estimation of stator coil

(Rossouw, 2009)

2.4.2.4 Types of Losses in the Generator

The machine no-load loss consists of loss components in both stator (copper and eddy current losses) and rotor disks (windage and bearing/frictional losses).

Per-phase copper losses are calculated by (Rossouw, 2009)

$$P_{cu} = 3I_{ph}^2R_{ph} \quad \text{………………………………. 2.17}$$

where I_{ph} is the RMS value of stator phase current calculated as follows (Ani, 2013)

$$I_{ph} = \frac{\sqrt{2}}{2}k_wN_{ph}\omega B_p\left(r_{so}^2 - r_{si}^2\right) \quad \text{…………... 2.18}$$

where N_{ph} is the number turns of a stator phase and k_w the winding factor which can be calculated as follows (Won-Young *et al.*, 2007)

$$\boldsymbol{k_w = k_p k_d} \text{ ………………………………….. 2.19}$$

Stator eddy current losses equation is given as (Wang & Kamper, 2004)

$$\boldsymbol{P_{eddy} = \frac{1}{32}\left(\omega B_p d\right)^2 \left(\frac{Q N_{cN_p} l_a}{\rho_{cu}}\right)(\pi d^2)} \text{ ………. 2.20}$$

where d is wire diameter and N_p is the number of parallel strands per conductor.

The mechanical or rotational losses are the sum of the frictional losses occurring in the bearing and the losses due to rotation of the rotor in air, also referred to as windage or air friction losses. The frictional losses in the bearing are estimated using the equation below (Nasrin, 2011)

$$\boldsymbol{P_{fr} = 0.06 k_{fb}(m_r + m_b)\omega} \text{ ………………. 2.21}$$

where m_r and m_b are the masses of rotor disks and bearing respectively. The value of bearing friction coefficient, k_{fb} should be selected in the range of 1-3 m^2/s^2. In this design, the value of 1 m^2/s^2 was selected.

The windage losses can be calculated from the equation below (Nasrin, 2011)

$$\boldsymbol{P_{wind} = \frac{1}{2} C_f \rho_a (2\pi\omega)^3 \left(r_o^5 - r_b^5\right)} \text{ …………... 2.22}$$

where ρ_a is the specific density of cooling medium (air) and r_b is the shaft diameter of bearing. C_f is friction coefficient calculated as follows (Gieras *et al.*, 2004)

$$\boldsymbol{C_f = \frac{3.87}{\sqrt{R_e}}} \text{ …………………..……………… 2.23}$$

where R_e is Reynolds number for outer radius of the machine given by (Gieras *et al*., 2004)

$$\boldsymbol{R_e} = \frac{\boldsymbol{2\pi n_s \rho_a r_o^2}}{\boldsymbol{\mu}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; 2.24$$

where μ is the kinematic viscosity of air and n_s generator speed in runs per second.

2.4.2.5 Generator Efficiency

The total electromechanical efficiency of the generator is given by

$$\boldsymbol{\eta} = \frac{\boldsymbol{P_{out}}}{\boldsymbol{P_{in}}} \times \boldsymbol{100}\% \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; 2.25$$

where P_{out} and P_{in} are generator power output and power input respectively. Power input is obtained by

$$\boldsymbol{P_{in}} = \boldsymbol{P_{out}} + \boldsymbol{P_{loss}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; 2.26$$

$$\boldsymbol{P_{loss}} = \boldsymbol{P_{cu}} + \boldsymbol{P_{eddy}} + \boldsymbol{P_{mech}} \quad \ldots\ldots\ldots \; 2.27$$

$$\boldsymbol{P_{mech}} = \boldsymbol{P_{fr}} + \boldsymbol{P_{wind}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \; 2.28$$

2.5 Finite Element Analysis of AFPM Generator

The Finite Element Analysis (FEA) is a flexible, reliable and effective method for the analysis and synthesis of power-frequency electromagnetic and electromechanical devices (Gottipati, 2007). There are several FEA computer packages available in the market for determining electromechanical parameters by using the analytical or semi-empirical formulae. These packages thus provide a simple way to obtain the electromagnetic field distribution and integral parameters to the user even without having the knowledge of applied mathematics. In this research, Finite Element Method Magnetics (FEMM 4.2) software was used in the analysis.

The performance of FEA was necessary for two main reasons. First, was to determine the possibility of demagnetization of the PMs and the insulation material of the windings. Electric machines are generally limited by thermal constraints (Du-Bar, 2011). The PMs and the insulation material of the windings are components that are sensitive to high temperature. At high speeds, the PMs can become demagnetized by a rise in temperature and this has direct impact on the torque, and hence, the power produced by the machine. Demagnetization of PMs can also be caused by the induced flux due to the current in the windings. The effect of demagnetization directly affects torque and power production by the generator. In FEA, the distribution of magnetic field lines generated by the PMs with respect to the radial symmetrical axis of the magnets can be used to detect for any possibility of demagnetization of PMs at high speeds. A symmetrical distribution of the magnetic field lines with respect to the radial symmetrical axis of the magnets is taken as an indication of negligible influence of currents on resultant magnetic field (Gottipati, 2007), and hence reduced chances of demagnetization.

The second reason was to check for inconsistencies during manufacture. This is achieved by making a comparison between the values of sizing equations and FEMM analysis of generator resistance and inductance. Significant differences in resistance and inductance may indicate a fabrication error (Ani, 2013).

FEMM 4.2 was not used for generator design optimization because the design and development of the generator was guided by availability of materials locally and cost reduction rather than optimized dimensions.

2.5.1 Finite Element Method Magnetics (FEMM 4.2) Program

FEMM 4.2 is a suite of programs for solving low frequency electromagnetic problems on two-dimensional planar and axisymmetric domains. FEMM may be divided into three parts, namely, interactive shell (femm.exe), mesh generator (triangle.exe) and solvers (Meeker, 2003):

a) **Interactive Shell -** The interactive shell is a multiple document interface which consists of a *pre-processor* and a *post-processor*. The *pre-processor* is used for drawing the problems geometry, defining materials, and defining boundary conditions. The *post-processor* used to view solutions generated by the solver. It displays the field solutions in the form of contour and density plots, also allowing the user to inspect field at arbitrary points and plot various quantities of interest along user-defined contours. The results can be post-processed in order to derive the machine integral quantities and associated parameters.

b) **Mesh Generator -** The mesh generator breaks down the solution region into large number of triangles or triangular elements. The advantage of breaking the domain into a number of small elements is that the problem becomes transformed from a small but difficult to solve problem into a big but relatively easy to solve problem (FEMM 4.2, 2013). The solution is approximated by a linear interpolation of the values of potential at the three vertices of the triangle of each element.

c) **Solver -** The data files that define the problem are acquired by each of the solvers and it solves the relevant Maxwell's equations to obtain values for the desired field throughout the solution domain. The magnetics problems solved by FEMM are low frequency problems, in which displacement currents can be ignored. These currents are relevant to magnetics problems at radio frequencies.

2.6 Generator Cost Analysis

Studies have shown that the cost of electricity generated by a wind turbine depends on several factors which include: the site specific factors (e.g. wind speed and quantity of electricity generated, cost of land, and installation cost); cost of wind turbine, and its economic life span; operating and maintenance costs; electricity tariff and incentives and exemptions (Adaramola *et al.*, 2011). The three major component cost categories are turbine (wind turbine components), balance of station (e.g., permitting, transport, assembly, installation), and soft costs (e.g., insurance, construction finance) (Tegen *et al.*, 2010). The specific cost of a wind turbine is also dependent on the rated power but varies widely from one manufacturer to another.

Apart from the cost of the wind turbine which is set by the manufacturers, costs of other activities are location dependent. For instance, the breakdown of wind turbine component and installation costs varies significantly between land-based and offshore turbines (Tegen *et al.*, 2010). From Figure 2.10, the cost of land-based (on-shore) wind turbine accounts for about 68% of all total initial investment cost for wind energy development. On the other hand, the drivetrain alone accounts for up to 37% of the total initial investment cost for wind energy development. The drive train is therefore the most expensive component of a wind turbine and costs about 54% of the total cost of a wind turbine.

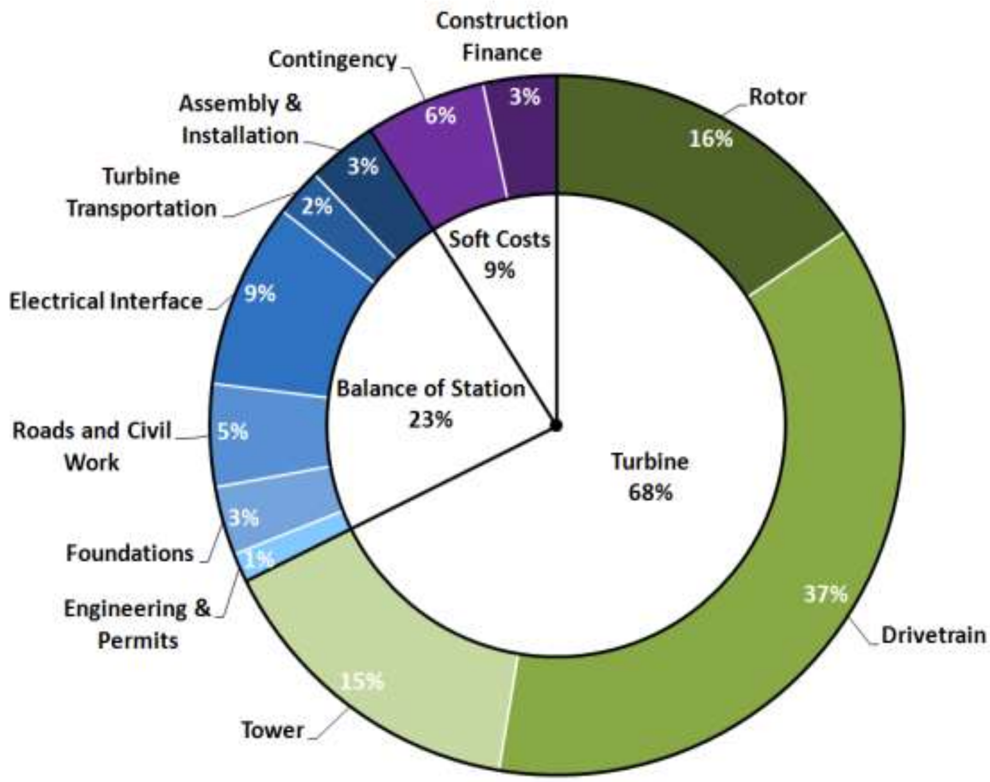


Figure 2.10: Installed capital costs for the land-based wind baseline project

(Tegen *et al.*, 2010).

Accurate estimate of all the costs involved in generating electricity over the life span of a Wind Energy Conversion System (WECS) is essential for its economic viability in order to produce energy at a low operating cost (Gökçek *et al.*, 2007). Out of the three different ways of quantifying the cost of wind turbines, namely, cost per unit kilowatt, cost per unit rotor area, and cost per unit kilowatt hour of electricity produced (Ohunakin *et al.*, 2013); the cost of electricity per unit kilowatt hour is adopted in this study. There are different methods for estimating the operating cost of a unit energy produced by the WECS and whether such an investment makes economic sense. These include Simple Payback, Net Present Value (NPV), and The Levelised Cost of Electricity (LCOE).

Simple Payback, or Payback Period, is the number of years it takes for the energy savings to offset the initial investment – payback can also account for operation and maintenance costs (O&M). The common assumption is the shorter the payback period, the more economical the investment. Simple Payback is attractive because it is easy to calculate and understand. In reality, simple payback can be simply misleading. Payback ignores several important investment characteristics, including: time value of money, cost and savings after payback, increases in energy prices and gains on alternative investment options one might have pursued instead of the Renewable Energy (RE) project. Without these characteristics, Simple Payback generally underestimates the payback period making RE investments appear to be better deals than they really are (Rashford, 2010).

A more flexible and meaningful calculation for evaluating RE projects is NPV which provides the present value of a potential investment by taking all costs and savings for the lifetime of the project and converting them to present value and accounting for the time value of money. NPV can also accommodate energy price increases over time and can be used to directly compare alternative projects. NPV includes more information than Simple Payback and as a general rule, a project makes economic sense if the NPV is positive and greater than the NPV of other alternatives. When comparing two alternatives, such as a wind turbine and solar panels, the one with the larger NPV makes the most economic sense (Rashford, 2010).

The most commonly used method however, is the Levelised Cost of Electricity (LCOE) (Gökçek and Genç, 2009). In this research, LCOE method is used to ascertain the economic analysis of the generator. The LCOE is the price of electricity required for a project where revenues would equal costs, including making a return on the capital invested equal to the discount rate. An electricity price above this would yield a greater return on capital, while a price below it would yielder a lower return on capital, or even a loss (IRENA, 2012). LCOE is most commonly used for evaluating the cost of energy delivered by projects utilizing different generating technologies because it specifically ranks options and determine the most cost-effective energy source. It can also be used to compare the cost of energy from new sources to the cost of energy from existing sources. Because it captures total operating costs, LCOE enables comparisons between significantly different technologies, but it may also be used to compare the cost of energy from variations of the same technology. Options related to components or system design can be evaluated to see what impact they have on LCOE.

The LCOE of renewable energy technologies varies by technology, country and project, based on the renewable energy resource, capital and operating costs, and the efficiency/performance of the technology (IRENA, 2012). LCOE is computed using the following expressions given by (Ohunakin *et al.*, 2013) as:

$$\boldsymbol{LCOE = \frac{CRF}{E_{WT}}\left[I + C_{om(esc)}\right] Cost/kWh} \quad \text{……………………….. 2.29}$$

$$\boldsymbol{E_{WT} = 8{,}760 P_{eR} C_F} \quad \text{…………………………..…………… 2.30}$$

where I is the total capital/initial cost, E_{WT} is the annual energy output in kilowatt hour over the life-time of the WECS, P_{eR} is the rated power output of WECS, C_F is the capacity factor, and CRF and $C_{om(esc)}$ are the capital recovery factor and present worth of the annual cost throughout the lifetime of the WECS, respectively, and expressed in equations 2.31 and 2.32 as given by (Gökçek and Genç, 2009):

$$\boldsymbol{CRF = \frac{(1+r)^{n_o}\, r}{(1+r)^{n_o} - 1}} \quad \text{…………………………………...……….. 2.31}$$

$$\boldsymbol{C_{om(esc)} = \frac{C_{om}}{r - e_{om}}\left[1 - \left(\frac{1+e_{om}}{1+r}\right)^{n_o}\right]} \quad \text{…………...……….……. 2.32}$$

where C_{om}, e_{om}, n_o, and r are the operation and maintenance costs for the first year, escalation of operation and maintenance, useful lifetime of the WECS, and discount rate, respectively. The discount rate can be corrected for inflation rate (*i*) and inflation escalation rate (*e*) using the following expressions (Adaramola *et al*., 2011, Mathew, 2006):

$$\boldsymbol{e_a = (1 + e)(1 + i) - 1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; 2.33$$

Where e_a is the apparent escalation rate, and the real rate of discount (*r*) adjusted for both inflation and escalation can be obtained from the expression (Adaramola *et al*., 2011; Mathew, 2006):

$$\boldsymbol{r = \left(\frac{1+i_r}{1+e_a}\right) - 1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; 2.34$$

Where i_r is the interest rate.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Field Survey Findings on Small Wind Turbine Generators

This research study began by literature review of existing documentation on the status of Kenyan SWTs sector in general, and wind turbine drive train systems in particular. This was considered important in order to become familiar with local context, issues and existing work relating to the SWT sector. However, from the review of literature, it became apparent that the relevant literature on the Kenyan SWT sector, and more specifically wind turbine drive train systems, is rather scarce and of insufficient quality. A field survey was therefore necessary to provide more information and to inform the choice of drive train technology that the study should focus on, in terms of cost effectiveness, efficiency, and feasibility of construction locally.

The field survey targeted the four major companies dealing in SWTs at the time and these were, with location coordinates in brackets, Craft Skills (-1.27749, 36.89338), PowerTechnics (-1.32857, 36.88586), WindGen (-1.34418, 36.88161) and Kijito Wind Pumps (-1.04454, 36.98644), all located within the vicinity of Nairobi (see the map of locations in Figure 3.1). The four provided a good representative sample in terms of companies manufacturing locally (Craft Skills and Kijito Wind Pump) and importing companies (WindGen and PowerTechnics). A structured questionnaire attached in Appendix A was used to conduct the interviews. The structured questionnaire was developed jointly by the Wind Research Group led by the senior research Supervisor. The questions generally sought to find out the different experiences of these dealers in the SWT sector; from the types of wind turbines available in the market, whether they are locally manufactured, assembled or wholly imported, the types of drive trains the turbines utilize (and their advantages and disadvantages), the issue of costs involved, and the level of sales (as a measure of the demand or rate of adoption of such technologies).

Figure 3.1: Map showing sites of field visits

In terms of drive train technologies, Craft Skills make use of used motors and gearboxes which they re-arrange to desired power output. These gearboxes result in bulky and expensive wind turbines which are also susceptible to frequent failures. Kijito Wind mainly deals in wind mills for water pumping. PowerTechnics and WindGen (now re-named PowerGen Renewable Energy) mainly import complete SWTs with in-built more efficient permanent magnet generators. However, these turbines, including their spare parts, are more expensive and there’s limited local skill for their maintenance. Survey samples of drive train from Craft Skills (Plate 3.1) and power generation systems from PowerGen (WindGen) (Plate 3.2) and PowerTechnic (Plate 3.3) are shown below.

Plate 3.1: Power transmission gear-box from Craft Skills

Plate 3.2: A HAWT imported by PowerGen

Plate 3.3: A VAWT imported by PowerTechnic

The conclusion drawn from the field survey was that a locally manufactured low cost SWT, with an efficient drive train transmission system that eliminates the use of gearbox, is an attractive option to the drive train challenge for SWTs in Kenya. Therefore, the power transmission system, specifically generator, became the focus of this study. Design objectives of such a generator were to embrace achieving a good compromise between performance characteristics and feasibility of construction, which results in a cost competitive machine. To meet these objectives and as already highlighted under the Literature Review section in Chapter Two, a direct drive double rotor coreless stator AFPM generator became the transmission system of choice in this research. The requirements of the desired AFPM generator configuration were specified based on the analysis of different SWT generator topologies and on the proposal objectives. The important deductions from these analyses which are relevant for the generator and which formed our design requirements are as follows:

1) Cost of our design need to be lower in comparison with average cost of existing systems to make it affordable and applicable in rural and remote parts of Kenya. One way of doing this is by using local resources (local skills and materials) since the generator contributes significantly to the total turbine cost.
2) The system need to be built such that it can be manufactured and maintained by people with basic technical skills, like those in the informal sector. By building SWT generators locally, growth of the local industry can be stimulated thereby increasing local technical capability for system operation and maintenance.
3) Good operation in low wind speed. To fulfil this requirement the desired generator should have low cogging torque and good efficiency. SWTs are usually self-starting, relying on the torque produced by the wind acting on the blades in order to start, leading to possible starting problems when the wind speed is not high enough. Starting problems are exacerbated when the turbine operates in low wind speed areas and by the presence of cogging in the permanent magnet generator. The combined effect of low wind speed operation

and cogging causes the turbine to experience frequent *start-stop* operation with low periods of sustained operation which has negative consequences on the energy yield (Ani *et al.*, 2012). One way of eliminating the cogging torque is by having a coreless (air cored) stator.

4) The generator should be easy to manufacture and assemble in small workshops. This means that a simple generator design is desired, one which can be built in a small workshop using easily available materials. It also means that the manufacturing process should be as short and as simple as possible.

3.2 Sizing Equations

There are many unknown parameters concerning the design of a PM machine so that it is necessary to fix some of them (Hũng, 2012). The remaining parameters are determined by using sizing equations for finding the starting point for the design of the PM machine. The fixed parameters in this research are provided in Table 3.1 below.

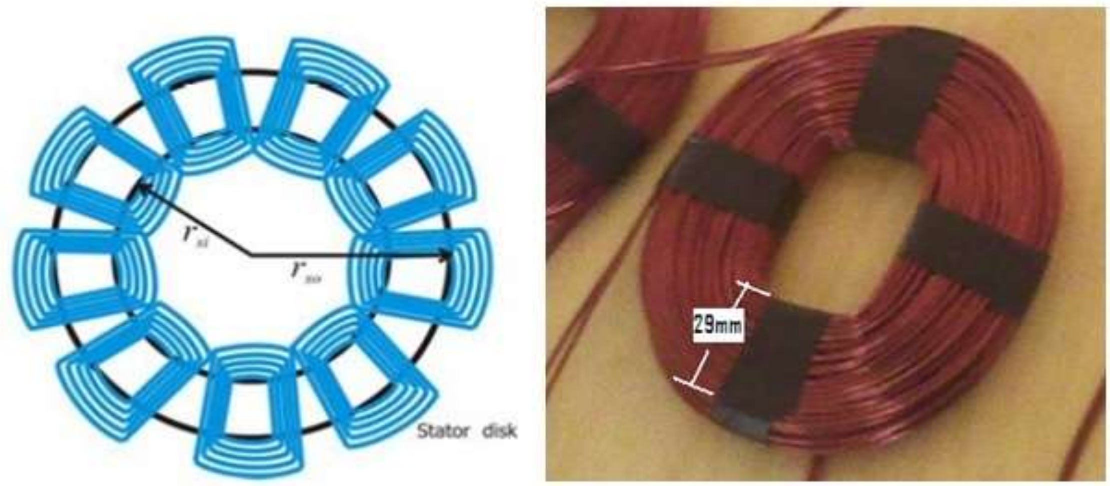
Table 3.1: Generator fixed parameters

Symbol	Quantity	Value
P_r	Rated Power	1kW
N_r	Rated Speed	250 rpm
V_r	Rated Voltage	24V
p	Number of Poles	12
Ph	Phase Number	3
D_r	Rotor diameter	350mm

Some of the fixed parameters such as the generator rated power, rated voltage, and rated speed were agreed upon as default parameters by the Wind Research Group as part of the larger research. At the same time, the study settled on 3-phase generator as opposed to single phase because single phase generators have higher losses and higher vibration due to the pulsations in torque (Piggott, 2003). While single phase generators are simpler to make, normally the wind turbine experiences an abrupt vibration for each pulse. This can hinder turbine performance and cause damaging vibration. It is also more complicated to overcome the inefficiency when rectifying the AC voltage into DC voltage for battery storage (Fahey, 2006). A 3-phase operation overcomes these challenges. In 3-phase connection, at any given point, only one third of the alternator is at peak power, the other two are either dropping or rising to their next peak. In other words, the coils generate AC outputs at different timings and this creates a smoother output to the load (Piggott, 2003). Vibration is reduced not only by having peak currents ⅓ as intense, but also by having them 3 times more often. When rectifying the 3-phase power so that a DC battery can be charged, the current is also much smoother. The cost of extra rectifiers should not be considered an obstacle. They will last a long time if properly selected (Fahey, 2006).

While the decision on how many coils per magnets should be put into the generator is somewhat arbitrary, generally, in a generator producing 3-phase power, when one group of coils is at peak current, the others are not. Therefore the magnets align with only one phase at a time. In other words, for every coil of wire in the 3-phase stator, there are 1.33 magnets (Fahey, 2006) or 3 coils for every 4 magnets (Piggott, 2003). This study settled on 9 coils and 12 magnets.

After fixing the above parameters, the next step was to determine the necessary generator dimension sizing equations. Some of these equations are gathered from valid books and papers, but some of them are devised. For a coreless stator AFPM generator, the inner and outer radii of rotor disk, and hence stator (see Figure 3.2(a)), are set equal (Gieras *et al*., 2004). The inner radius of the rotor, r_i is defined by the diameter of hub bearing and shaft assembly. That is, the inner diameter of the rotor disk cannot be smaller than the bearing diameter since this part of the bearing has to fit into this space (Ani, 2013). Given that the rotor diameter is set at 350mm, the rotor outer radius, r_o is 175mm while rotor inner radius is 129mm.



(a) (b)

Figure 3.2: Stator coil windings:

(a) Illustration of inner and outer stator/rotor radii (Ani, 2013); (b) One of the coil winding used in this research showing coil width.

3.2.1 Generator Dimensions

The geometry of the AFPM generator is described in Figure 3.3. The following dimensions are used during the design procedure:

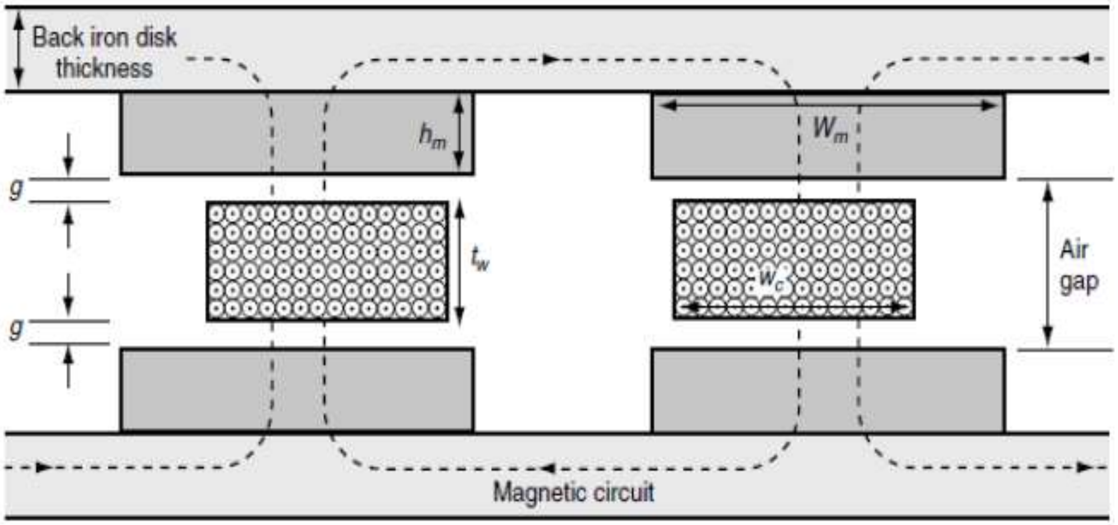


Figure 3.3: Cross-section of AFPM Generator System

(Murphie, 2013).

a) ***Axial Length of the Stator, (L_s):***

In a coreless stator AFPM machine, stator axial length, L_s is equal to stator (winding) thickness, t_w. PM material is best utilized when operating at the point where its energy product is maximum thereby achieving minimum volume and cost of the PM material. For NdFeB permanent magnets in AFPM machines, this point corresponds to the case where $t_w \sim h_m$ (Libert, 2004). Therefore,

$$\boldsymbol{L_s = t_w = h_m} \quad \text{3.1}$$

b) ***Axial Length of the Rotor, (L_r):***

If t_r is the rotor disk thickness, then the axial length, L_r of the rotor can be expressed as:

$$\boldsymbol{L_r = t_r + h_m} \quad \text{3.2}$$

c) Average Air-gap Diameter of the Machine, (D_g):

$$D_g = r_o + r_i \quad \text{……………………...…………….. 3.3}$$

d) Effective Air-gap, (g_e):

A machine must be held with a small air-gap between the rotor and stator for good energy conversion. Literature suggests that air-gap, g between the rotor and stator is 1/1000th the air-gap diameter D_g of the machine (Grauers, 1996). In practice, however, maintaining such a small air-gap is difficult in AFPM machines. Effective air-gap can be expressed as follows:

$$g_e = 2h_m + 2g + t_w \quad \text{……………………………. 3.4}$$

e) Axial Length of the Machine, (L):

$$L = 2L_r + L_s + 2g \quad \text{………………………………. 3.5}$$

f) Average Pole Pitch, (τ_p):

$$\tau_p = \frac{\pi D_g}{p} \quad \text{…………………………………………. 3.6}$$

g) Number of Stator Coils, (Q):

The ratio of number of magnet poles to number of coils for a 3-phase machine is normally taken as 4:3 (Fahey, 2006). This can be mathematically expressed as follows:

$$Q = \frac{3}{4} p \quad \text{…………………………………..…….. 3.7}$$

h) *Number of Turns per Coil, (N_c):*

The number of turns is estimated using Hugg Piggott's formula (Piggott, 2003) for calculating average voltage, V_{avg} per phase of an AFPM generator. For a star connected stator winding, the average phase voltage is calculated as follows:

$$\boldsymbol{V_{avg} = \frac{V_r}{2.72}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. \ 3.8$$

where V_r is the generator rated voltage. The average phase voltage can also be expressed as:

$$\boldsymbol{V_{avg} = \Phi_{ph}.N_{ph}.n_s} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ 3.9$$

where Φ_{ph} is the total flux per phase, N_{ph} is the total number of turns per phase and n_s is $N_s/60$. N_s is the generator rated speed. The total flux per phase can be calculated from the following expression:

$$\boldsymbol{\Phi_{ph} = m.A_m.B_m} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ 3.10$$

where m is the number of magnets per phase, A_m the magnet area and B_m the magnetic flux density.

Total number of turns per phase is expressed as

$$\boldsymbol{N_{ph} = N_c.C_{ph}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ 3.11$$

where N_c is the number of turns per coil and C_{ph} the number of coils per phase.

Combining equations (3.17) and (3.18), we have

$$\boldsymbol{\frac{V_r}{2.72} = \frac{mA_mB_mN_cC_{ph}N_s}{60}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ 3.12$$

The number of turns per coil can now be calculated as follows

$$N_c = \frac{60V_r}{2.72m.A_m.B_m C_{ph}.N_s} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ 3.13$$

i) *Flux Density in the Air-gap, (B_g):*

The air-gap flux density B_g is usually set equal to the magnetic flux density B_m and is calculated as:

$$B_g = B_m = \frac{B_r h_m}{h_m + g + t_w} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ 3.14$$

where B_r *i*s the remanence flux density of the permanent magnet. Appendix B shows the B_r values and other properties of Neodymium Iron Boron (NdFeB) magnets.

Using the sizing equations to calculate generator dimensions and determine its characteristics, the following results as summarized in Table 3.2 below were obtained. The workings are presented in Table 3.3. The mass of active materials in the generator consist of mass of copper windings, permanent magnets, rotor disks and car hub bearing. The different masses were useful in determining generator losses. The mass of PMs is calculated as the product of volume and density. Density of NdFeB magnets is provided by the manufacturer as 7.5g/cm^3. The two rotor disks, car hub, mounting frame, nuts, studs (bolts) and washers were separately weighed. Table 3.4 below gives a summary of masses and costs of the different generator components.

Table 3.2: Generator dimensions and characteristics

Symbol	Quantity	Value
r_o	Outer radius of rotor	175mm
r_i	Inner radius of rotor	129mm
λ	Ratio of inner to outer rotor radius	0.74
D	Diameter of machine	350mm
L_s	Axial length of stator	10mm
L_r	Axial length of rotor	20mm
L_g	Axial length of machine	53mm
h_r	Thickness of rotor disk	10mm
g	Air-gap between stator and rotor	1.5mm
D_g	Average air-gap diameter of machine	304mm
g_e	Effective air-gap	33mm
τ_p	Average pole pitch	0.08
Q	Number of stator coils	9
N_c	Number of turns per coil	110
B_g	Flux density in the air-gap	0.60T

Table 3.3: Design Calculations

INITIAL DATA	DESIGN CALCULATIONS	RESULTS
	Dimensions of the Magnet Magnet Length, l_m = 46mm Magnet Width, w_m = 30mm Magnet Thickness, h_m = 10mm	l_m **= 46mm** w_m **= 30mm** h_m **= 10mm**
	Ratio of Inner to Outer Stator Radius, (λ) r_i = 129mm r_o = 175mm λ = 129/175 = 0.74	λ **= 0.74** r_i **= 129mm** r_o **= 175mm**
r_o = 175mm	**Diameter of the Machine, (D)** $D = 2\ r_o$ = 350mm	D **= 350mm**
h_m = 10mm	**Axial Length of the Stator, (L_s)** $L_s = t_w = h_m$ = 10mm	L_s **= 10mm**
	Rotor Disk Thickness, (h_r) A thickness of 10mm was adopted. Therefore, h_r = 10mm	h_r **= 10mm**
h_r = 10mm h_m = 10mm	**Axial Length of the Rotor, (L_r)** $L_r = h_r + h_m$ = 10 + 10 L_r = 20mm	L_r **= 20mm**
r_o = 175mm r_i = 129mm	**Average Air-gap Diameter of the Machine, (D_g)** $D_g = r_o + r_i$ = 175 + 129 D_g = 304mm	D_g **= 304mm**

g = 1.5mm *h_m = 10mm* *t_w = 10mm*	**Effective Air-gap, (g_e)** Airgap, g used was 1.5mm $g_e = 2h_m + 2g + t_w$ $= 20 + 3 + 10$ g_e = 33mm	**g_e = 33mm**
L_r = 20mm *L_s = 10mm*	**Axial Length of the Machine, (L_g)** $L_g = 2L_r + L_s + 2g$ $L_g = 40 + 10 + 3$	**L_g = 53mm**
p = 12	**Average Pole Pitch, τ_p** $\tau_p = \pi D_g/p$ $= 0.304\pi/12$ $\tau_p = 0.08$	**τ_p = 0.08**
p = 12	**Number of Stator Coils, (Q)** $Q = \frac{3}{4} x\, p$ $Q = 9$	**Q = 9**
V= 24V *P = 1000W* *ρ_{cu} = 1.68x10^{-8} Ωm* *C_c = 0.21m*	**Number of Turns per Coil, (N_c)** $N_c = \frac{AV^2}{3C_c\rho_{cu}P}$ $=\pi(0.8\text{x}10^{-3})^2\text{x}24^2/3\text{x}0.21\text{x}1.68\text{x}10^{-8}\text{x}1000$ $= 109.42$	**N_c=110**
For N40 NdFeB magnet, *B_r = 1.29T* *(Appendix D)*	**Flux Density in the Air-gap, (B_g)** $B_g = B_r h_m/(h_m+g+t_w)$ = 1.29x0.01/(0.01+0.0015+0.01 = 0.6T	**B_g = 0.6T**

Table 3.4: Mass of generator

Component	**Weight (Kg)**
Windings	5.053
Permanent Magnets	2.484
Rotor Disks	9.020
Car Hub	2.200
Mounting Frame	2.600
Nuts, bolts and washers	0.430
Total	**21.787**

3.2.2 Improvement to the AFPM Generator Design

The majority of the AFPM wind turbines are based on the Hugh Piggott design. However, in the design process, it became apparent that there is a major short coming in the Piggott approach that must be addressed if the generator is to be successful for several SWT applications in Kenya. The problem is that AFPM generators are known to have stability problems (Bang *et. al.,* 2008) and besides, the generator assembly in Piggott turbine is all overhung and not well supported. This could cause the tight tolerances to come to zero and make the spinning rotors crash into the stator in strong wind conditions (Kellie *et al.,* 2010). To solve this problem, the AFPM generator design in this research adopted the use of a T – frame (Plate 3.6) for supporting the stator and rotor assembly. Other than providing a strong support to the generator through the hub bearing, the T – frame also provides a flexible mounting support to the turbine blades so that the generator can easily be mounted both on a HAWT as well as a VAWT.

3.3 Generator Model and Simulation in FEMM 4.2 Program

FEMM 4.2 software was used for generator modelling and simulation. The generator was drawn in the interactive shell of the FEMM 4.2 software, while specifying the outline, dimensions and materials of the motors as described below.

First, the problem was defined and the model drawn using nodes, line and arc segments. The problem was defined as follows (Weifang, 2011):

Problem type: Planar
Length of units: mm
Solver Precision: 1e-008
Min. Angle: 30
AC Solver: Succ. Approx

The block labels were then assigned to each solution region, materials added and their properties defined. The materials are Mild Steel for rotor disk; "Air" for the air-gap, with a relative magnetic permeability of 1; magnetic wire type "16AWG" with number of turns as "110" and magnet type as NdFeB 40 entered as "N40." Since N40 was not available in the materials library, this magnet model was built in the library with the assumption that the relative permeability of the magnet is 1.05 (just a touch higher than the magnetic permeability of air). The coercivity was then specified using the equation below:

$$H_c = 155319 \text{ A/m} * \text{sqrt}(BH_{max}/\text{MGOe})$$

$$H_c = 155319 \text{ A/m} * \text{sqrt}(40) = 982324 \text{ A/m}$$

The circuit properties were then specified to be applied to a wound region by selecting “Series” followed by the current value. The modelling considered a case in which a steady current of 1 Amp is flowing through each phase of the stator. Finally, the boundary conditions were set and the "Asymptotic Boundary Conditions" were used as this makes the simulation act as if the analysis were performed on an unbounded domain, rather than a small finite element domain. To do this, the outer edge of the solution was made circular. The boundary condition type was selected as "mixed" and the “c0 coefficient” defined as “1/(uo*1*in).” The problem was then analysed and results viewed.

The FEMM model was created for the entire generator. However, Figure 3.4 indicates only a part of the FEMM model.

3.3.1 Magnetic Flux Distribution

Demagnetization of PMs can occur as a result of induced flux due to the current in the windings (Du-Bar, 2011). The effect of demagnetization directly affects torque and power production by the generator. Thus it is necessary to determine magnetic flux distribution and examine how the stator current influences it. Figure 3.5 shows the distribution of magnetic field lines generated by the permanent magnets. The relatively symmetrical distribution of the magnetic field lines with respect to the radial symmetrical axis of the magnets is taken as an indication of negligible influence of currents on resultant magnetic field (Gottipati, 2007).

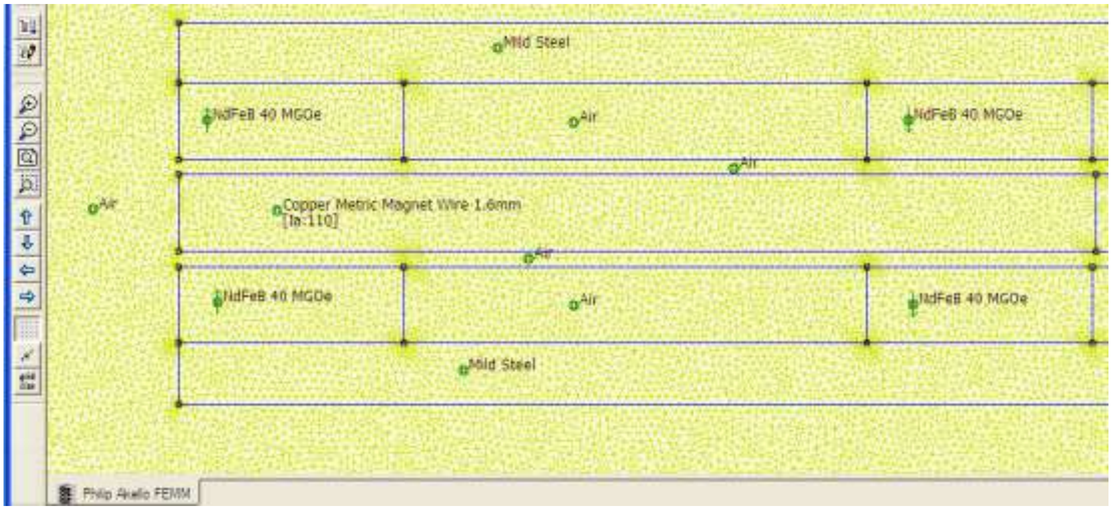


Figure 3.4: A section of 2-D generator model in FEMM 4.2

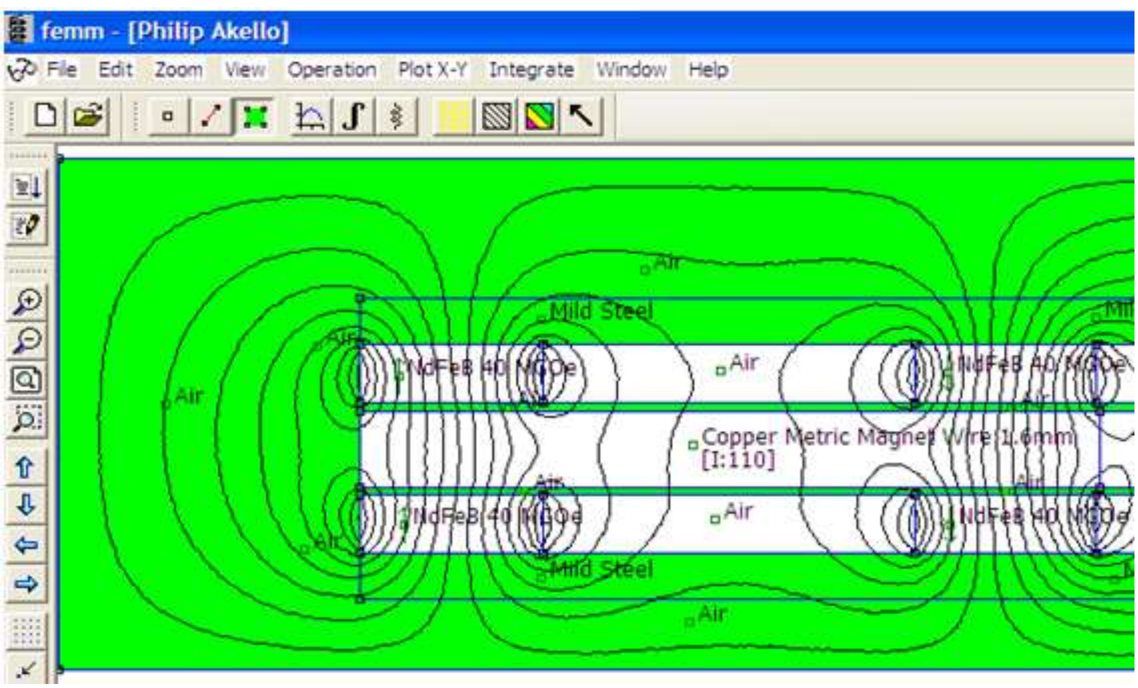


Figure 3.5: Magnetic field lines plot for the AFPM generator

3.3.2 Stator Resistance and Inductance

The obtain the phase resistance and inductance of the stator winding, the permanent magnets on the rotor are changed to air and the current is assigned only to the phase whose self-inductance is to be found. The other phases are given a zero current. The FEMM model is then analyzed and the values for phase resistance and inductance are noted down by clicking on the circuit icon. In our model, the three phases are differentiated by stator winding labels. Phases 1, 2 and 3 coils are labeled as I_a, I_b and I_c respectively. A current of 1A was assigned to Phase 1. The results of circuit analysis are presented in Figure 3.6.

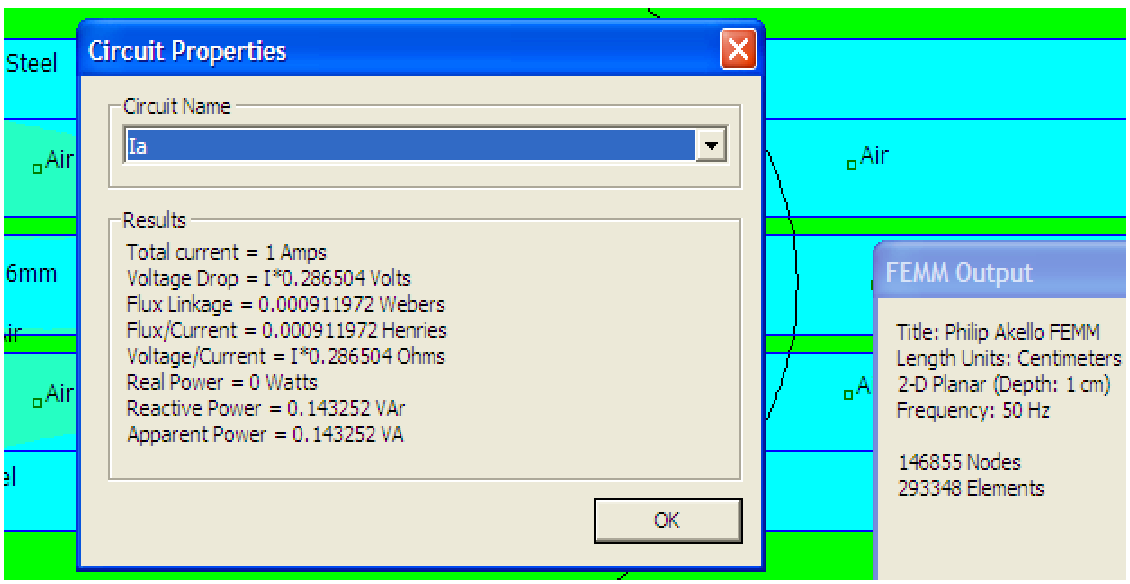


Figure 3.6: FEMM circuit properties for determining inductance and resistance

3.4 Fabrication of the Prototype AFPM Generator

After obtaining the necessary sizing equations as listed in Tables 3.2 and 3.3, the generator was fabricated according to the design specifications. This section provides in brief the process used in the manufacture of the 1kW AFPM small wind generator for charging a 24V battery. The materials used included Neodymium Iron Boron (NdFeB) magnets and copper magnetic wire, mild steel rotor disks, polyester resin, epoxy hardener, fibre cloth, talcum powder, car hub bearing, studs, nuts and washers among others. Some of these materials are illustrated in the Plates below.

Plate 3.4: Rotor disk with magnets

Plate 3.5: Copper magnet wire

Plate 3.6: T- frame Plate

Plate 3.7: Spanners and nuts

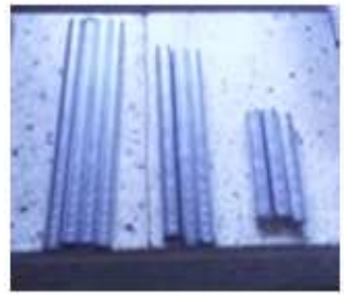


Plate 3.8: Used car hub **Plate 3.9: Mounting studs**

3.4.1 Mould Preparation

A mould is a shaped container in which resin castings are formed. Stator and rotor moulds were cut from plywood together with the stacks. The stacks are the boards serving as the lid and base of mould. The finished moulds for stator and rotor are shown below.

Plate 3.10: Stator mould **Plate 3.11: Rotor mould**

3.4.2 Stator Fabrication

The stator consists of the windings and the epoxy resin winding support. The coils were made by turning the handle of a coil winder designed to accommodate the desired size and shape of stator coils. In our case, the winder was made for round coils with a width of 10mm.

The coil centres were also designed to leave a rectangular space of 46mm x 30mm, which are dimensions of magnet length and width respectively. Special attention was paid to keep the same number of turns per coil and to identify the 'start' and 'stop' end of each coil. These ends were used in connecting the coils together. The coils were weighed to check for consistency. Generally, the difference in weight between any two coils should not exceed 5%. From the design calculations in Table 3.3, the number of turns of each coil was determined as 110. The copper magnet wire used for winding had diameter 1.6mm. Later, the coils were connected by soldering them inside the stator mould to give a three phase configuration. Finally, the polyester epoxy mixture was made according to manufacturer's specifications and poured to make the stator cast. Fibre cloths were used to strengthen the cast. After a period of about 24 hours, the stator manufacture is completed. Three mounting holes equally spaced and marching those of the mounting frame were then drilled. Pictures of stator moulding process are presented in the Plates below.

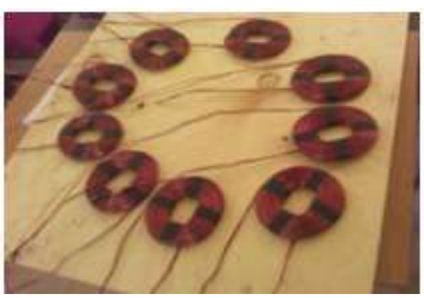


Plate 3.12: Coils after winding

Plate 3.13: Coils in mould

Plate 3.14: Cutting fibre cloth **Plate 3.15: Resin poured on stator**

Plate 3.16: Stator top fibre **Plate 3.17: Complete stator**

3.4.3 Fabrication of Rotor

The rotor component consists of the two rotor disks, permanent magnets and the bearing assembly. The bearing assembly used in this study was a recycled low cost and easily available rear vehicle (Toyota 110) hub bearing components consisting of a hub and a flange (Plate 3.8). The hub connects to the rotor while the flange connects to the mounting frame. The hub bearing also comes with a stub shaft which can easily be used in integrating the generator with a test motor or even turbine blades using coupling mechanism. The rotor disks were cut from steel plates to design dimensions once the hub bearing had been selected. Appropriate holes were drilled on the two rotor disks to allow for connection with the hub bearing. The magnets were glued to the disk surface with the aid of a magnet jig (Plate 3.18) that was specifically designed for this purpose. This jig cut from a piece of plywood guides the magnets to pre-marked locations on the disks ensuring that during rotation, the magnets are not out of phase with the stator coils. The magnets were placed such that a magnet with a north pole on one face is adjacent to a south pole on the other.

The rotors with magnets were then moulded in a similar manner to the stator, the only difference is that one sheet of fiberglass cloth was used and this was placed on top of the magnets. The Plates below show magnet jig and rotor moulding process.

Plate 3.18: Magnet jig

Plate 3.19: Resin mixture on rotor

Plate 3.20: Fibre cloth on rotor

Plate 3.21: complete rotor disk

3.4.4 Generator Assembly

Other than the stator and rotor disks moulds, other requirements before mounting are the mounting frame, car hub, studs, nuts and washers. Necessary tools including spanners and pliers were needed for this task. First, the car hub was greased before being mounted onto the frame. This was followed by the back rotor, stator and front rotor respectively. Appropriate air-gap (1.5mm) between each rotor disk and the stator was observed. Illustrations of the assembling process and the final generator assembly are shown in the Plates below.

Plate 3.22: Car hub on frame

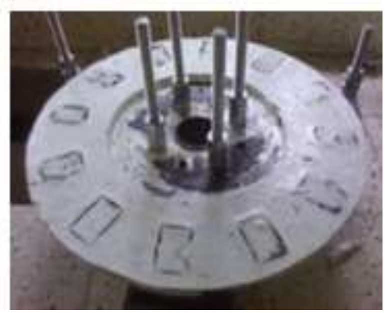


Plate 3.23: Mounting back rotor

Plate 3.24: Adjusting air-gap

Plate 3.25: Complete generator

Plate 3.26: Generator front view

Plate 3.27: Generator back view

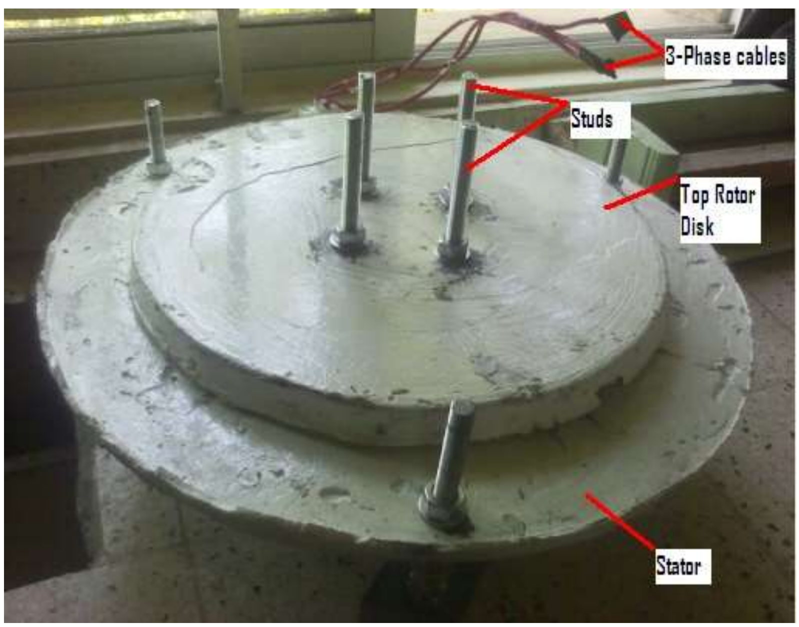


Plate 3.28: Assembled AFPM generator

3.5 The Power Control Unit

One of the greatest challenges associated with wind power is the unpredictable nature of the wind so that even sites with reasonably steady and high wind speeds normally experience variations in speed and direction of the wind. This affects the ability of the wind turbine to deliver power. It is therefore necessary to connect SWTs to a battery because the power they produce is too erratic to be useful without storage. This requires that the generator AC power be converted to DC power for storage. At the same time, some form of control is still needed so as to maintain the desired electrical output. Larger wind turbine systems have complex control systems which automatically track changes in wind direction and speed, and adjust turbine orientation, blade pitch, and generator gearing to maintain the desired electrical output. SWTs, on the other hand, are much less sophisticated, however they generally still need some form of control to improve their longevity and power production. Therefore, other than power conversion from AC to DC for battery storage, the control unit also assists in preventing damage to the wind turbine and the load (battery) and to maximize power production (Gitano-Briggs, 2010).

The control unit (Plate 3.29) consists of a break switch, bridge rectifier, charge controller, dump load and fuse (circuit breaker). The AFPM generator produces three-phase, variable-frequency, variable-voltage, AC power. This AC power is then directed to the bridge rectifier through the brake switch. The brake switch is a useful cut-out functionality feature for periodically stopping the wind turbine from spinning if necessary, for instance, if there is a mechanical or electrical fault or even during periodic maintenance. The bridge rectifier converts the generator AC power to DC. Batteries need DC current (flowing in one direction) to charge them and the diodes in each bridge ensure that current will only flow in one direction into the battery and not discharge it. The result of the rectification of the 3-phase AC is as shown in Figure 3.7. The connection is such that the positive terminals are connected to battery positive via the fuse or circuit breaker while all the negative terminals are connected to the battery negative. The DC voltage is stabilized with two batteries since the generator is configured to produce 24 Volts (DC transmission is also more efficient than AC - unless a transformer is being used to step the voltage). The disadvantage of diodes is that there is a large drop of voltage across them at all times when they are operating. Each diode loses 0.7 volts or so and the circuit always passes through two, losing 1.4 volts or more (Piggott, 2003). Meanwhile, the circuit breaker protects the system wiring from overheating and also protects other control unit devices from serious damages by disabling them in the event of a short circuit.

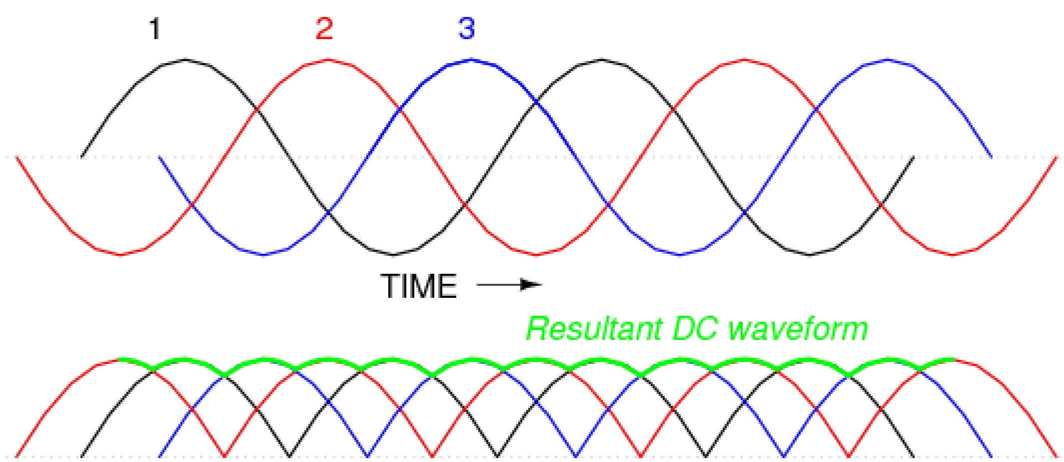


Figure 3.7: Three-phase AC full-wave rectifier output

(Krag and Vernersen, 2010)

A charge controller for SWT charging system protects batteries from overcharge and discharge, just like for a solar Photovoltaic (PV) controller. However, unlike for solar modules, a load must be kept on the generator at all times to prevent the turbine from over-speeding or spinning out of control and getting damaged at high speeds. Instead of disconnecting the generator from the battery like for a PV system, in this case, the charge controller diverts excess energy to a special load that absorbs most of the power from the generator. That load is usually a heating element, which "burns off" excess energy as heat, and this load is known as the dump load. The dump load can also be replaced by a different device such as electric heater so as to put the heat to good use.

The wiring schematic is presented in Figure 3.8. The generator is connected to the VSD and the power control unit (Plate 3.30).

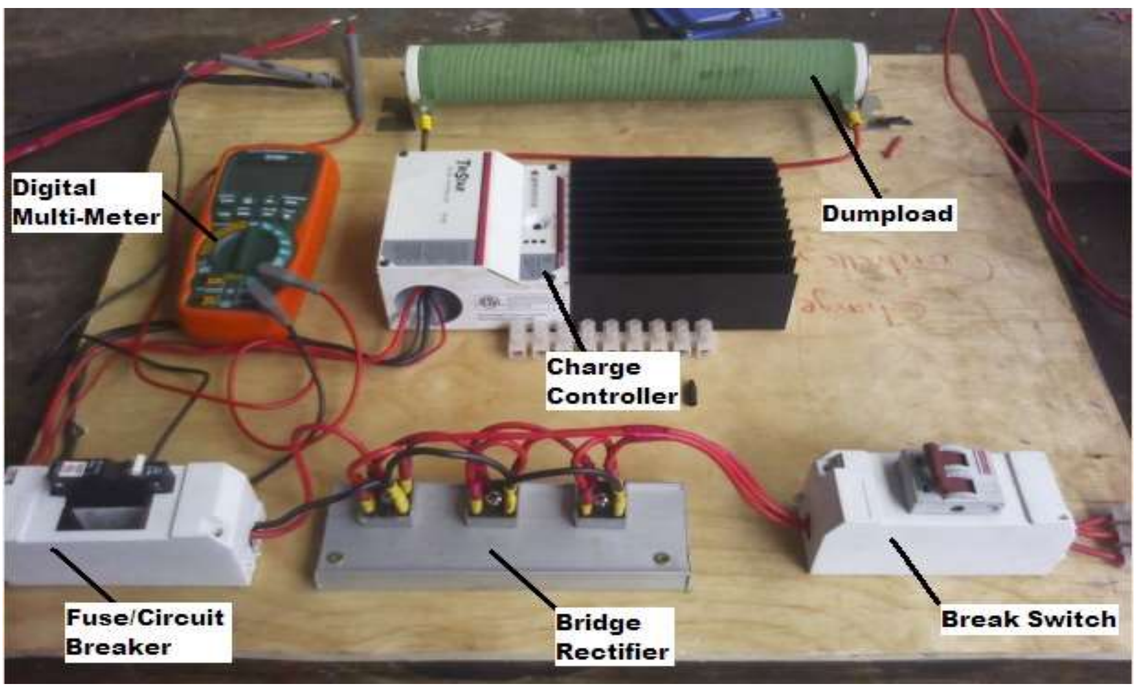


Plate 3.29: The control unit

3.6 Generator Testing

Generator testing was carried out in order to determine its performance and study its operational behavior. This is also useful in making recommendations for further design improvements. Initial generator performance tests were conducted in a workshop using a suitable test set-up to enable generator performance to be measured at a wide speed range. There are two levels of tests that were carried out:

1) No-load (open circuit) Test Situation
2) Full Load Test Situation

3.6.1 Testing at No-load Test Condition

The tests were carried out by coupling the generator to a 3-phase motor. The test set-up consists of a Variable Speed Drive (VSD) providing flexible power control to the motor. Within the VSD (Plate 3.21(a)), the AC supply voltage is converted into DC by the use of a rectifier. DC power contains voltage ripples which are smoothed using filter capacitors. This section of the VSD is often referred to as the DC link. This DC voltage is then converted back into AC to drive the motor (see Plate 3.31(b)). In industrial environments, flexible control, energy efficiency, and low cost maintenance are some of the benefits of VSDs. However, when electric motors are connected with VSDs, some precaution on motor cable length must be taken. Long cable length can create short time overvoltage at the motor terminal. This phenomenon results in premature ageing of the motor winding insulation and eventually the motor itself may fail (Vang and Chiari, 2013). It is therefore advisable to use a short cable length.

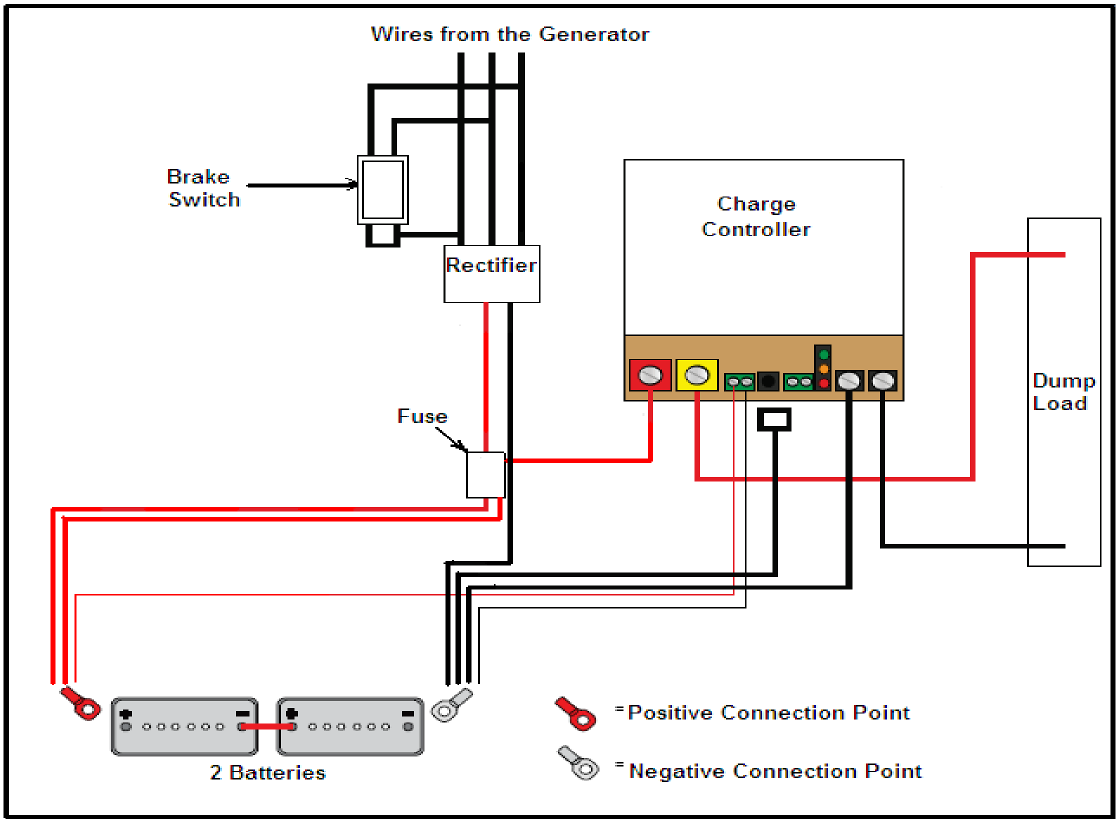


Figure 3.8: The wiring schematic

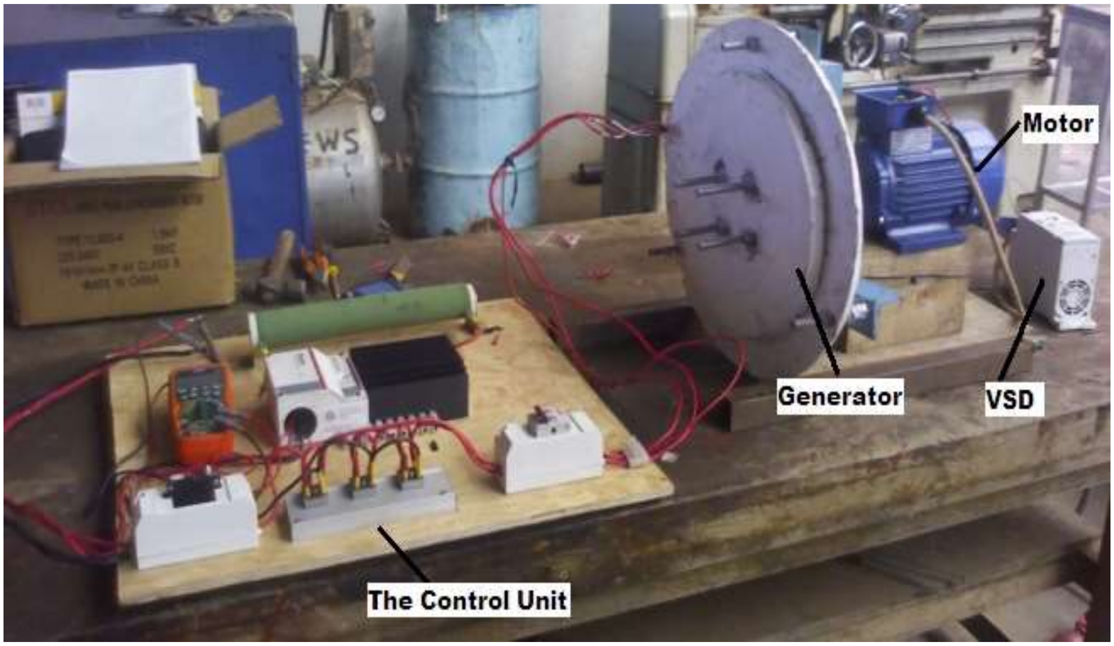
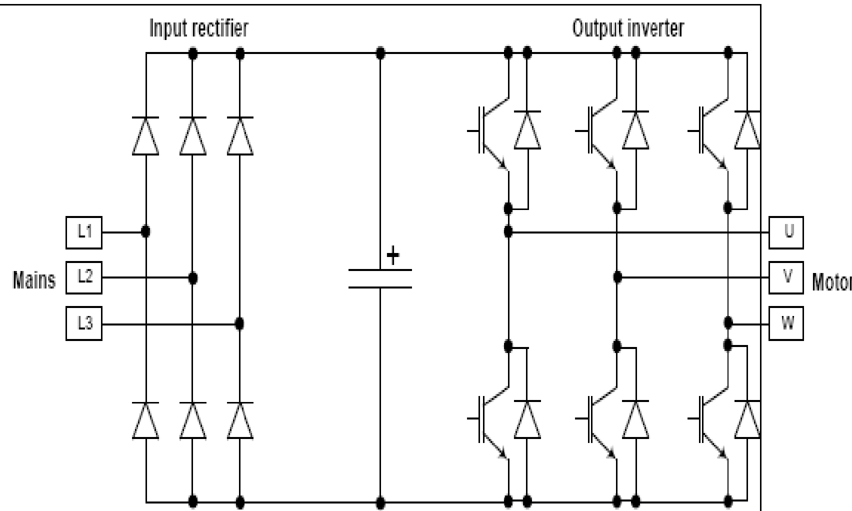


Plate 3.30: The AFPM generator connected to VSD and the power control unit

The motor is used as a prime mover emulating the mechanical characteristics of a wind turbine. The VSD measures the input frequency (hence speed in rpm) into the generator. A multi-meter (Plate 3.32(a)) is used to measure line ac-voltages. The combination of a VSD and motor is a cheaper, faster and very effective option for generator testing that is also suitable for use in small workshops. Common methods of testing generators often employ the more expensive lathe machines or DC motors that are associated with bigger workshops.

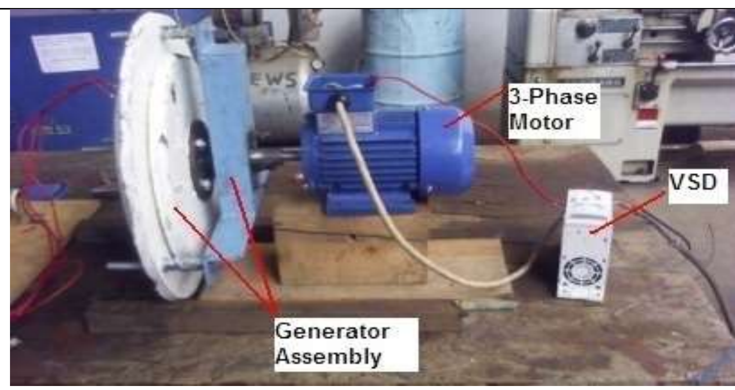
Plate 3.32(b)) shows the generator connected to the motor and VSD. Measurements taken were open circuit voltages at different generator speeds.



(a) (b)

Plate 3.31: VSD and a basic schematic of VSD linked to a motor

(Vang & Chiari, 2013)



(a) (b)

Plate 3.32: Digital Multi-meter with data logger and generator test set-up

3.6.2 Testing at Load Conditions

Load tests were carried out by loading the generator with the battery through the power control unit, where the three phase generator AC output is rectified to DC output. The battery load is connected to the rectifier output. Plate 3.33 shows how the rectifier terminals are connected to one battery. During the rectifier-battery load test, the generator speed is varied at low speeds using the VSD and the multi-meter is used to measure electrical output power (current and voltage). The rectifier-battery load test was performed to evaluate how the generator would operate in the field under low wind speed conditions.

Plate 3.33: Battery load connected to rectifier output terminals

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Field Survey Findings

The field survey revealed that in deed there is low rate of adoption of SWTs in Kenya. Major reasons for this situation are the high costs involved (includes cost of set-up, repair and maintenance), lack of consumer awareness of existence of the technologies, and frequent failures of the drive-train. In Kenya, the findings further revealed that the locally manufactured drive trains for electricity production mainly consist of used gearboxes which result in slightly cheaper turbines as compared to the imported turbines. However, they generally lack quality, are less efficient, easily breakdown and produce less power. The imported turbines, on the other hand, utilize PM generators. They are produced by foreign suppliers and are generally more reliable and efficient. Their main disadvantages are their high costs including spare parts and the missing local skills and knowledge about the working of these turbines.

The conclusion drawn from the field survey was that a locally manufactured low cost SWT, with an efficient drive train transmission system that eliminates the use of gearbox, can play a great role in improving the performance of SWTs in Kenya. Therefore, the power transmission system, specifically generator, became the focus of this study.

4.2 Generator Performance Analysis

From the test set-up in Plate 3.32(b), measurements recorded were generator voltages at different motor frequencies which were then converted to speed in rpm. The results of measurements are tabulated in Table 4.1. It can be observed that there is an increase in open circuit voltages as the generator speed increases.

Performance equations under section 2.4.2 are used in calculating generator phase resistance, phase inductance, power output, no-load losses, and efficiency. The machine loss consists of loss components in both stator and rotor parts. Sample calculations at rated speed for all the parameters are demonstrated below using equations 2.2 to 2.31. Results of measurements and corresponding calculations are presented in Table 4.1.

Generator Power Output at rated speed

Speed of rotation of generator, N = 250rpm,

Open circuit voltage, V_{oc} = 14.84V

Copper resistivity, ρ_{cu} = 1.68×10^{-8} Ωm

Length of each coil, l = 22m

Wire diameter = 1.6mm

Wire cross-section area, $A = \pi d^2/4 = 2.01 \times 10^{-6} m^2$

a) Angular speed of generator, $\omega = 2\pi N/60$

$= 2\pi \times 250/60$

$=$ **26.19 rad/s**

b) Internal resistance per coil, $R_i = \rho_{cu} \frac{l}{A}$ ……………equation (2.10)

$$= \frac{1.68 \times 10^{-8} \times 22}{2.01 \times 10^{-6}}$$

$=$ **0.1839Ω**

c) Generator phase resistance, $R_{ph} = 3R_i$ ……………....equation (2.11)

$= 3 \times 0.1839$

$=$ **0.5517Ω**

d) Per-phase generator power output, $P_{ph} = \frac{V_{oc}^2}{4R_{ph}}$ ………..equation (2.12)

$= 1\ 4.84^2/(4 \times 0.5517)$

$=$ **99.79W**

e) Total generator power output, $P_{out} = 3P_{ph}$ ……………....equation (2.13)

$= 3 \times 99$

$=$ **299W**

Generator No-load Losses

a) Generator Copper Losses, $P_{cu} = 3I_{ph}^2 R_{ph}$ ………….……equation (2.17)

$$I_{ph} = \frac{\sqrt{2}}{2} k_w N_{ph} \omega B_p (r_{so}^2 - r_{si}^2)$$ ………….….equation (2.18)

Number of turns per stator phase, $N_{ph} = 330$

Angular speed of generator, $\omega = 26.19$ rad/s

Stator outer radius, r_{so} = rotor outer radius, r_o = 175mm

Stator inner radius, r_{si} = rotor inner radius, r_i = 129mm

Air-gap flux density, $B_g = 0.6$T

Number of coils per stator phase, $n = 3$

Number of poles, $p = 12$

Total number of stator coils, $Q = 9$

Generator air-gap, $g = 1.5$mm

Generator axial length of air-gap, $l_g = 2g = 3$mm

Peak air-gap flux density, $B_p = \frac{2\sqrt{3}B_g}{\pi}$ ………......……equation (2.2)

$= \frac{2\sqrt{3} \text{ X } 0.6}{\pi}$

$=$ **0.66T**

Winding factor, $k_w = k_p k_d$ …………………..………….equation (2.19)

Distribution factor, $k_d = \frac{sin(n[\theta_m - \pi]/2)}{n\,sin([\theta_m - \pi]/2)}$ ………....……..equation (2.9)

Pitch factor, $k_p = \frac{\sin(\theta_m[1-k]/2)\sin(k\theta_m/2)}{(k\theta_m/2)}$ …………...….equation (2.5)

$$\theta_m = \frac{\pi p}{Q} \text{ ……………………………….……………..equation (2.6)}$$

$$k = \frac{\theta_{re}}{\theta_m} \text{ ………………………………………..equation (2.7)}$$

$$\theta_{re} = \frac{\pi}{3}\left(\frac{r_i - l_g}{r_e}\right) \text{ …………………………..……equation (2.8)}$$

$$r_e = \frac{r_i + r_o}{2} \text{ ……………………………...……equation (2.3)}$$

$$= \frac{r_i + r_o}{2}$$

= [(175+129) x 10^{-3}]/2

= **0.152**

$$\theta_{re} = \frac{\pi}{3}\left(\frac{r_i - l_g}{r_e}\right)$$

= [π(0.129-0.003)/0.152/3]

= **0.87**

$$\theta_m = \frac{\pi p}{Q}$$

= 12π/9

= **4.19**

$$k = \frac{\theta_{re}}{\theta_m}$$

= 0.87/4.19

= **0.21**

$$k_p = \frac{\sin(\theta_m[1-k]/2)\sin(k\theta_m/2)}{(k\theta_m/2)}$$

$$= \frac{\text{Sin}(4.19[1-0.21]/2)\ \text{Sin}(0.21 \times 4.19/2)}{(0.21 \times 4.19/2)}$$

= **5.06 x 10^{-4}**

$$k_d = \frac{sin(n[\theta_m - \pi]/2)}{n\, sin([\theta_m - \pi]/2)}$$

$$= \frac{\text{Sin}(3[4.19-\pi]/2)}{3\text{Sin}([4.19-\pi]/2)}$$

= **1.0**

Winding factor, $k_w = k_p k_d$

= **5.06 x 10^{-4}**

$I_{ph} = \frac{\sqrt{2}}{2} k_w N_{ph} \omega B_p (r_{so}^2 - r_{si}^2)$

$= \frac{\sqrt{2}}{2}$ x 5.06 x 10^{-4} x 330 x 26.19 x 0.66 x (0.175^2 – 0.129^2)

= **0.03A**

Per-phase copper loss, $P_{cu} = 3 I_{ph}^2 R_{ph}$

= 3 x 0.03^2 x 0.5793

= **0.0016W**

b) Stator Eddy Current Losses, $P_{eddy} = \frac{1}{32} (\omega B_p d)^2 \left(\frac{Q N_c N_p l_a}{\rho_{cu}}\right) (\pi d^2)$

Diameter of copper magnet wire, *d* = 1.6mm

Number of turns per coil, N_c = 110

Number of parallel strands per conductor, N_p = 1

Active length of stator winding, $l_a = r_o - r_i$ ……………… …equation (2.13)

= 0.175-0.129

= **0.046m**

Stator eddy losses, P_{eddy} =

$$\frac{1}{32} (26.19\ x\ 0.66\ x\ 0.0016)^2 \left(\frac{9\ x\ 110\ x\ 0.046}{1.68\ x\ 10^{-8}}\right) (\ \pi\ x\ 0.0016^2)$$

= **0.52W**

c) Frictional losses, $P_{fr} = 0.06 k_{fb} (m_r + m_b) \omega$ ……………….…equation (2.4)

Bearing friction coefficient, k_{fb} = 1 m^2/s^2

Mass of rotor disks (including magnets), m_r = 14.504 Kg

Mass of hub bearing, m_b = 3.10 Kg

Frictional losses in bearing, P_{fr} = 0.06 x $(6.504 + 2.1)26.19$

= **27.66W**

d) Windage losses, $P_{wind} = \frac{1}{2} C_f \rho_a (2\pi\omega)^3 (r_o^5 - r_b^5)$……………..equation (2.31)

Generator speed in runs per second, n_s = 250/60

Shaft diameter of bearing, r_b = 55mm = 0.055m

Rotor outer diameter, r_o = 175mm = 0.175m

Specific density of cooling medium (Air) at 1 atm, 20°C, ρ_a = 1.2 Kg/m^3

Dynamic viscosity of air at 1 atm, 20°C, μ = 1.50 x 10^{-5} m^2/s

Reynolds number, $R_e = \frac{2\pi n_s \rho_a r_o^2}{\mu}$ ………………………..…..equation (2.22)

$= \frac{2\pi \, x \, 250 \, x \, 1.2 \, x \, 0.175^2}{60 \, x \, 1.50 \, x \, 10^{-5}}$

= **6.41 x 10^4**

Coefficient of friction, $C_f = \frac{3.87}{\sqrt{R_e}}$ ………………………..…..equation (2.23)

$= \frac{3.87}{\sqrt{64,100}}$

= **0.02**

Windage losses, $P_{wind} = \frac{1}{2} \, x \, 0.02 \, x \, 1.2 \, x \, (2\pi \, x \, 26.19)^3 (0.175^5 - 0.055^5)$

= **6.70W**

Generator Efficiency

Total mechanical power loss, $P_{mech} = P_{fr} + P_{wind}$

= 27.66 + 6.70

= **34.36W**

Total power loss, $P_{loss} = P_{cu} + P_{eddy} + P_{mech}$

= 0.0016 + 0.52 + 34.36

= **34.88W**

Input power into the generator, $P_{in} = P_{out} + P_{loss}$

= 299 + 34.88

= **<u>333.88W</u>**

Generator efficiency, $\eta = \frac{P_{out}}{P_{in}} \times 100\%$

$= \frac{299}{333.88} \times 100\%$

= **<u>89%</u>**

<u>Stator Inductance</u>

Number of stator coils per phase, q = 3

Number of turns per coil, N_c = 110

Number of poles, p = 12

Rotor outer diameter, r_o = 175mm = 0.175m

Rotor inner diameter, r_i = 129mm = 0.129m

Active length of stator winding, l_a = 0.046m

Axial height of coil, h = 10mm = 0.01m

Width of coil side, w = 29mm = 0.029m (Figure 3.11(b))

Coil pitch or coil span, θ_m = 4.19

Weibull shape parameter, k = 0.21

End-winding length of coil, $l_e = 2\theta_m(r_o + r_i)\,\frac{1-0.6k}{p}$

$= 2\ x\ 4.19(0.175 + 0.129)\,\frac{1-0.6\ x\ 0.21}{12}$

= **<u>0.19</u>**

Nagaoka constant, $K_n = \frac{1}{1+0.9\left(\frac{2l_a+l_e}{2\pi h}\right)+0.32\left(\frac{2\pi w}{2l_a+l_e}\right)+0.84\left(\frac{w}{h}\right)}$

$= \frac{1}{1+0.9\left(\frac{2\ x\ 0.046+0.19}{2\pi\ x\ 0.01}\right)+0.32\left(\frac{2\pi\ x\ 0.029}{2\ x\ 0.046+0.19}\right)+0.84\left(\frac{0.029}{0.01}\right)}$

= **<u>0.13</u>**

Stator phase inductance, $L = \left[\frac{q(2l_a+l_e)^2 N_c^2}{h}\right] 10^{-7} K_n$

$$= \left[\frac{3(2\,x\,0.046+0.19)^2 110^2}{0.01}\right] 10^{-7} x\ 0.13$$

= **<u>0.003758H</u>**

Table 4.1: No-load Measurement and Calculation Results

N (rpm)	ω (rad/s)	V_{oc} (V)	P_{ph} (W)	P_{out} (W)	P_{cu} (W)	P_{eddy} (W)	P_{fr} (W)	P_{wind} (W)	P_{loss} (W)	P_{in} (W)	P_{out}/P_{in}	η
30	3.14	2.81	3	10	0.00	0.01	3.32	0.03	3	14	0.75	76
43	4.50	3.57	7	21	0.00	0.02	4.76	0.08	5	26	0.81	78
65	6.81	5.06	13	38	0.00	0.04	7.19	0.23	7	45	0.84	82
82	8.59	6.29	20	59	0.00	0.06	9.07	0.41	10	69	0.86	85
95	9.95	7.63	24	72	0.00	0.08	10.51	0.60	11	83	0.87	88
105	11.00	8.56	30	89	0.00	0.09	11.62	0.77	12	102	0.88	89
144	15.09	10.40	49	146	0.00	0.17	15.93	1.69	18	164	0.89	89
177	18.54	11.45	59	177	0.00	0.26	19.58	2.83	23	200	0.89	89
188	19.70	12.09	66	197	0.00	0.29	20.80	3.29	24	222	0.89	89
200	20.95	12.76	73	220	0.00	0.33	22.13	3.84	26	246	0.89	89
235	24.62	13.97	88	263	0.00	0.46	26.00	5.74	32	296	0.89	89
250	26.19	14.84	99	297	0.00	0.52	27.66	6.70	35	332	0.89	89
300	31.43	16.41	121	364	0.00	0.75	33.19	10.57	45	408	0.89	89
312	32.69	16.84	128	383	0.00	0.81	34.52	11.66	47	430	0.89	89
350	36.67	18.23	150	449	0.00	1.02	38.72	15.55	55	504	0.89	89
390	40.86	19.97	179	538	0.00	1.27	43.15	20.38	65	603	0.89	89
412	43.16	20.89	196	589	0.00	1.42	45.58	23.37	70	660	0.89	89
454	47.56	22.67	231	694	0.00	1.72	50.23	29.79	82	776	0.89	89
486	50.91	23.78	254	763	0.01	1.97	53.77	35.32	91	854	0.89	89
504	52.80	24.20	264	791	0.01	2.12	55.76	38.68	97	887	0.89	89
517	54.16	25.21	286	858	0.01	2.23	57.20	41.23	101	959	0.89	89
576	60.34	27.52	341	1,022	0.01	2.77	63.72	54.02	121	1,143	0.89	89
621	65.06	29.30	386	1,159	0.01	3.22	68.70	65.19	137	1,296	0.89	89
628	65.79	29.27	386	1,157	0.01	3.29	69.47	67.04	140	1,296	0.89	89

4.2.1 Generator Resistance and Inductance

The generator phase resistance and inductance are calculated and the results compared with those of FEA analysis. This serves as a way to check for inconsistencies during manufacture (Ani, 2013). Significant differences between FEA and calculated values of phase resistance and inductance may indicate fabrication inconsistency. From the simulation results in Figure 3.6,

Phase inductance, $L = (flux / current) = 0.000911972H = \underline{0.9120mH}$.

Phase resistance, $R_{ph} = (Voltage / Current) = (1*0.286504)\ \Omega = \underline{0.2865\Omega}$.

The calculated values of phase resistance and inductance are compared with those from FEA analysis in table 4.2 below.

Table 4.2: Resistance and inductance results

Parameter	**Sizing Equation**	**FEMM Analysis**
Resistance	0.5517 Ω	0.2865 Ω
Inductance	0.003758H	0.0009120H

It can be observed that calculated values of stator phase resistance and inductance are slightly higher than the desired FEA values. While the differences are not very large, it is worth noting that there's need for improving the fabrication process through better workmanship as these differences indicate slight inconsistency in the fabrication.

4.2.2 Generator Power Curve

A plot of open circuit generator power curve in Figure 4.1 shows that power output increases with increase in generator speed. The power output peaks at about 1.2kW after which further increase in generator speed beyond 600 rpm does not increase generator power output. Since SWTs usually operate under relatively low wind speed regimes, power at lower rpm (around rated speed of 250 rpm) is much more crucial to take into account.

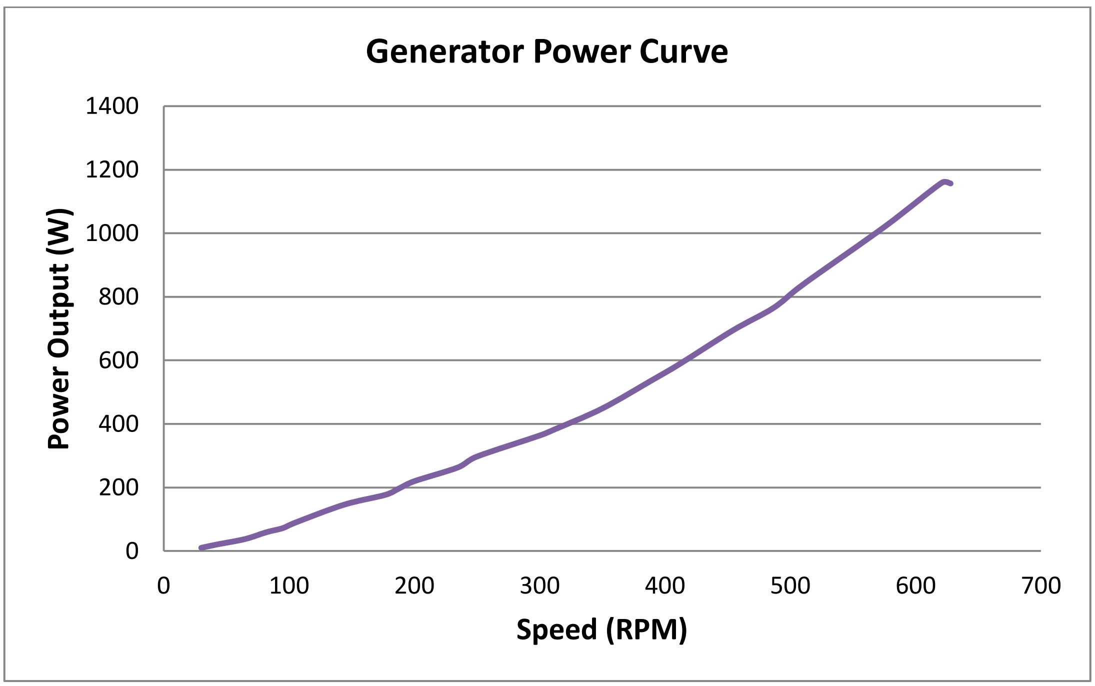


Figure 4.1: Generator power curve

Since the theoretical maximum power that this kind of AFPM generator can produce is 1.7kW (Kellie *et. al*., 2010), the 1.2kW maximum power produced by the generator under this study is therefore considered as significantly high.

4.2.3 Analysis of No-load Losses

The graph of no-load losses against speed is presented in Figure 4.2. The losses were calculated using equations (2.17) – (2.28) and the results tabulated in Table 4.1. Mechanical losses make significant contribution to the total generator losses. A summary of contribution of each loss at rated speed is presented in Table 4.3.

Table 4.3: Generator losses at rated speed, 250 rpm

Symbol	**Loss Component**	**Value**	**% Contribution**
P_{fr}	Friction/Bearing	27.66W	79
P_{wind}	Windage	6.70W	19
P_{eddy}	Eddy currents	0.52W	2

It can be observed that mechanical losses account for 98% of total losses. The bearing friction losses accounts for the biggest share of the mechanical losses and stands at 79% of total losses. The loss contribution due to stator eddy current is only 2% of total losses at rated speed. Copper losses were insignificant and were therefore not plotted on the graph.

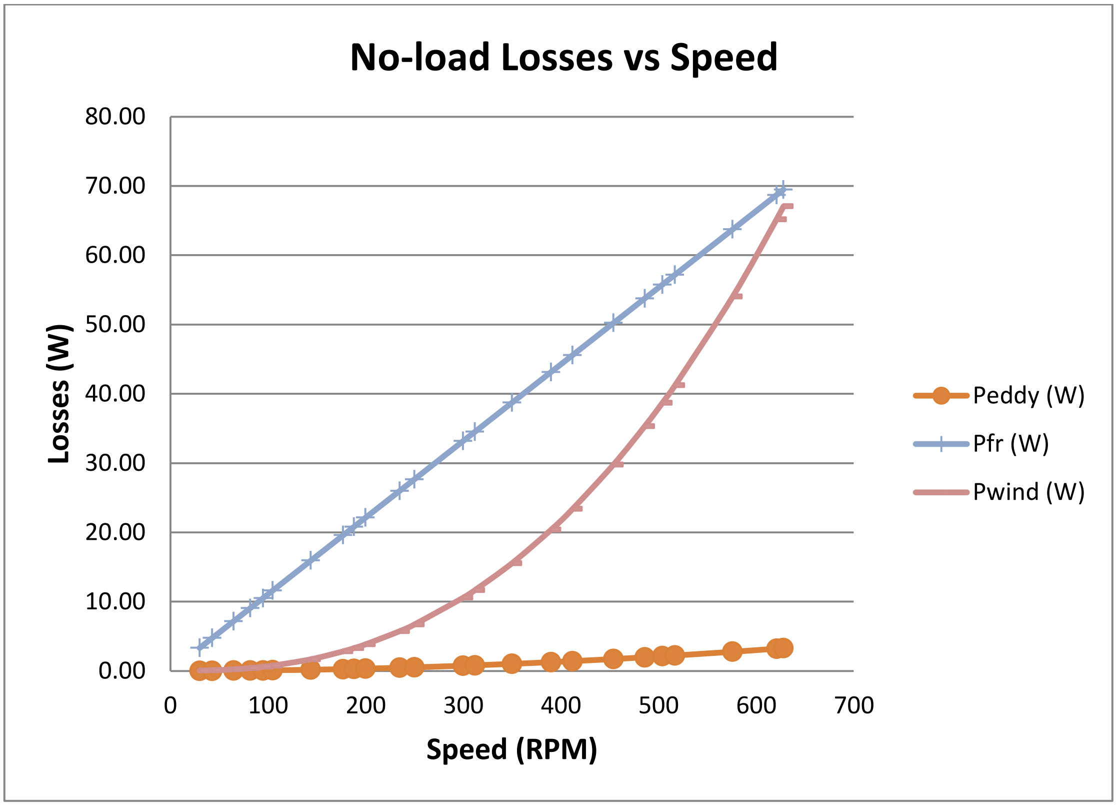


Figure 4.2: No-load losses curve

In comparison with other research work, most of the losses in core-less AFPM generators are mechanical losses, which, for instance, can account for up to 93% of total generator losses (Ani, 2013). In this study, mechanical losses are also the leading and account for 98% of total losses.

4.2.4 Generator Performance at Load Test

The generator is run at low speeds and at short time intervals. The battery charging voltages and currents at the different generator speeds are presented in Table 4.4 below. The generator begins battery charging when charging voltage is about 24V because the generator has been designed for a 24V system. From Table 4.4, the generator speed of about 154 rpm (2.82m/s) produces battery charging voltage of 23.97V (approx. 24V) and current 4.15A. This speed is referred to as the generator cut-in speed for battery charging. The generator power output at this speed is 99.48W. This corresponds to the minimum power that a SWT coupled to this generator and the control unit should produce in order to start charging the battery.

Table 4.4: Charging voltages and currents at different speeds

Speed (rpm)	Charging Voltage (V)	Charging Current (A)	Charging Power (W)
38	3.67	0.18	0.66
60	6.54	1.17	7.65
81	10.13	1.36	13.78
103	14.69	2.36	34.67
119	18.23	2.93	53.41
131	20.32	3.49	70.92
143	22.12	3.94	87.15
154	23.97	4.15	99.48
164	24.83	5.54	137.56
229	24.98	6.23	155.63
245	25.06	7.19	180.18
250	25.68	7.86	201.84
258	25.54	7.92	202.28

Another observation is that at the generator rated speed of 250rpm, battery charging attains a peak voltage level of 25.68V which is about 7% above the battery system standard voltage of 24V. The voltage peaks because the battery system attains full charge condition. Graphs of charging voltage and charging current against generator speed are shown in Figures 4.3 and 4.4 respectively. As the battery continues to be charged (load increases) to rated value, the output power and voltage also increases until voltage reaches peak level (remaining nearly constant). At this point power produced also begins to decline (see Figure 4.5).

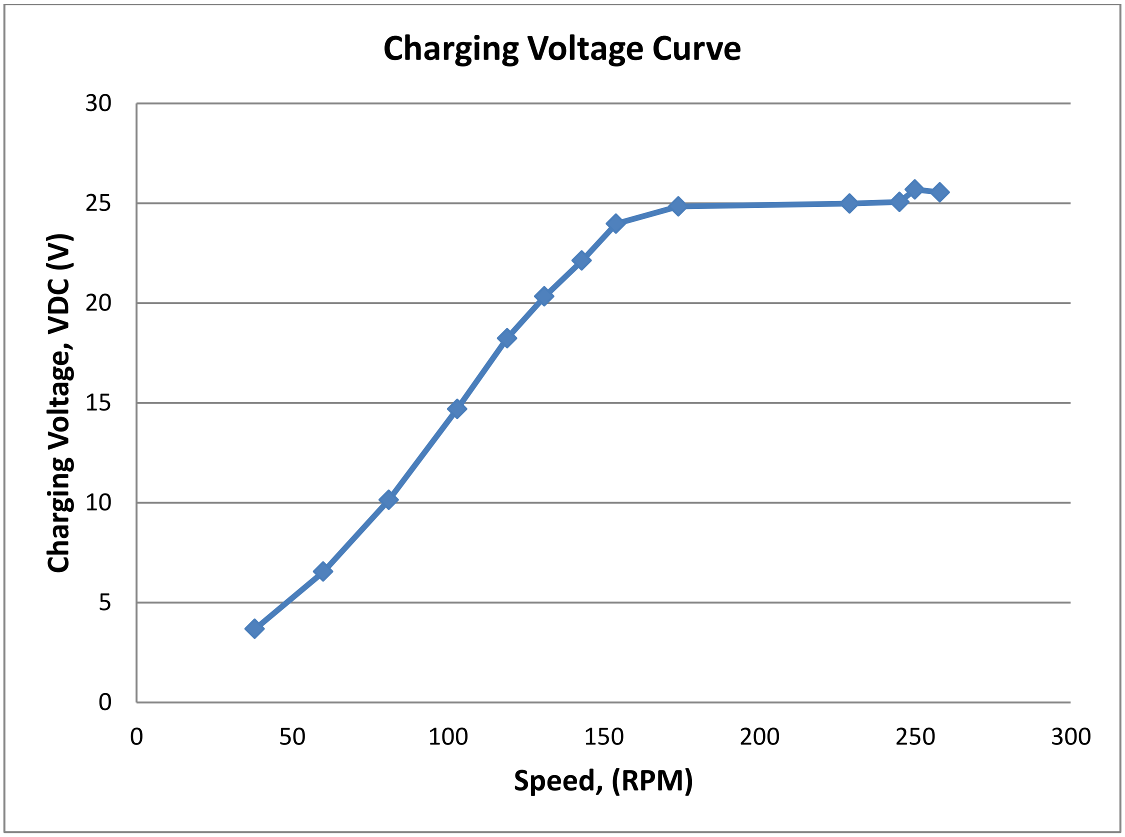


Figure 4.3: Charging voltage (VDC) curve

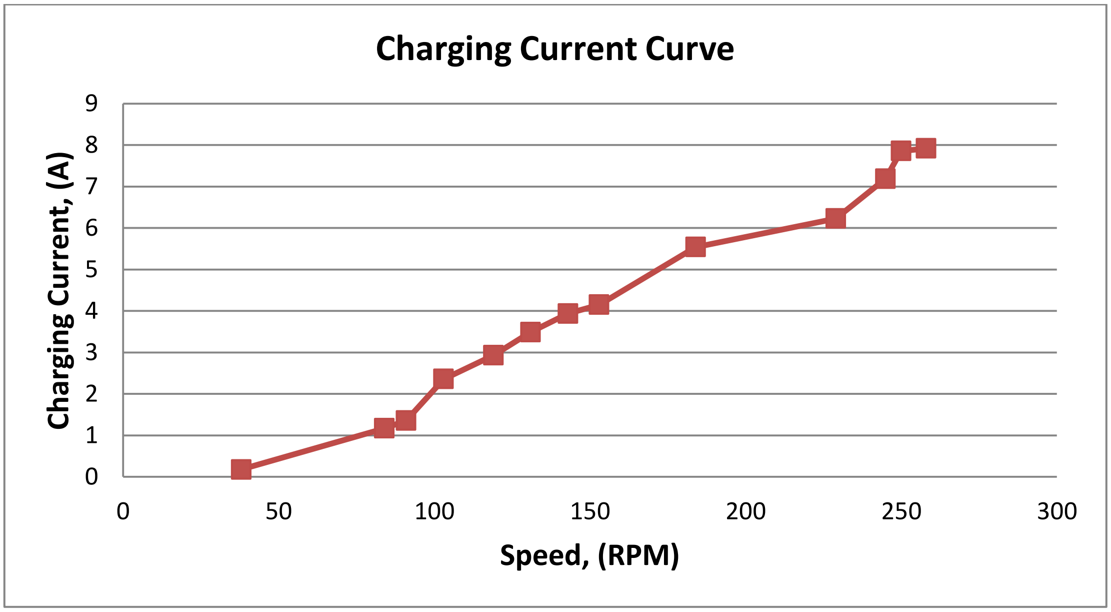


Figure 4.4: Generator charging current curve

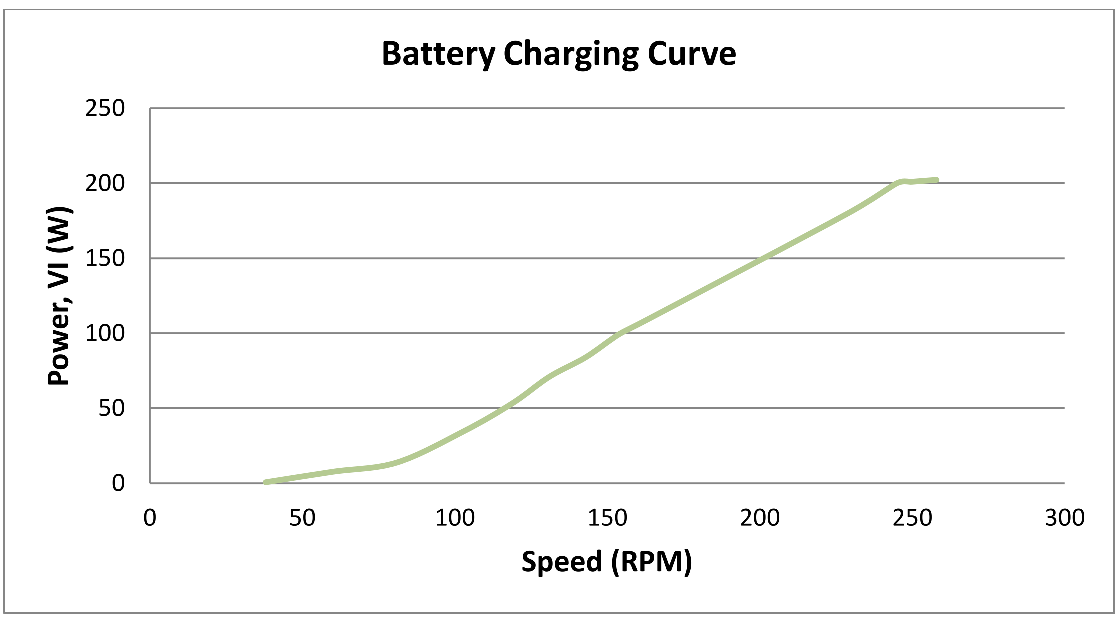


Figure 4.5: Battery charging curve

4.2.5 Generator Efficiency

Efficiency is the ratio of the output energy (or power output) to the input energy (or power input). It is the measure of how much of the energy given to a device or machine is consumed by it in order to function, when modifying a specification of that energy (Hemami, 2012). Input energy, or power input, was obtained from equation (2.26) while power output was calculated from the measurement results. The graph of generator efficiency is presented in Figure 4.6. The efficiency increases from lower speeds to a maximum of 89% at rated speed and beyond. In comparison with similar work, this efficiency is acceptable as high for a non-optimized prototype (Ferreira *et al.*, 2007) and is near the acceptable maximum efficiency for AFPM machines. The maximum efficiency of the typical AFPM is in the range of 90 to 97% (Auinger 2001, Hey *et. al*., 2010). Mechanical losses are largely responsible for the lower efficiency at low speeds.

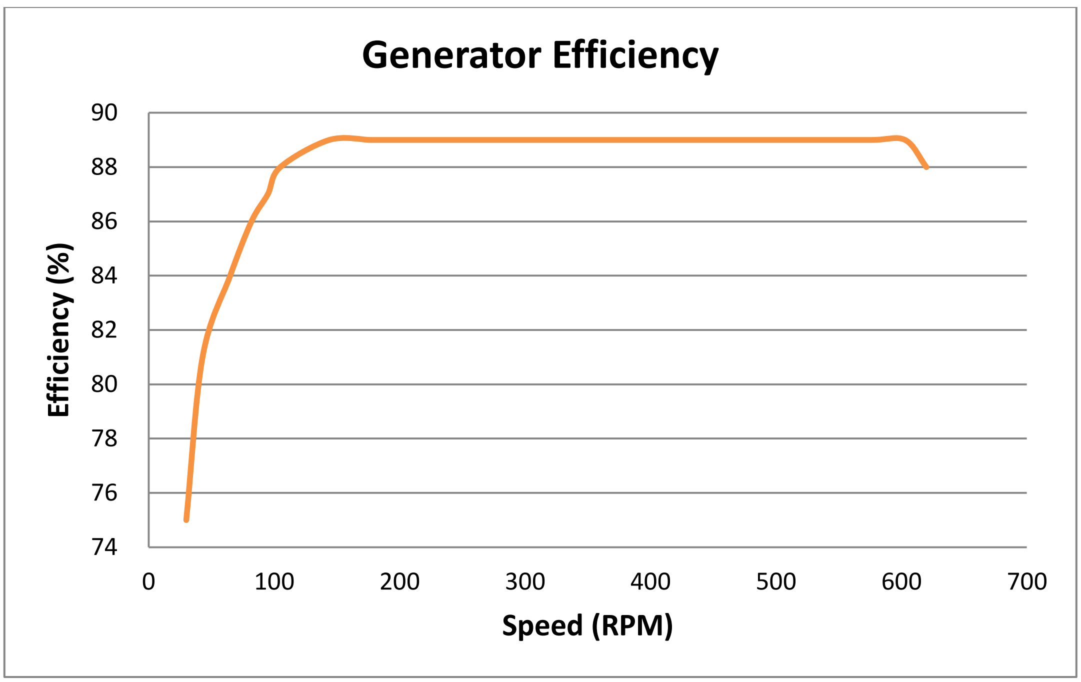


Figure 4.6: Generator efficiency against speed

However, some power is lost in the rectification process leading to low battery charging efficiency. The power loss is attributed to the diodes in the bridge rectifier because they usually experience a large drop of voltage across them at all times when in operation (Piggott, 2003). Charging efficiency at rated speed is about 68% (ratio of charging power at rated speed to generator output power at rated speed). Therefore the efficiency of bridge rectifier is about 76%.

4.2.6 Estimating Cut-in-Wind speed for Battery Charging

Bridge rectifier efficiency can be included in equation (1.3) and the equation used to estimate the cut-in-wind speed at which SWTs of different rotor blade lengths connected to this generator will start battery charging. The new equation is presented below:

$$\boldsymbol{P_{min} = \frac{1}{2} C_p \rho_a A_s v_w^3 N_g N_{br}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; 4.1$$

where P_{min} is the minimum power for battery charging and N_{br} is the bridge rectifier efficiency.

The SWT should produce minimum power of 99.48W (Table 4.3) at generator cut-in-battery charging speed of 154rpm to charge the battery. The rotor blade power coefficient C_p is assumed to be 0.45, which is below the theoretical limit (Betz limit) of 0.59 as a result of the inefficiencies and losses attributed to different configurations, rotor blades profiles, finite wings, friction, and turbine designs (Ragheb and Ragheb, 2011). A sample calculation for a SWT with rotor blade length of 2m is illustrated below:

Minimum power, P_{min} = 99.48W

Power coefficient, C_p = 0.45

Density of air, ρ_a = 1.2 kg/m^3

Generator efficiency, N_g = 0.89

Bridge rectifier efficiency, N_{br} = 0.76

Rotor swept area, A_s = $\pi r^2 = 4\pi$

From equation (4.1), Speed of wind, $v_w = \left(\frac{P_{min}}{C_p \rho_a A_s N_g N_{br}}\right)^{\frac{1}{3}}$

$$= \left(\frac{99.48}{0.45\ x\ 1.2\ x\ 4\pi\ x\ 0.89\ x\ 0.76}\right)^{\frac{1}{3}}$$

= **3.5 m/s**

The results for different other rotor blade lengths are presented in Table 4.5 below.

Table 4.5: Estimated cut-in-wind speeds for different rotor blade lengths

Rotor blade length (m)	**Cut-in-wind speed for battery charging (m/s)**
1.0	5.6
1.5	4.2
2.0	3.5
2.5	3.0
3.0	2.7

4.3 Economic Analysis of the Generator

4.3.1 Cost of Generator

Table 4.6 below shows the estimated market value for the AFPM generator in terms of its cost.

Table 4.6: Cost of generator

Component	Cost (Kshs)
Windings	6,000
Permanent Magnets	21,600
Rotor Disks	10,000
Car Hub	3,500
Mounting Frame	1,200
Nuts, bolts and washers	1,000
Sub-total	43,300
VAT (16%)	6,928
Logistics	3,000
Labour cost	5,000
Total	**58,228**

Most 1 kW SWT power transmission systems currently in use cost between Kshs 89,000 and Kshs 98,000 (see Table 4.7 below and Appendix B). The AFPM generator therefore costs 35 – 41% cheaper than locally manufactured SWT transmission systems of the same capacity.

Table 4.7: Wind Turbine Transmission Costs and Characteristics of Select Kenyan Companies

Name of Company	Type of Turbine	Major Transmission Components	Cost of Wind Generator/ Transmission System (KES)	Nature of Wind Business
Craftskills	HAWT	Used gearbox & motor	98,000	Assembler
RIWIK	HAWT	Permanent magnets	89,000	Manufacturer

4.3.2 Economic Cost Analysis of the Generator

In using the LCOE method to evaluate the costs of kilowatt hour of energy produced by the generator, the following assumptions were taken into consideration:

i. The lifetime (n_o) of generator is considered to be 20 years.
ii. Interest rate (i_r) and inflation rate (i) are taken as 16% and 8%, respectively. The escalation rate is taken as 5%. (Values of interest and inflation rates derived from 2015 Facts and Figures Report by Kenya National Bureau of Statistics).
iii. Operating and maintenance cost (C_{om}) is assumed to be 6% of the generator cost which falls within the annual operation and maintenance costs which have been reported to vary from about 1% to 7% of the initial system cost (Manwell *et al*., 2009 and Nouni *et al*., 2007). Given the higher assumed initial operation and maintenance costs, the escalation rate of operation and maintenance ($C_{om(esc)}$) is assumed to be 0%. (Ohunakin *et al*., 2013).
iv. The generator is also assumed to produce the same amount of energy output each year during its useful lifetime, at a site with mean wind speed of about 4 m/s, which is the average wind speed for most parts of Kenya (SWERA 2008; RCMRD-MoE, 2005).
v. Exchange rate is 1 US$=KES 92.

LCOE was calculated from equations (2.29) to (2.34).

$$LCOE = \frac{CRF}{E_{WT}}\left[I + C_{om(esc)}\right] Cost/kWh$$

Total capital/initial cost of generator, I = Kshs. 58,228

Useful lifetime of the generator, n_o = 20 years

Operation and maintenance cost for the first year, C_{om} = 6% of Kshs. 58,228

= Kshs. 3,494

Escalation rate of operation and maintenance, $C_{om(esc)}$ = 0%

Interest rate, i_r = 16%

Inflation rate, i = 8%

Escalation rate, e = 5%

Rated power output, P_{eR} = 1 kW

Capacity factor at rated speed, $C_f = \frac{297W}{1000W}$ = 30%

Apparent escalation rate, $e_a = (1+e)(1+i) - 1$

= (1+0.05) (1+0.08)

= **<u>0.134</u>**

Discount rate adjusted for inflation and escalation,

$$r = \left(\frac{1+i_r}{1+e_a}\right) - 1$$

$$= \left(\frac{1+0.16}{1+0.134}\right) - 1$$

= **<u>0.02</u>**

Capital recovery factor, $CRF = \frac{(1+r)^{n_o}\, r}{(1+r)^{n_o} - 1}$

$$= \frac{(1+0.02)^{20}\ x\ 0.02}{(1+0.02)^{20} - 1}$$

= <u>0.06</u>

Annual energy output, $E_{WT} = 8{,}760 P_{eR} C_F$

= 8760 x 1 x 0.3

= **<u>2628 kWh</u>**

Levelised Cost of Electricity, $LCOE = \frac{CRF}{E_{WT}}\left[I + C_{om(esc)}\right]$

$= \frac{0.06}{2628}$ x 58,228

= **<u>Kshs 1.33/kWh or US$ 0.014/kWh</u>**

The current cost of electricity in Kenya is about KES 20.01/kWh or US$0.2175/kWh (KPLC, 2015). From the calculated LCOE value of US$0.014/kWh, under the assumed conditions, it can be concluded that electricity generation by this type of transmission system is an economically viable option. If Government incentives, such us zero-rating of permanent magnets used for SWTs are provided to encourage investment in wind energy development, the costs would reduce further, making SWTs an even more economical option for generating electricity for majority rural households without access to grid connection.

It should be noted that LCOE is sensitive to all the input parameters and the degree of sensitivity can be classified into two different groups. The first group is made up of the wind turbine cost, the civil work and infrastructure costs, the interest rate, and the operation and maintenance costs. When the value of these parameters are increased, the LCOE increases, and hence, they have negative impact on the economic viability of wind energy system development. The second group comprises the capacity factor and useful life of the wind turbine. These parameters affect the LCOE very positively, that is, LCOE decreases as their values increase. This explains why a site with wind resource that provides high wind turbine capacity factor is desirable economically (Ohunakin *et al*., 2013). In addition, by increasing the generator lifespan from 20 to 25 years, the LCOE is observed to decrease by about 14% (from US$0.014/kWh to US$0.012/kWh). Economic life span of the generator and turbine in general, influences the cost calculations of wind energy systems. Generally, the life of a wind turbine may vary from 20 to 30 years, and designing a generator system to last longer will distribute the initial cost of the turbine over more number of years, and this will in turn reduce the annual cost of operation (Mathew, 2006).

4.4 Summary of Results

The performance results and analysis of the AFPM generator has been presented. The following is a summary from this chapter.

a) The generator costs 35-41% cheaper than locally manufactured SWT electric power transmission systems.

b) Comparison of FEA and sizing equation shows that the calculated values of stator phase resistance and inductance are slightly higher than the desired FEA values. While the differences are not very large, it is worth noting that there's need for improving the fabrication process through better workmanship as these differences indicate slight inconsistency in the fabrication.

c) The contribution made by mechanical losses, especially bearing losses, is higher as compared to other no-load losses at rated speed. It was shown that bearing loss is 27.66W (about 79% of no-load losses) at 250 rpm. The windage loss is also significant standing at 6.70W (about 19% of total losses). Losses due to eddy currents were however very low at 0.52W (8% of total losses).

d) The maximum power output of the generator is around 1.2kW which is slightly beyond the rated power of 1kW.

e) The generator has a low cut-in speed for battery charging at 154 rpm. At the generator rated speed of 250rpm, battery charging attains a peak voltage level of 25.68V which is about 7% above the battery system standard voltage of 24V.

f) The maximum generator efficiency at no-load conditions was found to be 89%, which is reasonably high as the maximum efficiency of a typical AFPM is in the range of 90 to 97% (Auinger 2001, Hey *et. al*., 2010). The generator efficiency is also acceptable as high for a non-optimized prototype (Ferreira *et al.*, 2007). Charging efficiency at rated speed is about 68% meaning that efficiency of bridge rectifier is about 76%. The reduced efficiency is a result of power loss in the cables.

g) The Levelised Cost of Electricity (LCOE) for the generator was US$0.014/kWh, under the assumed conditions. Electricity generation by this type of transmission system is therefore an economically viable option.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

Axial flux permanent magnet machines are an attractive option for low speed direct drive electricity generation by SWTs. While the set of analytical expressions relied on may lack the precision and accuracy that a final analysis deserves, the obtained prototype achieves a good compromise between performance characteristics and feasibility of construction locally, while giving room for further research and optimization of this machine structure. The conclusions drawn from this thesis are presented with respect to the field survey findings and contribution to knowledge. Recommendations for further research are also presented.

5.1 Potential for Small Wind Turbines in Kenya

The field survey findings revealed that in deed there is low rate of adoption of SWTs in Kenya. Major reasons for this situation are the high costs involved (including cost of set-up, repair and maintenance), inadequate consumer awareness of existence of the technologies, and frequent failures of the drive-train. This thesis proposes the following measures to be taken for increased adoption and long-term stability of SWT industry in Kenya.

First, an enabling policy environment that acts as an incentive to the development of SWT industry should be created. The government's Feed-in-Tariffs (FiTs) have tended to attract mainly big investors dealing with large wind turbines (above 500 kW per turbine) such as the Ngong wind park and the Lake Turkana Wind project. FiTs have also tended to support wind projects for electricity generation that is fed into the grid. Appropriate incentives, such as tax exemptions and preferable loans, are needed to promote uptake of SWT stand-alone or mini-grid systems, which can then complement the government's rural electrification efforts.

The SWT market also requires support through consumer awareness on existing technologies, and on the potential sites with good wind speeds for SWT installations, among others. The market can also be strengthened through the development of information feedback mechanism between the consumers, manufacturers, research institutions and the government, leading to better design of machines, programmes and policies.

Finally, and as the sector develops, greater emphasis should be placed on technology transfer by supporting local production of quality SWTs as opposed to importation of ready-made SWTs which are more expensive to buy and maintain. For instance, this can be achieved by supporting further research in the sector by universities, skills development, and further incentives that attract production of quality low cost SWTs in Kenya. This could further provide employment opportunities in the entire value.

5.2 Thesis Contributions

The following is a summary of contributions from this thesis:

a) It has provided additional information on the status of SWT sector in Kenya and specifically on drive train technologies for power generation, which from the review of literature, is information that has not been documented before. In this thesis, an analysis of different generator topologies has been provided and the choice of Axial Flux Permanent Magnet generator as the best option for SWTs in Kenya justified, in terms of performance and feasibility of production locally. The generator was further developed confirming that it can be fabricated using locally available materials, and that its construction is feasible in a small workshop using basic tools.

b) Another contribution is the method of performance testing of the generator using a combination of VSD and AC motor. This is a cheap, fast and very effective local option for generator testing that is also suitable for use in small workshops. Common methods of testing wind generators often employ the more expensive lathe machines and variable speed DC motors that are associated with bigger workshops. The generator was successfully tested by this method and its performance analysed.

c) From the generator analysis, the thesis has proposed the adoption of the AFPM generator by further illuminating its superior performance characteristics as opposed to locally used gear box-motor combinations, since the generator is efficient at low speeds, cost effective, has high power output and is economic in terms of electricity produced.

d) The final contribution is toward design improvement. The majority of the AFPM wind turbines are based on the Hugh Piggott design with the generator assembly all overhung and not well supported. This could cause the tight tolerances to come to zero and make the spinning rotors crash into the stator in strong wind conditions (Kellie *et al.*, 2010). Another challenge is that most AFPM generators are known to have stability problems (Bang *et. al.*, 2008). In this thesis, the AFPM generator design has adopted the use of a T – frame (Plate 3.6) for supporting the stator and rotor assembly. Other than providing a strong support to the generator through the hub bearing, the T – frame also provides a flexible mounting support to the turbine blades so that the generator can easily be mounted on either a HAWT or a VAWT.

5.3 Recommendations

The following are recommendations for further research:

There is need for improving the performance of this generator. One way of achieving improved performance is through better workmanship especially in the fabrication process in order to have more precise air-gap spaces between the rotor disks and the stator. This results in higher generator AC voltages. Another way is to use stronger magnets which then increase the flux density in the generator air-gap. The increased flux density also results in higher AC voltages which make it possible to reduce the number of turns of stator coil windings and this will in turn reduce stator weight, minimize stator resistance and hence increase generator efficiency.

From the analysis of generator power losses, it is apparent that the contribution made by mechanical losses, especially losses from the car hub (tapered roller) bearings, is higher as compared to other no-load losses. There's additional power loss in the control unit attributed to the diodes in the bridge rectifier. It is recommended that further research should be carried out to investigate the use of improved car bearing and diodes or alternative replacements for the same.

A final recommendation is that the use of VAWTs with the AFPM generators in Kenya should be investigated**.** The use of VAWTs is not popular in Kenya despite its numerous advantages. The vertical rotational axis of the VAWTs allows the generator to be located at the bottom of the tower. This greatly simplifies installation. At the same time, the exclusion of nacelle results in a much lighter tower/mounting frame and this reduces structural loads and problems with erecting the tower. These advantages make VAWTs an attractive option for power generation using the generator.

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APPENDICES

Appendix 1: Questionnaire used during Field Survey

TITLE: DEVELOPMENT OF A DIRECT DRIVE ELECTRICAL TRANSMISSION SYSTEM FOR USE IN SMALL WIND ENERGY APPLICATIONS IN KENYA

About the project

Mr. Philip Oketch Akello is a student pursuing MSc. in Energy Technology at the Institute of Energy and Environmental Technology (IEET) of JKUAT. As part of his Masters research, he is undertaking a survey that seeks to engage the stakeholders in Kenya's wind energy sector in the development of an efficient locally manufactured transmission system for use in small wind energy application systems. In this regard, your firm is one of those pre-selected to assist him with information in the development of this transmission system.

As a precursor to begin the development process, this questionnaire seeks to understand your role in the small wind turbine sector, the challenges experienced in manufacture, sale and maintenance of wind turbines and obtain your opinion on the challenges, expectations and possible solutions to better provide a niche for the small wind turbine. Your support and participation is thus highly appreciated.

Section 1: Developer information

Name of Organization: ……………………………………….……………………………..

Contact person(s): ………………….………… Physical Address: …………………………

Postal address: ………………… Postal Code: ………….. Town/City: …………………….

Tel: …………………………. Email: ………………………. County: …………………………

Organization Type: NGO/ CBO ☐ Registered Company ☐ Educational institution ☐ Others ☐ (if others please specify ……………………………………….)

Number of year involved in wind issues: 0 – up to 2 years ☐ 3 – up to 5 years ☐ over 5 years ☐

Nature of wind business (tick all applicable): Manufacturing ☐ Import &/or export ☐ Reseller ☐ Distributor ☐ assembler ☐ Others ☐ (if others please specify **………..)**

Section 2: Technology information

Model Number	**Rated Capacity (Watts) or relevant units**	**Rotor Diameter & tower Height**	**Cost of installation (KES)**	**Cost of Tower (KES)**	**Cost (KES) of Wind turbine ***	**HAWT or VAWT**	**Generator only**	**Generator plus tower**
							☐	☐
							☐	☐
							☐	☐
							☐	☐

***Indicate if the wind turbine cost is only for generator or is for generator plus tower**

Where in Kenya is the technology installed and how many

Model Number	Where installed (county and nearest town)	Number installed	Year of installation	Installation cost	Cost (KES) of Wind turbine *	Currently working	Not working or status unknown
						☐	☐
						☐	☐
						☐	☐

Description of Rotor blade used (Photograph included - yes ☐, photo number ………..)

…………………………………………………………………………………………
…………………………………………………………………….

…………………………………………………………………………………………
……………………………………………………………………….

Description of Transmission system used (Photograph included - yes ☐, photo number …………)

……………………………………………………………………………………………… ………………………………………………………………………

……………………………………………………………………………………………… …………………………………………………………………………

Performance rating of the wind turbines

Model Number	Rotor system	Transmission system	Tower	Power production	End user view of performance	further developme
						☐
						☐
						☐
						☐

(*Use a rating of 1= Excellent/Good, 2 = Average and 3 = poor)**

Section 3: Field experience of the technology

Technology SWOT analysis

Component	Advantages / opportunities	Challenges and disadvantages	Mainly affects which model
Rotor system			
Transmission system			
Tower			
Power production			

Policy, legal and regulatory framework

Component	Advantages / opportunities	Challenges & disadvantages	Mainly affects which model
Policy			
Legal & regulatory			
Financing			
Sale & distribution			
Operation & maintenance			
Others (please specify)			

Wind turbine manufacturing / Assembling process

Component	Assembling or manufacturing	Description of the process Photographs included - yes ☐, photo number ………… Equipments list used included - yes ☐, List of materials used to make component included - yes ☐
Rotor system		……
Transmission system		………

		………………………
Tower		……………………………………………………………… ……………………………………………………………… ……………………………………………………………… ……………………………………………………………… ……………………………………………………………… ……………………………………………………………… ……………………………………………………………… ……………………………………………………………… ……………………………………………………………… ………………………
Complete system		……………………………………………………………… ……………………………………………………………… ……………………………………………………………… ……………………………………………………………… ……………………………………………………………… ……………………………………………………………… ……………………………………………………………… ……………………………………………………………… ……………………………………………………………… ………………………

Wind turbine manufacturing / Assembling Materials and Equipment

Component	**Assembling or manufacturing**	**Equipment required**	**Materials used to make the components**
Rotor system		....	....
Transmission system		....	....

		....	....
Tower		....	....

			....
Complete system		....	....

Appendix 2: Magnetic Properties of Sintered NdFeB Magnets

Material Grade	Max. working Temp. (°C)	Remanence				Coercivity				Intr. Coercivity		Max. Energy Product			
		Br(T)		Br(kGs)		bHc(kA/m)		bHc(kOe)		iHc (kA/m)	iHc (kOe)	(BH)max (KJ/m^3)		(BH)max (MGOe)	
		Nom	Min	Nom	Min	Nom	Min	Nom	Min			Nom	Min	Nom	Min
N30	80	1.12	1.08	11.2	10.8	836	780	10.5	9.8	955	12	239	223	30	28
N33		1.17	1.14	11.7	11.4	876	820	11.0	10.3	955	12	263	247	33	31
N35		1.21	1.17	12.1	11.7	915	860	11.5	10.8	955	12	279	263	35	33
N38		1.26	1.22	12.6	12.2	915	860	11.5	10.8	955	12	303	287	38	36
N40		1.29	1.26	12.9	12.6	876	836	11.0	10.5	955	12	318	303	40	38
N42		1.30	1.27	13.0	12.7	876	836	11.0	10.5	955	12	334	318	42	40
N45		1.38	1.32	13.8	13.2	924	876	11.6	11.0	955	12	366	342	46	43
N48		1.42	1.38	14.2	13.8	890	835	11.19	10.5	876	11	390	366	49	46
N50		1.47	1.41	14.7	14.1	1035	829	13.0	10.5	876	11	414	382	52	48
N30M	100	1.12	1.08	11.2	10.8	836	780	10.5	9.8	1114	14	239	223	30	28
N33M		1.17	1.14	11.7	11.4	876	820	11.0	10.3	1114	14	263	247	33	31
N35M		1.21	1.17	12.1	11.7	915	860	11.5	10.8	1114	14	279	263	35	33
N38M		1.26	1.22	12.6	12.2	915	860	11.5	10.8	1114	14	303	287	38	36
N40M		1.29	1.26	12.9	12.6	915	860	11.5	10.8	1114	14	318	303	40	38
N42M		1.32	1.28	13.2	12.8	1010	955	12.7	12.0	1114	14	342	318	44	40
N45M		1.38	1.32	13.8	13.2	1050	994	13.2	12.5	1114	14	366	334	46	42
N48M		1.43	1.37	14.3	13.7	1090	1035	13.7	13.0	1120	14	392	360	49	45
N50M		1.47	1.41	14.7	14.1	1138	1043	14.3	13.1	1114	14	414	382	52	48
N27H	120	1.06	1.02	10.6	10.2	796	740	10.0	9.3	1353	17	215	199	27	25
N30H		1.12	1.08	11.2	10.8	836	780	10.5	9.8	1353	17	239	223	30	28
N33H		1.17	1.14	11.7	11.4	876	820	11.0	10.3	1353	17	263	247	33	31
N35H		1.21	1.17	12.1	11.7	915	860	11.5	10.8	1353	17	279	263	35	33
N38H		1.26	1.22	12.6	12.2	955	915	12.0	11.5	1353	17	303	287	38	36
N40H		1.28	1.24	12.8	12.4	955	915	12.0	11.5	1353	17	334	311	42	39
N42H		1.32	1.28	13.2	12.8	1010	955	12.7	12.0	1353	17	342	318	43	40
N45H		1.36	1.32	13.6	13.2	1050	1000	13.2	12.5	1360	17	376	344	47	43
N27SH	150	1.06	1.02	10.6	10.2	796	740	10.0	9.3	1595	20	215	199	27	25
N30SH		1.12	1.08	11.2	10.8	836	780	10.5	9.8	1595	20	239	223	30	28
N33SH		1.17	1.14	11.7	11.4	876	820	11.0	10.3	1595	20	263	247	33	31
N35SH		1.21	1.17	12.1	11.7	915	860	11.5	10.8	1595	20	279	263	35	33
N38SH		1.26	1.22	12.6	12.2	924	870	11.6	10.9	1595	20	311	286	39	36
N40SH		1.28	1.24	12.8	12.4	989	939	12.4	11.8	1592	20	326	302	41	38
N42SH		1.35	1.30	13.5	13.0	1013	963	12.7	12.0	1600	20	344	312	43	39
N44SH		1.37	1.32	13.7	13.2	≥963		≥12.1		1600	20	358	326	45	41

Appendix 3: Generator Prices Quotation from RIWIK

RIWIK
Energy Solutions that Work

SOLAR SYSTEMS
WATER PUMPS
POWER BACK-UP
WIND GENERATORS

QUOTATION

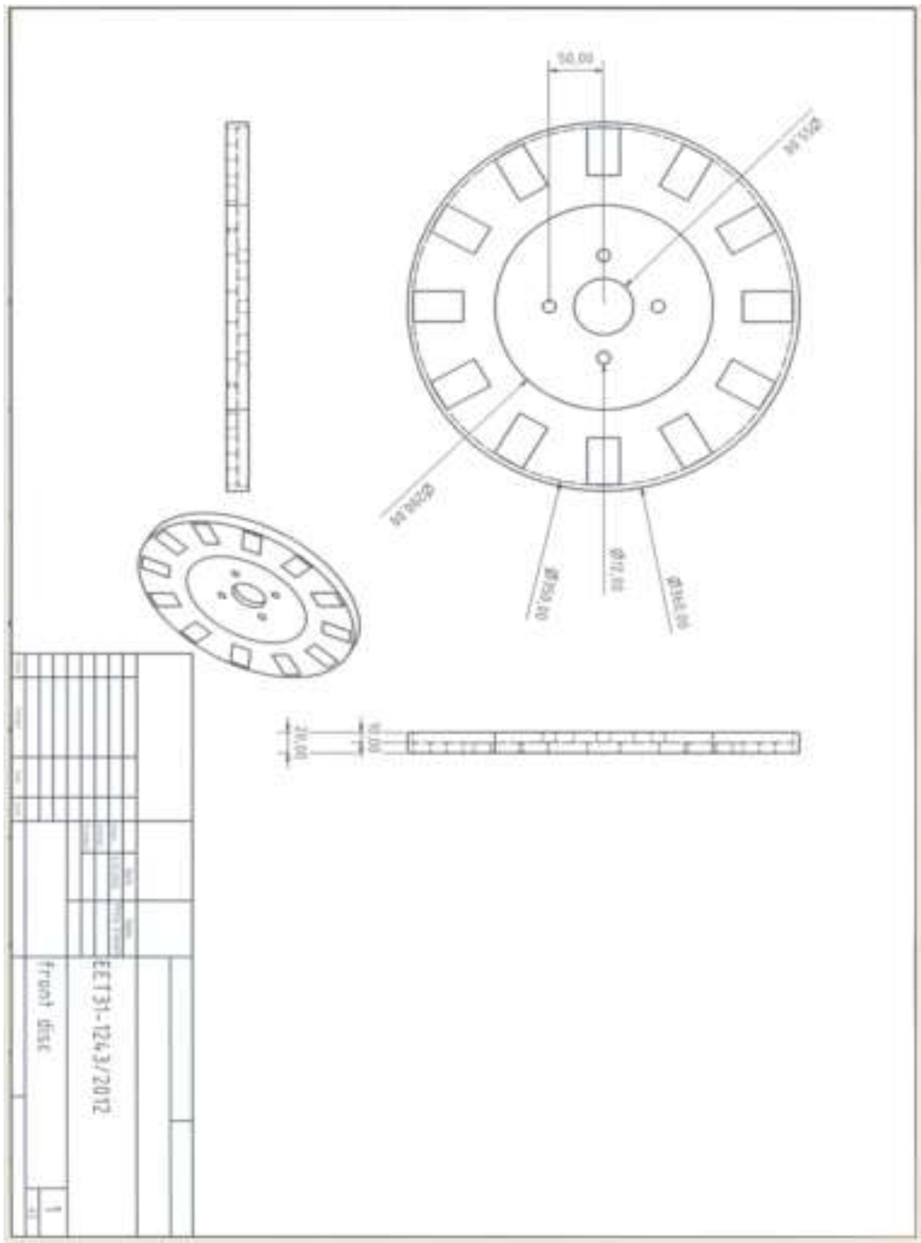
RIWIK EAST AFRICA
PO Box 68115-00200, Nairobi
W: www.riwikeastafrica.com
E: info@riwikeastafrica.com
T: +254708725026

Date: 28-3-14
Client name: JKUAT / Philip
Location:
Phone:
E-mail:

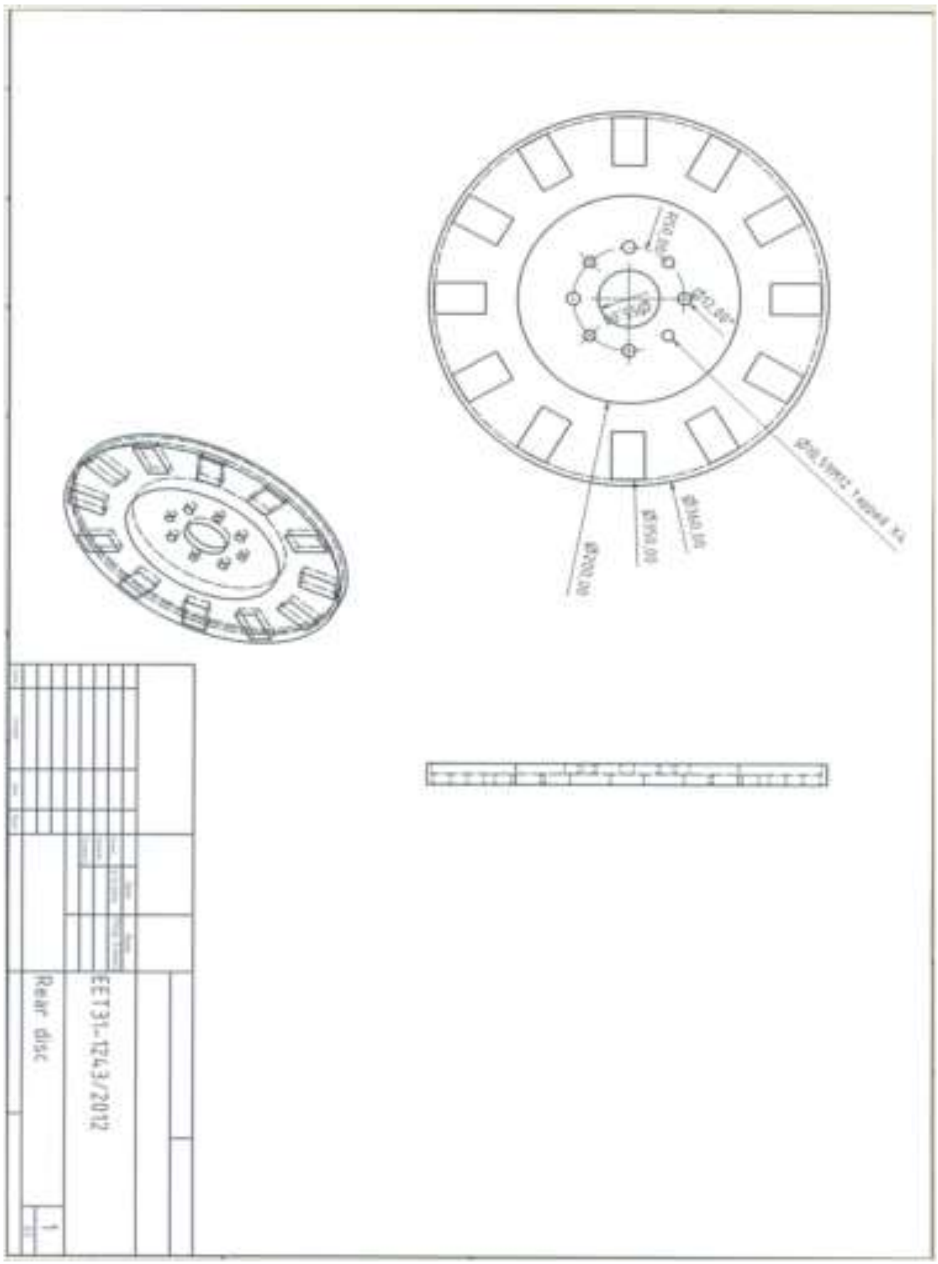
RE: Supply and Installation of Solar PV System

DESCRIPTION	QTY	RATE	TOTAL	VAT
Airflow 350, 12 Volt DC, wind generator	1	45,000	45,000	-
Airflow 350, 24 Volt DC, wind generator	1	45,000	45,000	-
Airflow 800, 24 Volt DC, wind generator	1	59,000	59,000	-
Airflow 800, 48 Volt DC, wind generator	1	69,000	69,000	-
Airflow 1000, 24 Volt DC, wind generator	1	89,000	89,000	-
Airflow 1000, 48 Volt DC, wind generator	1	79,000	79,000	-
Dumpload, controller, rectifier, fuse and break switch	1	30,172	30,172	4,828
Battery, Sealed DEKA 7T31, 105Ah 12V	1	18,200	18,200	2,912
Battery, TROJAN J185H-AC, 225Ah 12V	1	33,560	33,560	5,370
Inverter, VICTRON PHX180 w/o charger, 12V	1	13,200	13,200	2,112
Inverter, VICTRON PHX800 w/o charger, 24V	1	39,813	39,813	6,370
Inverter, MULTIPLUS3000, w/charger 35A 48V	1	176,313	176,313	28,210

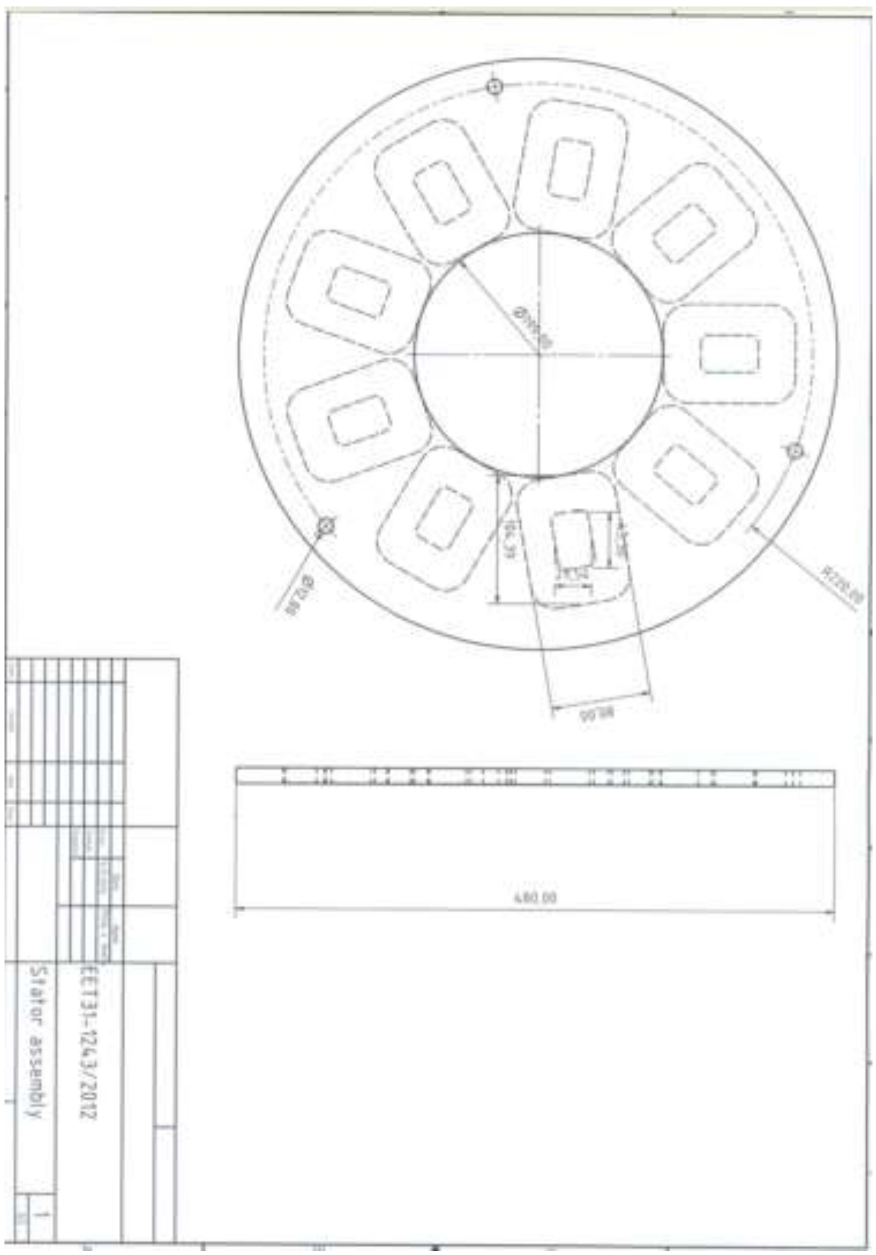
Appendix 4: Drawing of Front Rotor Disk



Appendix 5: Drawing of Rear Rotor Disk



Appendix 6: Drawing of Stator Assembly



Appendix 7: Drawing of Generator Main Assembly