Low Cost Small Wind Turbine

Generators for Developing Countries

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Proefschrift

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus prof. ir. K.C.A.M. Luyben,
voorzitter van het College voor Promoties,
in het openbaar te verdedigen op woensdag 06 maart 2013 om 10.00 uur
door

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Prof. dr. ir. G.A.M. van Kuik, Technische Universiteit Delft
Dr. J.O. Kroesen, Technische Universiteit Delft

ISBN 978-94-6203-287-3

Printed by
Wöhrmann Print Service
Loskade 4
7202 CZ Zutphen
The Netherlands

Cover layout: Dayo Oladunjoye
Cover photo by Jeroen Haringman (www.solarwebsite.nl)

To my best friend and my wife
Obioma,
and to our children
Lotanna, Somadina and Chimakaobimdi.

Acknowledgements

Each page of this thesis is a reminder of the pages of my life. When I arrived in Delft to begin the long journey of PhD research which culminated in this thesis, it immediately became clear how uncertain and complicated research work can be. After poring over pages of scientific papers, the deep insight of great scientists brought a feeling of inadequacy. However, a deep voice within gave me hope and strength, reminding me of the *small* victories I have recorded in my journey through life.

Just like in my journey through life, I am very grateful to my Father, the Almighty God, and His Son Jesus Christ, my Lord and Saviour, and the Holy Spirit, my Helper and Counselor, for guiding me through the years of PhD research. He has been kind and faithful, doing exceedingly abundantly more than I could ask or imagine, according to His power working in me.

In addition, I have also received help from many others. I thank my promotor Prof. Jan Abraham Ferreira for believing in me and accepting me as a PhD candidate at Electrical Power Processing (EPP) Group. I appreciate the feedback I received from you during our monthly meetings and your patience during the years of this work.

I appreciate the support and dedication of my co-promotor and daily supervisor Dr. Henk Polinder for the valuable hours we spent together discussion about my work and the chapters of this thesis. I also thank Dr. Polinder for his openness and how he was always available to discuss anything, including non-technical matters.

I thank Prof. Wubbo Ockels for the opportunity he gave me to work as a Direct Drive Researcher for the Superbus Project. I am grateful for the one year I spent under your supervision and the experiences I gathered during our discussions about Superbus.

In addition, I would like to thank the PhD defence committee for their comments and suggestions. These are Prof. Lauri Kettunen, Prof. Frances Brazier, Prof. Johan Smit, Prof. Gijs van Kuik, and Dr. Otto Kroesen.

I am grateful to Prof. Paulo Ribeiro for his willingness to be in the PhD defence committee. Although he could not join the PhD Committee his interest in this work is appreciated. I am also grateful to Prof. Lou van der Sluis for his interest in this work and his willingness to be in the PhD Committee.

My friend and former colleague Dr. Hung Vu Xuan is appreciated for his friendship. I am honoured to have shared the same office with you for more than four years. I thoroughly enjoyed our discussions about electrical machines, PhD challenges and life.

My gratitude is also extended to the friends I have made in the Electrical Power Processing Group for making the PhD journey enjoyable. Especially, I would like to thank Xun Gong, Ghanshyam Shrestha, Rodrigo Pinto, Johan Wolmarans, Marcelo Gutierrez Alcaraz, for their help and friendship. I also thank other friends and colleagues in the Group such as Ivan Josifovic, Milos Acanski, Anoop Jassal, Yi Wang, Martin van der Geest, Todor Todorcevic, Wenbo Wang, Yeh Ting, Ilija Pecelj, Jianing Wang, Silvio Fragoso Rodrigues, Tim Strous, Dong Liu, Tsegay Hailu, etc. Ex-colleagues such as Dr. Aleksandar Borisavljevic and Dr. Deok-je Bang are also appreciated.

Big thank you to Martin van der Geest for translating the propositions and the summary into Dutch. I thank Veronique van der Varst of TU Delft Central Liaison Office (CICAT) for arranging my residence permit and that of my family.

Suzy Sirks-Bong was my first personal contact with the Electrical Power Processing Group. Thank you Suzy for your kindness and readiness to help at all times. I also thank Laura Bruns, Veby Agus and Ellen Schwencke-Karlas, for the secretarial support I received. I acknowledge with thanks the practical advice received from our former Lab Manager Rob Schoevaars during the development of the Test Setup. The advice received from Harrie Olsthoorn and Kasper Zwetsloot is also appreciated. I appreciate the Masters students that I have supervised: Albert Munthe, Bart Fugers, Femi Ajayi, and Georgios Villias.

I am most grateful to the University of Nigeria for granting me study leave. I particularly thank the former Vice-Chancellor Prof. Chinedu Nebo for establishing the UNN-TU Delft Linkage, which provided the platform for my initial 3 months Research Visit to TU Delft. I thank Prof. Nebo for his personal words of encouragement and support which inspired me to forge ahead. I also thank the current Vice-Chancellor Prof. Bartholomew Okolo for his continued support of my PhD study. I thank Prof. A.N. Nzeako, the pioneer coordinator of the UNN-TU Delft Linkage for his support and encouragement, particularly during my 3 months Research Visit to TU Delft.

During my years in TU Delft, I received tremendous support from the Department of Electrical Engineering, University of Nigeria, Nsukka. I thank Engr. Dr. B.O. Anyaka and his predecessors for all the help I received. I particularly thank Prof. M.U. Agu who inspired me to pursue a PhD. I also thank Prof. Agu for his mentorship and encouragement. I thank Prof. E.S. Obe, Dr. L.U. Anih, Cajethan, Damian, Dr. Odeh, Cosmas, Steve, Josephine, and others, for all their support. In addition, I thank Prof. T.C. Madueme, Dean Faculty of Engineering (UNN) and his predecessors for the support I received from the Faculty.

I thank Dr. Sandra Irobi who facilitated my 3 months visit to TU Delft. Her advice and encouragement helped me during tough times. I also thank Sandra for the friendship and support extended to my family.

I thank Dayo Oladunjoye and his family for their friendship. Dayo, thank you also for the cover layout of this thesis. Dr. Solomon Agbo and his family, as well as David Oyediran, are also appreciated for the wonderful times we spent together in the Netherlands. I appreciate Ijeoma Okeke for her constant encouragement and for the time spent with my family.

The RCCG, Mount Zion International Parish Delft is appreciated for their great fellowship. I thank Pastor Hyacinth and Helena Nwosu, Sam and Chinelo Menkiti, Innocent Agbo, Jide, Juliet, Asamoah, and all members of the Parish.

I appreciate the RCCG, Praise House International Parish Voorburg for their love, fellowship and prayers. I am very grateful to Pastor Walter and Betty Ononogbu for their support and care for my entire family. I also appreciate the prayers and love from Uche & Annie, Nini, Alice Ajieh, Innocent Ukejianya, Gen Ojiri, Ade, John, Richard, Joy, Eric, and many others am not able to mention.

Ken Ojiri has been more than a friend to me. I thank you for your friendship and support, and your willingness to sacrifice for others.

I appreciate Rev. Chukwudi Ogbueli for the solid foundation I received at Dominion City. I also thank Pastor Norbert and other Pastors of the ministry for all the spiritual gifts deposited in me.

I appreciate the families of my two great friends: Onyeka Ogbodo and Lawrence Okwor. You have provided a home away from home, and I will always be grateful for your friendship.

My mother Serah Ani (*Ezinne*) is deeply appreciated. Although not educated, yet you helped me to understand the value of good education. I thank all Ani family, particularly David, Jane and Law. Your love and constant prayers has been a shield to me. I also appreciate my mother-in-law Onuezue Ifeanacho, and my brothers-in-law Okey and Chidi for their love and support.

I appreciate my three sons: Lotanna, Somadina, and Chimakaobimdi for doing their best to 'inject' me with positive energy. Kobi's contribution is to distract me and to tear some of my papers. This way he discouraged me from working at home by forcing me to prioritize and finish most work in the office. His elder brothers made even better contributions. Each morning, Loti and Soma always asked: 'Daddy are you going to your work?' 'Are you working on your wind turbine?' 'It's turning round and round?' Boys, thank you for the joy you have brought into my life.

Finally, I would like to say thank you to my best friend and my wife Obioma, for your love and care throughout these years. Thank you also for believing in me, and for constantly energizing me throughout the PhD journey.

Thank you all. We did it together!

Table of Contents

List of symbols and abbreviations

A	Rotor swept area	[m^2]
A_{Cus}	Stator conductor cross sectional area	[m^2]
b_p	Magnet width	[m]
b_s	Coil width	[m]
B_g	Air gap flux density	[T]
$\hat{B}_{gm}$	Amplitude of the fundamental space harmonic of the air gap flux density	[T]
B_m	Magnetic flux density in permanent magnet	[T]
B_{rm}	Remanent flux density of permanent magnet	[T]
c	Cost of generated electricity	[€/kWh]
C_{Cu}	Unit cost copper	[€/kg]
C_{Fe}	Unit cost iron	[€/kg]
C_m	Unit cost copper	[€/kg]
C_p	Turbines coefficient of performance	
d	Diameter	[m]
e	No-load voltage	[V]
E_p	RMS no-load voltage	[V]
E_y, E_{ay}	Energy yield, annual energy yield	[kWh]
k_{fill}	Stator conductor fill factor	
h_{ry}	Rotor disk thickness	[m]

h_s	Coil axial thickness	[m]
h_{sy}	Stator axial thickness	[m]
H_m	Magnetic field intensity in permanent magnet	[A/m]
l_{Cus}	Length of conductor phase winding	[m]
l_g	Physical clearance between magnet and stator	[m]
l_{geff}	Effective air gap	[m]
l_m	Magnet length in magnetization direction	[m]
l_t	Length of end turn	[m]
L	Inductance	[H]
M_{Cu}	Mass of copper	[kg]
M_{Fe}	Mass of iron	[kg]
M_{pm}	Mass of permanent magnet	[kg]
N_c	Number of turns per coil	
N_s	Number of turns of stator phase	
P_b	Bearing loss	[W]
P_{Cus}	Stator copper loss	[W]
P_{Cur}	Rotor copper loss	[W]
P_{Dio}	Diode rectifier loss	[W]
P_{eddy}	Stator eddy current loss	[W]
P_e	Eddy current loss	[W]
P_{Fes}	Stator iron loss	[W]
P_h	Hysteresis loss	[W]
P_{in}	Input power	[W]

P_{loss}	Total generator losses	[W]
P_{Mech}	Mechanical loss	[W]
P_{out}	Output power	[W]
P_{rotor}	Rotor losses	[W]
P_{stator}	Stator losses	[W]
P_w	Windage loss	[W]
r	Turbine radius	[m]
r_{ri}	Rotor inner radius	[m]
r_{ro}	Rotor outer radius	[m]
r_s	Average stator radius	[m]
r_{si}	Stator inner radius	[m]
r_{so}	Stator outer radius	[m]
T	Torque	[Nm]
T_{fri}	Frictional torque	[Nm]
v	Wind speed	[m/s]

Greek letters

ρ_{air}	Mass density of air	[kg/m^3]
ρ_{mCu}	Mass density of copper	[kg/m^3]
ρ_{mFe}	Mass density of iron	[kg/m^3]
ρ_{mm}	Mass density of permanent magnet	[kg/m^3]
λ	Tip speed ratio	
μ_{rm}	Relative recoil permeability of permanent magnets	
μ_0	Permeability of free space	[H/m]

μ	Frictional coefficient	
τ_p	Average pole pitch	[m]
τ_c	Coil span	[m]
ω_m	Mechanical angular speed	[rad/s]

Abbreviations

AC	Alternating current
AFPM	Axial flux permanent magnet
DC	Direct current
EU27	European Union 27 member states
UNDP/GEF	United Nations Development Programme / Global Environment Facility
ICE	Internal combustion engine
PM	Permanent magnet
PV	Photovoltaic
RFPM	Radial flux permanent magnet
SMC	Soft magnetic composite

Chapter 1

Introduction

1.1 Background

Much of the electrical energy utilized worldwide comes from conventional sources such as fossil fuels (coal, oil and gas), nuclear energy, as well as hydro. In such a traditional power system, the electrical energy is generated by a large power plant and transported over long distances to the user through the transmission and distribution lines. However, electricity generation from conventional sources has some consequences (Figure 1.1).

1. Reserves for fossil fuels are fast being depleted leading to limited fuel supply. It is estimated that if available reserves continue to be consumed at the current rate, the world may run out of fossil fuel in a couple of decades. Nuclear energy also has limited fuel supply.
2. Fossil fuel can cause serious problems to the environment. In the process of burning fossil fuels in power plants to generate electricity, greenhouse gases such as carbon dioxide (CO_2) and nitrous oxide are released to the environment which gives rise to smog, acid rain and other environmental problems. One big consequence of this is the buildup of CO_2 in the Earth's atmosphere which causes global warming.
3. Nuclear and radiation accident with damaging effects on the environment and human life. One recent reminder is the Fukushima Nuclear Accident following the Japan earthquake and tsunami on 11 March 2011. Accidents from nuclear power plants can lead to the release of high amounts of radioactivity into the atmosphere. Radioactive materials may also be released into the ground thereby contaminating agricultural land and domestic water. Deaths from direct exposure as well as future cancer deaths in the surrounding population may also occur.

The growing demand for electrical energy for industrial and domestic use, coupled with the limited amount of available fossil fuel reserves and its negative effects on the environment, have made it necessary to seek alternative and renewable energy sources. As a result, renewable energy sources such as wind, solar, small scale hydro, and ocean energy are becoming increasingly integrated to traditional electric power systems. Amongst the renewable sources, wind technology has emerged as the clear leader in terms of total available installed capacity.

Energy conversion type		Advantages	Disadvantages
Nuclear power plant: Nuclear power provides electricity for a significant percentage of the world's population. The cooling towers release the steam produced by the nuclear power plant. A domed containment building for the reactor can be seen on the right of the photo.		Emits relatively low amounts of CO_2, therefore it has low contributions to global warming and pollution; readily available technology; relatively inexpensive; possible to generate high amounts of power in a single plant.	High risks as accidents can release radioactivity with devastating consequences for humans and the environment; possible attack on nuclear power plants or diversion of nuclear materials by terrorists; radioactive by-products are difficult to dispose; thermal pollution; limited fuel.
Fossil fuel power plant: An example is coal-fired power plant, which is the dirtiest of all fossil fuels. Despite its negative effects on the environment it generates half the electricity in United States.		Fossil fuels such as coal, are easy to find (for now); the technology is well known; they can be built anywhere; when coal is used, it is cost effective; gas-fired power plants are very efficient.	When burned they emit high amounts of CO_2, contributing to pollution and global warming; thermal pollution; land devastation from extraction of raw materials (mining); environmental hazards such as oil spills on land as well as sea; limited fuel supply.
Hydroelectric: Falling water turns turbines at the base of the dam to generate electric power. Hydro power is the most widely used renewable energy accounting for about 16% of global electricity consumption.		Hydroelectric plants do not require fuels; absence of heat engines means no air, water or thermal pollution; high efficiency; relatively inexpensive; dams can control flooding and store energy; dam water can irrigate farms.	High initial investment cost; reservoir behind dams inundate scenic land; dams block upstream migration of fish; cannot be built anywhere, few available locations for new dams; drought can affect power generation.
Wind power: A wind turbine utilizes the power from the wind to generate electric power. Several wind turbines can be sited in the same area to form a wind farm. They can be sited on land (onshore) or at sea (offshore).		Wind turbines do not employ heat engines meaning no air, water or thermal pollution; wind technology is becoming increasingly cost competitive due to advances in technology; unlimited fuel supply (wind).	Large array of wind turbines may become eyesores; turbine blades can be hazardous to migratory birds; noise from turbines sited close to homes may become a nuisance; wind not always available.
Solar power: Photovoltaic cells convert sunlight to electricity. Solar power generation employs solar panels composed of solar cells containing a photovoltaic (PV) material. Panels may be strung together to form a PV array.		No air, water or thermal pollution due to the absence of heat engines; unlimited fuel supply (sunshine).	Requires large expanse of land to generate high power (space limitations); relatively expensive; not very efficient; sunshine not available always.

Figure 1.1: Electricity generation from different sources including nonrenewable and renewable energy.

Wind energy accounts for an increasing percentage of the energy supplied to the electricity network. According to the EU's statistics office, Eurostat, electricity generation from renewable energy accounted for 16.6% of gross electricity consumption in the EU27 (European Union 27 member states) in 2008 while in 2010 this increased to 19.9% of electricity consumption [1], [2]. A report from the European Commission states that electricity from renewables could provide up to half of EU's power by 2020 if current growth rates are maintained [1]. Wind energy is one of the key renewable sources driving this growth rate. The report in [1] points out that wind power exceeded the EU target of 40GW by 2010 by more than 80% in 2009, with total installed capacity of 74GW. By the end of 2010, total installed wind power capacity stood at 84GW [3], more than double the original target. Indeed, since 2004 installed wind power capacity has been increasing at an average annual growth rate of 27% bringing the global installed wind power capacity to 197GW at the end of 2010. Furthermore, advances in wind technology, particularly off-shore wind turbines, have led to new concepts with larger capacity and higher extraction of wind power. As a result, electricity generation from wind is now cheaper than other renewables and is now almost cost competitive with other traditional sources of electricity generation.

However, this impressive growth is largely due to advances in large (utility scale) wind turbines which are installed in wind farms. Small wind turbines on the other hand have not been developing at such an impressive rate. Table 1.1 shows a comparison of the growth of global installed large and small wind turbines. While global installed large wind turbines increased at an average of 28.1% the average growth of small wind turbines was 8.7%. Even among small wind turbines, the growth shows a continued market shift towards larger grid-connected systems. In 2009, 34.4MW of small wind turbines sold globally were grid-connected, which constitutes a market share of 82%, leaving only 7.6MW of off-grid systems.

Table 1.1: Growth of global installed large and small wind turbines from 2007 to 2010

	Large wind turbines [4]		Small wind turbines [5]	
	Installed (GW)	Growth (%)	Installed (MW)	Growth (%)
2007	93.8		345.7	
2008	120.3	28.3	367.7	6.4
2009	158.9	32.1	401.3	9.1
2010	197.0	24.0	443.3	10.5
Average growth		**28.1**		**8.7**

The market for small wind turbines is still fragile despite its large demand as production and sales are still largely dependent on government incentives. Governments continue to provide incentives for small wind turbines as part of their commitment towards curbing the continued release of CO_2 into the environment. Furthermore, small wind turbines are particularly useful for providing energy for a niche market in on-grid and off-grid applications such as application in the built environment, hybrid solutions used for telecomm base stations, battery charging, water pumping and rural electrification.

There is an additional benefit of small wind turbine deployments for the economy due to the potential domestic jobs linked to its manufacture, installation and sales. The number of jobs created per installed MW of small wind turbine is higher than jobs created for large utility-scale wind turbines [5], [6] as many units are manufactured annually. Deploying wind in smaller increments requires more labor per unit of power produced [5]. In fact, small wind creates more jobs per unit of installed capacity than any other power generation resource [5]. This could lead to an increase in the cost per installed MW of small wind turbine. However, this can be compensated for by a potential decrease in labour cost in developing countries.

Small wind turbines in rural areas

Off-grid systems are autonomous isolated systems usually installed in rural areas located far from existing grid. An estimated 1.3 billion people living mostly in rural areas of developing countries are currently without electricity as shown in Table 1.2. Small wind has a huge role to play in such areas where electrification is limited as this represents a huge untapped market. Traditionally, electrification of such places is by grid extension or using diesel powered generators. Due to the dispersed and low population density of the communities, grid extension may not be a viable option in most cases because the expected revenue is often too low to justify the huge capital investment. On the other hand, diesel powered systems are operated at high costs as a result of long distances and often difficult terrain that must be covered in order to deliver fuel on site. This often leads to failure of such a system as it becomes economically unsustainable; a fact that is further highlighted by recent increases in the price of oil.

1.2 Problem definition

Despite its huge potentials, the use of small wind turbines is not popular in many rural areas of developing countries. Several reasons are responsible for this continued low penetration in these areas which have been identified as having the greatest potentials for small wind turbines. In order to make small wind turbines attractive for developing countries, there is the need for research to address these identified challenges. In addressing these challenges, this research focuses on the generator which is a key component of small wind turbines and is responsible for converting the mechanical energy from the turbine into electrical energy.

Table 1.2: Electricity access of some selected regions in 2009 [7]

	Population without electricity (millions)	Electrification rate (%)	Urban electrification rate (%)	Rural electrification rate (%)
Africa	587	41.8	68.8	25.0
North Africa	*2*	*99.0*	*99.6*	*98.4*
Sub-Saharan Africa	*585*	*30.5*	*59.9*	*14.2*
Developing Asia	675	81.0	94.0	73.2
China & East Asia	*182*	*90.8*	*96.4*	*86.4*
South Asia	*493*	*68.5*	*89.5*	*59.9*
Latin America	31	93.2	98.8	73.6
Middle East	21	89.0	98.5	71.8
Developing countries	**1,314**	**74.7**	**90.6**	**63.2**
World	**1,317**	**80.5**	**93.7**	**68.0**

Cost of small wind turbines

The cost of current stand-alone small wind turbines vary from €2,500 to €6,000 per installed kW compared with €1,500/kW for large wind turbines [8]. For people living in rural areas of developing countries, this cost is prohibitive thereby making the technology an unattractive option. In comparison, a cheap petrol powered generator can easily be bought with less than 3% of this amount. Moreover, turbine components have to be imported at huge costs thereby significantly increasing the retail price. In the event of breakdown of the system, spare parts also have to be imported.

Energy yield of small wind turbines

Small wind turbines operate mostly in low wind sites, being sited mostly where the energy is needed and not necessarily where the wind is best. When the turbine operates in low wind speeds the energy yield will be low and hence may not be sufficient to meet demand. The starting of small wind turbines is another issue that influences the energy yield. Small wind turbines are usually self-starting, relying on the torque produced by the wind acting on the blades [9] – [14]. Before a wind turbine can start this torque must be high enough to overcome some resistive torque present in the turbine system. These includes the frictional torque in the gearbox (if present) and drivetrain as well as cogging torque of the generator. Most small wind turbines are directly connected to the turbine (direct-drive) thereby eliminating the need for a gearbox. In this case, cogging torque reduction or elimination will improve turbine starting. If the cogging torque is high the turbine might not be able to start at low wind speeds which further reduces the energy yield obtainable from the turbine.

Maintenance of small wind turbines

Small wind turbines are high tech systems which are not very easy to operate and maintain. Maintenance and repair of such systems require good technical skills which are often lacking in rural areas. Therefore, installing a small wind turbine in rural areas comes with the added challenge of transporting trained personnel from large distances to perform routine maintenance. Besides, if some components need to be replaced, the system may have to be shut down for long periods in order to source replacement parts which reduces its availability and reliability.

Thesis objectives

Based on the above problem description, the main objective of the thesis is to develop suitable low cost small wind turbine generators which can be manufactured easily. To achieve this objective, it is necessary to develop low cost solutions that are simple to manufacture, assemble and maintain. The following are therefore specified as the main research tasks:

1. *To perform analysis of why renewable energy systems often fail in developing countries.*
   This objective focuses on understanding the reasons for the poor performance of renewable energy systems in developing countries in order to provide guidelines for the thesis and for long term sustainability of renewable energy systems. This is achieved through thorough analysis of literature in terms of reasons for the failure of renewable energy projects.

2. *To find suitable generators for small wind turbine application in low wind speed areas.*
   The performance of some commercially available small wind turbine systems in low wind speed areas will be analysed to determine their energy yield and cost of generated electricity. Furthermore, the cost of manufacture and manufacturability of different generator topologies will be compared. The results obtained by fulfilling this objective, as well as the objective in 1, are used to define the requirements for our proposed generator and to select a suitable configuration.

3. *To design and manufacture a prototype generator using easily available components*
   The manufacturability and low cost objective of the selected generator configuration will be demonstrated. A simple design will be developed such that the generator can be

manufactured in a small workshop using available materials. A prototype generator will be manufactured as proof of concept.

4. *To verify the generator performance through measurement tests*

   The performance of the manufactured prototype generator will be verified via measurement tests. The generated output power (voltage and current), losses and efficiency will be measured, as well as the effect of design choices on generator performance.

5. *To investigate the feasibility of automotive alternator for small wind turbine application.*

   The feasibility of using automotive claw pole alternator as generator for small wind turbines will be investigated. This is necessary to increase available low cost solutions since there is the possibility of unavailability of materials for the manufacture of the generator proposed in 3.

1.3 Thesis layout

The thesis is divided into four parts:

- ***Background.*** Chapter 1 introduces the research subject and where this thesis fits in.

- ***Existing systems***. Chapters 2 and 3 analyses why existing systems fail and their performance in low wind speed areas.

- ***Concepts & performance***. Chapter 4 presents a comparison of generator topologies, Chapter 5 presents the design, manufacture and performance of a prototype generator, while Chapter 6 presents an alternative low cost generator.

- ***Conclusions.*** Chapter 7 summarises thesis conclusions.

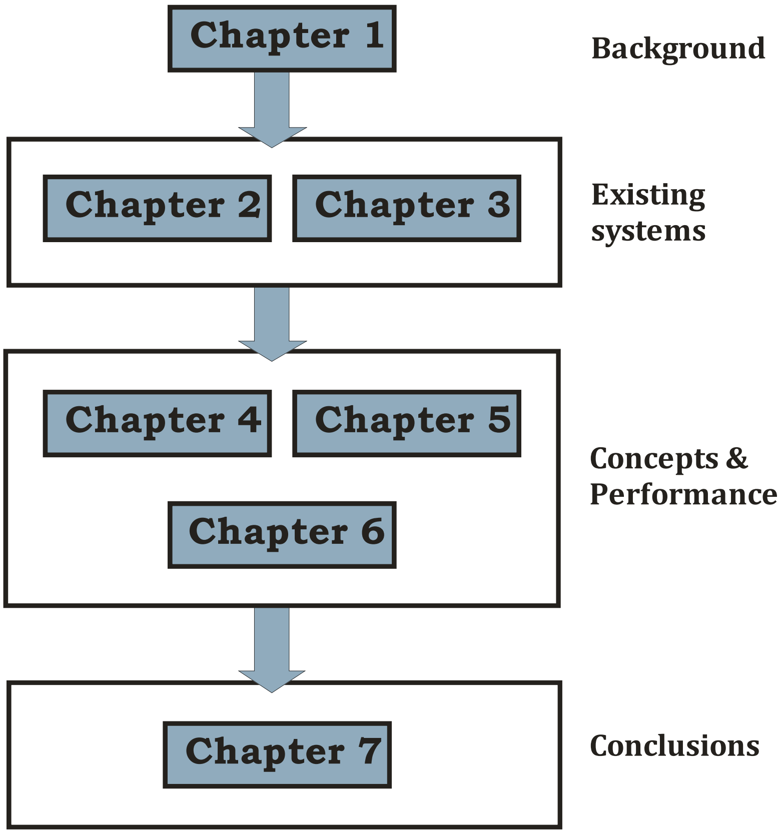


Figure 1.2: Thesis layout showing the organization of the chapters.

In order to adopt a suitable approach, the starting point of this thesis is to investigate why renewable energy system often fail. Chapter 2 looks at five renewable energy projects implemented in developing countries and identifies the reasons for their failure. The two major reasons identified were high cost of systems and lack of necessary technical skills for maintenance. The knowledge from this study gave impetus for the adopted research approach, and for defining research problems and objectives as presented in Chapter 1.

Chapter 3 analyses the performance of small wind turbines in low wind speed areas in terms of their energy yield and cost. An overview of configurations, applications and implemented technology is first presented in order to lay a foundation for small wind turbine systems. Since small wind turbines operate mostly in low wind speed areas, the chapter also presents the performance of commercially available systems in low wind speed areas by comparing their energy yield and cost of generated electricity using measured field data.

Chapter 4 starts the third part of this thesis which deals with the generator concepts. This chapter performs a comparison of different generators in order to find the configuration that satisfies the requirements developed based on research objectives. The requirements of the desired generator are first presented using the results of the analysis in Chapters 2 and 3. The required manufacturing processes for selected generator configurations are presented which will be used as basis for comparing their manufacturability and manufacturing cost. The chapter concludes by describing the selected generator and motivation for this choice.

In Chapter 5, the design, manufacture and measured performance of a prototype axial flux permanent magnet (AFPM) generator for direct drive small wind turbine application is presented. The chapter begins with a justification for the choice of direct drive topology. The generator structure, design choices and the effect of such choices on efficiency and energy yield, design equations used, and measured generator performance are highlighted. One of such choices is the use of vehicle hub bearing which is cheap but inefficient. The eddy current loss introduced by the use of coreless AFPM machine configuration as well as the loss due to the choice of bearing are quantified through measurement tests and calculations. The chapter highlights the penalty for the use of such bearing such as high bearing loss of about 50W (about 90% of no-load losses) at 300rpm. The chapter proposes some improvements to the prototype AFPM generator that can lead to better performance. The use of a smaller vehicle hub bearing is proposed to reduce the bearing losses. Optimization of the design is also proposed since the manufactured generator prototype presented in this chapter was based on the availability of materials rather than optimized dimensions. The implemented optimization focused on minimizing the cost of active materials (such as permanent magnets, copper and iron) to achieve a particular efficiency.

Chapter 6 proposes another generator concept using automotive claw pole alternator. This concept became necessary because the generator presented in Chapter 5 uses permanent magnets which are potentially a subject of politics and may not be readily available. Automotive alternators on the hand are inexpensive, easily available and with well-established skills albeit for vehicle application. The chapter presents the challenges that must be addressed to ensure applicability in wind and how such challenges can be overcome. Models are also developed to describe the performance of the alternator. To show the expected performance of this system, measurement tests were conducted on a typical vehicle alternator using the test setup described in Chapter 5. Optimization of the alternator system using measurement results is presented, as well as the adaptation of this alternator to a specified wind turbine. Design modifications to improve alternator performance and efficiency are proposed.

Chapter 7 gives the conclusion of the work presented in this thesis by summarizing the main results and recommending some directions for future research.

Chapter 2

Why do renewable energy systems often fail?

2.1 Introduction

The starting point of this research is to adopt a suitable approach for the project. Wind is a renewable energy based system having closely related features with other renewable energy systems such as solar. Renewable energy systems represent a cost effective alternative in many remote rural communities of developing countries where the expected revenue from extending the existing infrastructure is often too low to justify the huge capital investment. However, despite spending a huge part of its available public resources on the energy sector, developing countries are still faced with a huge deficit in basic energy supply especially for people living in rural areas. On one hand traditional energy sources, such as firewood and agricultural by-products, are used inefficiently with its attendant economic, health and environmental problems. On the other hand, modern energy sources such as petroleum products, electricity and gas are unevenly distributed such that many of the population living in rural areas have no access to them. Without access to modern energy supply it becomes difficult for people to engage in useful economic activities that require energy. Available time for farming and production of goods will be reduced as people spend so much time searching for diminishing woods for fuel.

Renewable energy systems such as solar photovoltaic systems, small wind turbines, and micro hydropower systems can be used to address the energy needs of rural people. A major advantage of using such systems is that high cost and losses on long transmission lines are significantly reduced since electricity is generated on site. Many renewable energy projects in developing countries have been implemented by foreign donor agencies supported in part by local agencies such as non-governmental organizations and local governments. These projects have recorded very little success.

The objective of this chapter is to perform a study on the use of renewable energy systems in developing countries and why they have recorded little success. Although the thesis focuses primarily on generators used for small wind turbines, this chapter puts the rest of the thesis in a larger framework by examining some of the developmental challenges associated with its implementation in developing countries. The knowledge from this study is useful in defining research approach, research problems and objectives as presented in Chapter 1. This study is also important because investment in renewable energy in developing countries is increasing with several millions of dollars spent annually, while access to energy has not improved significantly. Why are some projects successful while others are not? Are there some common factors that contribute to project failure or, are the reasons different for every project?

To achieve the above objective, six major questions were investigated.

1. What are the real needs that can be met using renewable energy technology?
2. What is the required technology and how can it be implemented to ensure that these needs are met in a sustainable way?
3. What are the technical and institutional challenges that must be dealt with?
4. Does the host community have the economic and technical capability to sustain and maintain the project?
5. How can such capabilities be developed?
6. What type of socio-cultural adjustment is required from host communities for a more sustainable renewable energy project?

First the characteristics of a rural environment are examined as it forms the main subject of this chapter. The chapter then investigates the reasons for the failure of five case study renewable energy projects implemented in rural areas of developing countries. The identified reasons are categorized and then discussed extensively. This discussion however, does not include a detailed analysis on development theory and cultural theory which is beyond the scope of this thesis. The chapter concludes by proposing some design considerations that will lead to long term success of future renewable energy projects in developing countries.

2.2 The rural environment

A rural environment is often characterized by the following:

1) poor population;
2) they lack basic infrastructure but have huge potential;
3) they lack technical skills but have organized groups;
4) strong influence of the socio-cultural environment.

These characteristics often makes the rural environment unique and sometimes a challenging place for the introduction of a new technology, different from the urban or semi-urban environment. Key aspects of the subjects raised above are presented below.

2.2.1 Economic challenges and affordability

Majority of the population living in rural areas of developing countries are poor and often forced to make hard choices such as buying medicine for children or buying food. Affordability of energy sources such as electricity is partly responsible for the absence of such facilities in many rural areas of developing countries as the rural population often cannot pay for energy services. In addition, energy consumption in these areas is low such that that on one hand investment in infrastructure is huge while on the other hand there is low economic yield. Many foreign and local agencies have introduced renewable energy technologies such as Solar Home System but it appeared that appropriate end-user financing is the most pressing problem [15]. In the case of renewable energy systems, affordability relates to not just the cost of energy services but the initial cost of systems. Therefore, in terms of renewable energy systems, the rural environment is, to a large extent, a market for which subsidies and special credit schemes have to be incorporated into the planning process. If the economic principle of "the customer pays the real costs" were to be generally applied, particularly the poorest of the rural population in developing countries would be unable to use electricity despite the fact that they generally consume very little electricity [15].

2.2.2 Huge potential

Although rural areas of developing countries are poor, they are a huge un-tapped market but such market need to be developed. For instance, there are currently over 90 million active mobile phone lines in Nigeria, yet the market penetration is still low. New and underserved markets are mostly in rural villages areas of the country due to lack of grid-connected electricity and the associated high cost of electrifying a remote communication base station using diesel powered generators. Furthermore, recent report states that only 40% of Nigerians (about 60 million people) have access to the official 3500 MW of electricity she generates and transmits. Therefore, there are probably more than 20 million Nigerians who own a mobile phone but no access to grid-connected electricity.

This represents a huge market for both the electricity and the telecommunication sectors. Electricity is required to charge the batteries of mobile phones. Without reliable and cost effective charging solutions, mobile phone users will leave their phones switched off most of the time resulting in reduced revenue from airtimes for mobile phone operators. The revenue potential from an estimated 500 million people worldwide who have a mobile phone connection but no access to electricity grid represents about US$2.3 billion market opportunity for mobile phone operators [16]. Besides, industries rely almost entirely on electricity, meaning that its availability (electricity) determine how far the available potentials in a rural environment can be harnessed.

2.2.3 Technical skills

Skills for modern energy technology such as renewable energy are inadequate and very often non-existent. Lack of skills for renewable technology often results in implementation problems such as operations and maintenance of systems which impacts negatively on performance. In addition, agro-based small-scale industries make useful contribution to the GDP as well as providing employment for the rural population. The growth and expansion of such industries have been hampered by the unavailability of modern energy services giving rise to the persistent use of inefficient and wasteful traditional agro processing methods. To encourage small industries to thrive, reliable electricity must be made available in rural areas. Furthermore, if renewable-based electricity is to be introduced to a rural area, skill for maintenance of systems should be available for a reliable power supply.

2.2.4 Socio-cultural challenges

Rural communities are often tied to traditions and culture where change is viewed as breaking away from the group and promoting anarchy. Tradition and culture ensure that people stick to traditional ways of doing things and even if they are dissatisfied with the status quo. Prioritizing an unknown future above well-known, albeit dissatisfactory state of affairs of the present is often considered an unfeasible choice. In addition, new types of organization involving many stakeholders may be required following the introduction of renewable energy technologies, which may be at odds with such uncertainty avoidant societies, where people are more valued for their adaptation and incorporation to tradition, culture and communal life. This suggests that in order to make the transition from a traditional energy system to a modern renewable energy-based technology, some socio-cultural adjustments is required.

2.3 Case studies and lessons learned

Five case studies of renewable energy projects were investigated, consisting of four failed projects and one successful project. This section presents a description of these projects, followed by the reasons that contributed to project failure or success. The selection of the investigated case studies was guided by the following criteria:

- location of the project;
- sufficient knowledge of project and or availability of data;
- type of renewable energy technology/application;
- length of project operation;
- good spread of selected projects.

The choice of the first criterion is very obvious since this study is concerned with renewable energy projects in developing countries. Available data on evaluation of projects implemented in developing countries is scarce, as a result, this chapter relied mainly on personal knowledge of renewable energy projects in developing countries, available project documents and published materials. The choice of case studies was also influenced by the type of technology or application resulting in the selection of at least three types of renewable energy technology/application.

Expectedly, most of the selected case studies (three) were photovoltaic systems due to its popularity. However, while two PV systems can be considered similar, the third is slightly different in terms of its unique management structure which is very attractive for this research. The remaining two case studies were systems based on wind technology: a wind turbine system used for battery charging (electricity generation) application, and a mechanical wind water pumping application. To ensure that a project has been operational for a sufficient length of time, it was decided that unless a project has completely stopped, projects selected must have been in operation for at least three years. Finally, the case studies have been selected to ensure a fair distribution in different socio-cultural environment.

2.3.1 Solar energy project in Folovhodwe, South Africa

Project objective

In 1998, the governments of South Africa, represented by the Department of Mineral & Energy and Bavaria started a joint venture project in Folovhodwe to provide solar powered off-grid electricity to the community. The villagers in Folovhodwe are mostly farmers who engage in small-scale agriculture while some work at the Venmag mine in the area. The objective was to use renewable energy technology to provide modern energy services to a remote rural village located far from existing grid as a means to improve their standard of living and eradicate poverty [17]. The project provided electricity to 582 households, 3 schools and 8 businesses in Folovhodwe at the cost of R2.7million or about US$400,000.

Implementation

Folovhodwe was selected primarily because data on environmental suitability had already been complied by government agency in 1996 [17]. A project steering committee was assembled to mobilize the participation of key stake holders in the community. The key player in project implementation was Sun Electricity, responsible for system installation in households. It was also responsible for the development of project implementation strategies such as terms of payment of monthly service fees, revenue collection and project maintenance.

Financing and tariff structure

A big part of project funding came from the German State of Bavaria which provided R1.9million (about US$280,000) while the rest came from the Department of Mineral & Energy. The system installed in each household comprised a 50W solar panel, battery, energy-saving lights, and outlets for small appliances (DC television and radio). In future a household may add an additional solar panel at a cost of R1400 (about US$206). A monthly fee is charged per household to cover the cost of system maintenance and payment of maintenance personnel.

Reasons for project failure

The main reasons for project failure were identified from the work in [17] as:

- Unclear definition of project ownership and assignment of responsibilities. When a PV system is installed in a household, it was not clear what is expected from such a household and what is expected from the implementing agency. Who owns the system and its components? Who should bear the cost for repair and maintenance?
- Project planners were not able to communicate clearly to beneficiaries the usefulness of the monthly service fee and the need for regular payment. As a result the beneficiaries claimed ignorance of this fee and hence showed little commitment to regular payment.
- The income of beneficiaries were not taken into account in deciding the tariff to be paid.
- Lack of basic skills for the technology. The beneficiaries lacked the skills to perform even basic maintenance of the system installed in their household. The project relied heavily on maintenance personnel for success without any consideration for capacity building.
- Breakdown of facilities and long down time of systems due to lack of proper maintenance. This happened because majority of the maintenance personnel left the project after few years because their wages were not paid.
- Apathy towards paying the monthly fee.
- Theft of components.

2.3.2 The UNDP/GEF solar project in Zimbabwe

Project objective

In 1993 an ambitious project to install 9,000 home PV systems was started in Zimbabwe funded by the UNDP Global Environment Facility [18], and [19]. The project known as Zimbabwe UNDP/GEF solar project was designed to promote the use of solar photovoltaic systems in rural communities, improve the living standards of rural people and achieve long term sustainability by encouraging the local PV industry.

Implementation

Initial survey by the Department of Energy in 1991 showed the existence of a huge market potential in rural Zimbabwe. Only 5% of rural households were electrified, leaving a large part of rural Zimbabweans un-electrified. Furthermore, about 2500 PV systems had been installed as at 1991 [18] and the reason for the low penetration of PV systems at that time was considered to be the high cost of systems as customers have to pay the full amount which was considered prohibitive by most rural households. The project was therefore intended to bridge this gap and make PV systems available to un-electrified rural households by spreading the system cost over a long period of time. The PV system in this project range from 18W to 83W at 12V DC and consists of PV panel, charge controller, battery, 12V DC lamps and wiring.

Financing and tariff structure

Funding for the project was provided by the GEF through the United Nations Development Programme and the Zimbabwean government [19], with GEF providing a greater part of the funds of about US$7 million while the Zimbabwean government provided US$400,000. The project developed a credit scheme to make funds available to potential beneficiaries of the new technology. It relied heavily on the success of the credit scheme for long term sustainability on the premise that repayment of loans will lead to increased availability of credit. The loan terms are a minimum of 15% deposit and loan repayment at 15% per annum over a period of 3 years [18], and [19]. The project hoped that by making credit available at low repayment, the PV market will increase such that it will lead to local manufacture of PV systems and increased capacity development in the technology. The success of this credit scheme was therefore regarded as key to long term sustainability of the project.

Reasons for project failure

The main reasons for project failure were identified from [18] and [19] as:

- The number of installations was perceived as more important than proper inspection and maintenance.
- Even with the credit scheme developed by the project, over 80% of the rural population could not afford even the smallest system thereby rendering the technology unsuitable for the majority of rural households.
- The number of personnel available for inspection were too few to handle large number of installations. It became evident as the number of installations grew that the activities of the inspection team was limited by lack of workforce.
- Increased down time of systems as technicians have to travel long distances mainly from the capital Harare to perform repairs.
- The main project design team did not consist of stake holders from Zimbabwe or the region. Involving the local stakeholders would have increased capacity of the project to respond to the real needs of rural communities.
- Theft of PV panels. Rural households are often forced to weigh the benefits of having modern lighting against the option of losing such a ‘huge’ investment.
- Devaluation of the local currency due to inflation significantly increased the cost of importation and replacement of system components.

2.3.3 The wind turbine system in Ciparanti, Indonesia

Project objective

In 1993, a wind turbine system was installed in Ciparanti (Indonesia) to supply electricity to the rural community. This followed a Memorandum of Understanding on Renewable Energy Pilot Project between the Ministry of Cooperatives of the Republic of Indonesia and the then Department of State Development of Western Australia. The main objective was to develop a pilot project using small-scale wind technology to meet the electricity needs and improve the economic capacity of people in rural Indonesia [20] and [21].

Implementation

Survivor Energy Systems (Western Australia Company) proposed a hybrid wind/diesel system to ensure 24 hours electricity supply to the community. The proposed system comprises a 20kW (S20000) wind turbine and 4.8kVA DC diesel generator to charge 24 units of 2V 700Ah batteries [20]. The diesel generator was used as backup to charge the batteries during periods of insufficient wind. The two generating systems give a voltage output of 48V DC to charge the batteries which is then inverted to 220V AC to feed 52 households, 2 mosques, a community centre and a light industrial load. The monitoring and evaluation of the project was conducted by the Indonesian National Institute of Aeronautics and Space and the Agency for the Assessment and Application of Technology [21].

Financing and tariff structure

Although the Department of State was interested in promoting the use of Western Australian technology to develop a wind turbine generating system for Indonesia's rural electrification program, it contributed *nothing* in the project [21]. The Indonesian government provided the needed infrastructure such as land, access road, system monitoring, maintenance of system, etc. Each household was charged Rp 5000 per month (not enough to cover fuel costs for the diesel generator) while the difference was subsidized by the government. The cost of grid connected electricity at that time was Rp 10000, or twice as much as the subsidized cost of the wind/diesel hybrid system.

Reasons for project failure

The main reasons for project failure were identified from the work in [21] as:

- The government clearly lacked a consistent policy for rural electrification. The hybrid wind/diesel system was implemented less than one year before the community was connected to the grid.
- The monthly fee per household was not enough to ensure continued operation of the system without government subsidy.

- There was no involvement by the people and no consultation with the community on critical decisions regarding the project.
- No attempt was made to develop knowledge about the technology or to educate beneficiaries on basic system operation. For instance, electricity was used on a 24 hour basis regardless of wind conditions which meant the diesel generator was needed regularly thereby increasing operational costs.
- There were no available local skills for repair and maintenance, personnel have to travel from the capital Jakarta to effect repairs.
- Low benefit of project to the people, generated power could have been used to encourage night education.

2.3.4 Wind water pumping in Senegal

Project objective

In the period 1982 to 1991 wind water pumping systems were installed in several villages in Senegal to supply water for agricultural and domestic needs using funding mainly from donor agencies [22] and [23]. However, most systems stopped working after few years due to lack of adequate maintenance and repair. The villagers require regular supply of water to grow their crops and generate income for the family but as long as the pumps do not work water remained a scarce commodity.

Implementation

A local man who had participated in the installation proposed to manage the pumps by providing needed expertise while the beneficiaries paid an agreed fee. In order to implement this *new* project, a company VEV (wind/water for life) was formed to handle pump maintenance for the villages using revenue from water sold to the villagers. Each community has a committee to oversee system operation and revenue collection. The collected revenue help the company to repay loan, pay salaries and invest some part in a repair fund. Presently, the wind pumps are being manufactured in Senegal using about 95 of local components [22].

Financing and tariff structure

The company developed a finance scheme which received a boost from the United Nation's African Rural Energy Enterprise Development in the form of a loan to commence pump maintenance for the villages. The loan was used to purchase parts to rehabilitate broken down pumps to guarantee water supply for agriculture and domestic use. The beneficiaries are charged per quantity of water consumed. The price structure shows that in a typical village the fee is CFA 10 (about US¢2) for a 20-liter bucket and CFA 150 (about US¢32) for a 200-liter barrel [22].

Reasons for project failure

The main reasons for project failure (before VEV intervention) were identified from the work in [22] as:

- There were no long term plans for pump maintenance after the departure of project team.
- The host community obviously did not participate in project decision making resulting in the project being abandoned after some years.
- The communities did not take ownership of the project.
- The project focussed on short term funding without due consideration to how project should be sustained on the long term.

2.3.5 The Nyimba PV project in Zambia

Project objective

The Nyimba (Zambia) PV project started in June 1998. The main objective of this project is to evaluate the feasibility of integrating the Energy Service Company project approach into the rural electrification strategy of Zambia [24] and [25]. An Energy Service Company project approach recognizes that renewable energy systems are costly and unaffordable by most rural people and adopts a strategy that offer energy services to people without owning the hardware, thereby increasing affordability.

Implementation

The project was implemented by the Department of Energy of the Zambian government supported financially by the Swedish International Development Authority. The project installed 100 units of solar home systems comprising a 50W (12V) PV panel, 96Ah deep cycle battery and charger, 4 units of 7W fluorescent lamps and 1 unit of (double) 12V socket outlet. The unique feature of the project compared with other solar PV experiences in developing countries lies in its adopted strategy which provides many rural people who may not afford the cost of buying a PV system the opportunity to enjoy modern energy services at the payment of a monthly fee. This strategy is comparable to the structure of conventional grid-connected systems in which the utility company owns the hardware while users pay a monthly fee.

Financing and tariff structure

Once a user signs a contract with the Energy Service Company, a 50W PV system will be installed by the energy company while the client is expected to pay a monthly fee of 25,000 Zambian Kwacha (about US$7.5). The monthly fee covers the cost of hardware, installation, replacement of damaged components and maintenance of the system.

Reasons for project success

The reasons that contributed to project success were identified from [24] and [25] as:

- Ownership of the hardware was clearly defined using a structure that is comparable to conventional grid-connected systems.
- Plans were put in place for maintenance and project management by assigning defined roles to relevant agencies. For instance, a local company (Nyimba Energy Service Company) was set up to take care of project management and maintenance.
- Bidding companies were asked to include plans for training technicians from the local company.
- Beneficiaries also received training on system operation, end users were able to operate their systems efficiently.
- The Nyimba Energy Service Company had a local office where users can report faults.
- Furthermore, there is a regular monthly visit by technicians to check for faults and routine maintenance
- Good strategy on how repair and maintenance costs should be funded.
- Monthly tariff was determined annually to avoid harmful effects of inflation. Part of the monthly fee is saved to purchase new battery when needed.

2.4 Discussions about failure

Why did renewable energy projects fail to meet its intended targets, encourage the growth of the technology, improve the living standard of rural people and reduce poverty? In this section, the major reasons identified for project failure are discussed in greater detail under five headings, namely, institutional, technical, economic and social, as shown in Table 2.1. The first three headings, that is, sections 2.4.1 to 2.4.3 belong to institutional category while sections 2.4.4 and 2.4.5 belong to technical and economic category respectively. The social category was not captured in the discussion presented in this section as they did not have direct influence on project failure in these case studies. However, it is presented later in section 2.5 as it is our view that social issues should be given due consideration in renewable energy project implementation in developing countries.

2.4.1 Meeting real needs of local people

Crucial to the success of a renewable energy project in developing countries is the question: what need will the project meet and who will benefit from it? While it is true that part of the objectives of many donor-funded projects in developing countries has always been to alleviate poverty in rural communities by providing access to modern energy services, the reality is that this has not always been the case. The cost of renewable energy systems are mostly beyond the reach of poor rural people. Even with a credit scheme that makes funds available at low interest rates, many rural people are still not able to afford very basic systems. This can be illustrated by the following examples.

Table 2.1: Summary of reasons for the failure of renewable energy projects

Category	**Reasons**
Institutional	Insufficient involvement of benefiting community in key aspects of the project. The communities did not take ownership of the project. Unclear assignment of responsibilities to key players. Lack of adequate personnel for inspection and maintenance. Inconsistent policy on rural electrification. No long term planning for project management following the departure of implementing team. No clear plan to develop local skills.
Technical	Rural people lacked skills for the technology. Long down time of systems. Improper use and management of systems such as batteries. Lack of regular or planned maintenance of systems. Unavailability of spare parts for repair.
Economic	Short term funding without due consideration to long term sustainability. Low tariff. Irregular payment of tariff. High cost of systems, majority of the rural population could not afford it. Low benefit of project to the people. Increased cost of importation and replacement of components, for instance due to high inflation.
Social	Apathy towards the project. Theft of system components.

In an electrification project in Indonesia [26] households needed access to a small, affordable amount of electricity, around 20W (enough to power two 10W bulbs) as a replacement to candles. The smallest amount of energy the utility would offer was 100W which most people considered too expensive and therefore unable to take up the offer. The UNDP/GEF project in Zimbabwe was severely criticized because many argued that the project did not benefit the poor despite the fact that poverty alleviation was one of the objectives of the project. Many of the beneficiaries of the UNDP/GEF project in Zimbabwe were the small percentage of the relatively rich people living in rural areas or rural people with rich relatives in the city [19]. Furthermore, the requirements of the credit facility was such that many rural people could not qualify for loans to install the systems. One of such conditions is that beneficiaries need to demonstrate a steady flow of income before they can be recommended to access project loans. Since rural villagers are often subsistence farmers, this condition proved difficult to meet. On the other hand, the wind water pumping project in Senegal illustrates how meeting needs that benefit the poor in a rural community can lead to project success.

2.4.2 Project planning and ownership

Part of the aims of renewable energy project planning is to define '*ownership*' of the project. In this context, it means to make clear the roles and responsibilities of the different players and to build such into the management structure of the project. The concept of ownership also includes decision on project siting which has to be made tactfully to ensure that the project do not convey the wrong meaning to the community. In a rural community in Thailand, the siting of a water pump within the compound of the village head caused the community to stay away believing that the pumps were not for their benefit [27].

In the Folovhodwe solar energy project, one of the reasons for project failure bordered on the inability of project planners to define ownership of the project. For instance, when a PV system is installed in a particular household, what is expected from such a household and what is expected from the implementing agency? Who owns the PV panels, batteries and other system components? When there is system failure, who is responsible for the cost of repair and maintenance?

The beneficiaries in Folovhodwe imagined that PV systems worked just like grid connected electricity where at the payment of a connection fee, a customer is connected to the grid. The customer is required to pay a monthly bill based on the consumed energy (kWh) while the major hardware is owned by the utility company. The solar home systems implemented by the government of Zambia in Nyimba (Zambia) was designed to mimic this structure [25]. An agreed monthly fee is charged by the implementing company for repair and maintenance of the system. The government of Zambia *own* the system hardware, similar to the structure used in conventional grid connected system.

Therefore, despite the initial enthusiasm that welcomed the PV project in Folovhodwe, as some components began to fail the issue of who is responsible for what, particularly, who should carry out these repairs and maintenance and who should pay for it began to arise? It was not surprising that apathy and mistrust soon led to a decreasing commitment by the community towards project success.

2.4.3 Community participation

The problem of ownership also raises an equally important issue in terms of the involvement of the host community and how this affects the success of renewable energy project in rural communities. The host community can play a role in the following project areas: choice of location, appropriate tariff, management of collected funds, system maintenance/repair, project supervision, protection of project equipment against theft, etc. This approach ensures that project planners have the full support of the community, a clear understanding of the real needs of the community and insight into specific problems peculiar to the community in order to adopt the right strategy for project success.

In the UNDP/GEF solar project in Zimbabwe, this was not the case. No local stakeholder within Zimbabwe or international non-governmental organization formed part of the project team [19]. It is possible that due to the overly ambitious target of installing 9,000 PV systems in five years, key aspects of planning such as consultations with important stake holders were compromised. Similarly, in the Folovhodwe solar energy project, the host community did not participate in determining the monthly tariff to be paid for repair and maintenance of system components. The beneficiaries actually questioned the tariff claiming ignorance of the purpose of the monthly tariff. Thus, despite the fact that the fee was eventually reduced from R35 to R20, the beneficiaries could not pay regularly.

2.4.4 Maintenance and local capacity

Maintenance related issues are the most frequently encountered problems when renewable energy systems are implemented in developing countries due to lack of skilled manpower. Unlike in conventional rural electrification schemes such as grid extension, renewable energy systems require maintenance. During project implementation, technicians from the implementing agency are available but this may not be economically viable on the long term. What happens after the departure of project personnel? It is surprising that despite the apparent lack of technical skills in rural areas that project developers still fail to take this into account during project planning. In the Folovhodwe project, many households thought that the new PV systems work in the same way as the conventional grid system where one can add an almost infinite units of domestic load.

This apparent lack of long term plan for developing local skills is illustrated by the UNDP/GEF project in Zimbabwe. The project was conceived to address barriers to the use of

PV technology such as lack of locally produced components, trained manpower and data for PV system design [28]. Yet, the project did not have a clear plan of how to develop local skills in PV technology. The ambitious nature of the project to install 9,000 PV systems in five years should also have meant an equally ambitious plan for training and workshops for human capacity building. According to [19], there were few personnel for inspection and it soon became obvious as the number of installations grew that there were insufficient number of workers for installation and inspection. The project team relied on existing PV companies in Zimbabwe to carry out installations, maintenance and repairs, without making any attempt to impact basic skills to end users. Technicians have to travel long distances (mostly from the capital Harare) to carry out even basic tasks thereby increasing the length of down time of the systems. For instance, only 20% of repair jobs got a response within 1 month while 30% took longer than 3 months to get a response [19]. Maintenance of systems can also be linked with the prevailing socio-cultural environment. Technicians responsible for system maintenance may feel too important to travel long distances to a rural village to perform repairs for people who are not so important.

The approach of using technicians located far from the project had serious consequences on project success. Firstly, the cost of repair and maintenance became high, possibly due to the long distances travelled in order to carry out repairs which could have been done by a local technician or even the end user had they been trained for such tasks. Secondly, the long down time of systems meant that users have to wait for a long time to get their system running. This added to the frustration of users, and possibly led to reduced interest in the project and even default on the repayment of their loans thereby making less funds available for the project.

Maintenance problems also contributed significantly to the failure of the PV project in Folovhodwe. In this project, the implementing agency relied on the payment of a maintenance *fee* to take care of salaries of technicians and cost of maintenance. Just like in the UNDP/GEF project in Zimbabwe, many end users developed apathy for the project and this (again) led to irregular payment of the maintenance fee to the detriment of system maintenance and repair. The collapse of the monthly tariff may have led to the collapse of the maintenance team which were supposed to receive remuneration from collected maintenance fee. At the start of the project in 1998, there were 6 service technicians but by 2004 all the technicians had left the project due to irregular payment of their wages [17]. Expectedly most of the installed PV systems stopped working after the technicians left. As at 2004, only 13 PV systems were still functional, less than 3% of installed systems [17].

The donor-funded wind water pumping project in Senegal illustrates what would happen if there are no plans for maintenance after the departure of project team. The local communities did not participate in the project as they were neither involved in the planning process nor in taking ownership of the wind pumps. Naturally after the withdrawal of project personnel hundreds of wind pumps stopped working due to lack of maintenance and spare parts to replace worn out components.

2.4.5 Cost, tariff and finance management structure

The cost of renewable energy system hardware is still considered high and unaffordable for most people living in rural areas of developing countries. Renewable technologies such as solar and wind systems require huge initial capital investment which are beyond the reach of most rural people. The implementation of renewable energy projects in developing countries therefore relied on part (sometimes full) funding from foreign donor agencies and the host government. Since donor funded projects usually have a fixed period of implementation sustainability of the project becomes difficult once funding is exhausted. To address the issue of high initial cost, many projects implement finance schemes that spread the investment cost over many years. The beneficiaries pay an initial down payment (typically about 10% of total investment cost) while the rest can be paid over many years using low interest loans. Even with this approach system cost may still prove prohibitive for most rural people.

Beneficiaries may also be asked to pay a tariff (usually a fixed monthly fee) which is used to purchase spare components and to pay maintenance technicians and other project personnel. Determining an appropriate tariff or a monthly fee can be a source of disagreement and disaffection if not carefully handled. Most rural households are poor and cannot afford additional expenses which compete with food, medicine and tuition for children. If the tariff is too high, most people cannot pay but if it is too low it may not be sufficient to carry out repairs and pay wages. To resolve this issue, the host community should play a role in determining a suitable tariff. It has been shown that rural people are willing to pay a fee for maintenance and repair if they were involved in determining what is appropriate and if the proposed fee is modest as reported in [24], [25], and [22]. In the Nyimba PV project in Zambia, the monthly fee is set on a yearly basis to account for inflation while clients can also renew their contracts annually. Initially, the fee was ZMK 20,000 (about US$5), this was later increased to ZMK 25,000 in 2001 and ZMK 30,000 in 2002.

Irregular payment of the monthly maintenance fee was a major reason that led to the failure of the solar project in Folovhodwe according to [17]. In the first year of the project the fee was R35 (about US$5) yet only 40% of the households paid this fee. One year later the monthly fee was reduced to about US$3, yet the number of households that paid dropped to 25% [17]. The end users, according to [17], claimed that they did not understand the purpose of the fee. This misunderstanding indicates a possible lapse in communication where the beneficiaries had a certain expectation while project planners had a different expectation. Irregular payment of fees for renewable energy service could also arise if the end users decide to take advantage of the charitable nature of donor-sponsored projects. Removing ambiguity about the amount to be paid and the purpose of the fee at the initial stage will encourage end users to pay.

In the Nyimba solar energy project Zambia, beneficiaries willingly paid a monthly fee of about US$7.5 [25], which is twice the monthly fee in Folovhodwe. In the wind water pumping project in Senegal, the beneficiaries also paid the agreed fee because they participated in determining the fee and are also responsible for managing collected funds. In this project, the finance structure is slightly different: instead of paying a monthly fee for repair and maintenance, villagers are charged per quantity of water consumed. These cases show the importance of involving the community in determining tariff and management of collected funds.

2.5 Design considerations for renewable energy projects

The previous sections identified and examined the reasons for the failure of renewable energy projects. In Table 2.1 the identified reasons for failure were categorized as belonging to institutional, technical, economic or social reasons. This section proposes some design considerations that can contribute to long term success of renewable energy projects taking into account the discussions in previous sections.

2.5.1 Institutional considerations and needs assessment

Institutional considerations

Institutional considerations focuses mainly on developing an appropriate and implementable plan for the project. An inclusive and participatory planning process involving all stakeholders, especially the host community is key to achieving long term success. The first task in the planning process is to define the need to be met in order to achieve project acceptance and economic viability. Meeting the identified needs requires that an appropriate technology be employed. What type of technology is most suitable and yet simple enough for rural people to manage? Does the host community have the technical and economic capability to maintain and sustain the project? Institutional challenges forms an integral part of other design considerations such as technical, economic and social considerations and will be presented further in subsequent design considerations.

Needs assessment

A key question to be addressed by renewable energy project planners in developing countries is *what need will the project meet and who will benefit from the project*? Since it is difficult for renewable energy systems to meet all energy needs of a community, the capacity of such a system should be clearly assessed to ensure that the need it proposes to meet is well understood and that the community is also sufficiently informed. The energy needs of a rural community can be grouped into three major categories [29]:

(i) energy to meet domestic needs
(ii) energy to meet agricultural needs
(iii) energy for small scale industrial needs

In rural areas of developing countries, the importance attached to the need being met by a renewable energy project determines to a large extent its long term sustainability. A community where most women and children spend one third of the day in search of water may find it difficult to attach great importance to home lighting. By extension, the importance attached to the need being met determines the motivation to pay an agreed tariff which has an important correlation to project success. Furthermore, the capacity and the willingness to pay an agreed fee is greatly increased when the need being met leads to an increase in family income.

2.5.2 Technical considerations

Appropriate technology

When the needs to be met have been properly assessed, the next consideration is to choose an appropriate technology suitable to meet the needs. An appropriate technology can be defined in this context as one that can be adapted to meet the energy needs of such a community and at the same time be economically sustainable. The choice of an appropriate technology should be influenced by the needs of the community and how those needs are presently being met. In [30], the approach adopted is to use a suitably sized wind generator to charge batteries as an alternative to conventional means of charging. Before the implementation of the project, many households used car, lorry or motorcycle batteries to provide electricity for lighting and to power some house appliances. In this case, the wind powered system ensured battery charging needs are easily available and at reduced cost compared with the traditional method.

Maintenance consideration

In the case studies analysed in this work, maintenance-related challenges were the greatest contributor to failure. On the other hand, the project that succeeded was mostly because maintenance problems were addressed. A number of options can be considered regarding how system maintenance should be implemented, such as the use of project personnel, training local technicians and training beneficiaries. In the long term, it may not be economically viable to keep project personnel permanently in a rural area to handle repair and maintenance. A locally trained technician may present a more sustainable alternative. Since renewable energy technology is a *new* technology in many rural communities, the long term plan of project developers should include a strategy for local capacity building by increasing available knowledge and skills for dealing with the technology.

Local content considerations

Another important technical consideration for renewable energy projects in developing countries is local content design consideration. This consideration involves the development of local capacity, development of local industry, technology transfer, use of local skills in project implementation and local manufacturing of components. It should be considered how available local skills can be utilized during project implementation and the type of skills improvements that are required. The problem of availability of spare parts to replace damaged or broken components should be considered to avoid long delay in carrying repairs. The cost of the systems can be significantly reduced if some components were manufactured locally. Such approach also encourages the development of local industry, increases job creation and local income generation.

2.5.3 Economic considerations

A scheme for generating funds from the energy services provided by the project should be considered . Furthermore, the tariff should be carefully adopted to ensure that rural people pay a comfortable amount and yet sufficient for economic viability. To arrive at an agreeable amount, it may be necessary to determine what households currently pay for traditional methods of energy use. Can the project be implemented such that it leads to increased income generation and economic empowerment of the local community? In this context, the project design can include the development of a business model that can benefit from the newly introduced modern energy services.

2.5.4 Socio-cultural considerations

Socio-cultural issues refer to attitudes and way of life and should be considered in the design of renewable energy projects in developing countries but are often neglected. Socio-cultural challenges such as ownership, lack of trust, social discontent, urban migration, cultural conflict with new technologies, gender, among others, can significantly determine the acceptance of renewable energy technologies in rural communities. It also has some influence on other design considerations which have been presented.

The ownership structure of the renewable energy project depends on the prevailing socio-cultural environment of the community. An important aspect of ownership is project location as this can be a source of disagreement and apathy. As a result of this, the decision on project location has to be carefully made in order not to convey the wrong meaning to the community. Theft and vandalism are also important considerations for the location of the project. *Theft* can go can go deeper into social relationships. A village head may decide that his need for a TV is far greater than the needs of the community [31].

There are three main ownership structures that can be considered for a renewable energy projects in a rural community. The first is private ownership (entrepreneurial) in which a privately owned company runs the project based on an agreement with the implementing agency. State-owned rural electrification agencies may also take ownership of the project as demonstrated in the solar energy project in Zambia. The third type of ownership is community-based, which encourages community participation by involving the community or its representatives in running the project. This type of ownership has been a successful strategy for some self-help projects in Cameroon [32] – [34]. However, further research is required to demonstrate the effectiveness (or otherwise) of a community-based approach.

2.6 Conclusion

Several reasons are responsible for the poor performance of renewable projects in developing countries. The major reasons identified are:

- **Cost –** high system costs and tariff, as presented in Section 2.4.5;
- **Technical skills –** required for maintenance are lacking, as presented in Section 2.4.4;
- **Complex systems** – rural people are not familiar with renewable energy systems, as presented in Section 2.4.2 and 2.4.3.

Faulty planning, lack of community participation, technical problems and unsuitable tariff structure have played major roles in the failure of the projects investigated. Project planners in developing countries often fail to clearly define the need to be met and who will benefit from the project. The cost of renewable energy systems are mostly beyond the reach of poor rural people, even with a credit scheme that makes funds available at low interest rates. As a result only few rich people in the community and those that have rich relatives in the city can afford such systems. Furthermore, the absence of community participation in project planning and implementation results in general apathy and lack of acceptance.

Perhaps, the greatest problem responsible for the low penetration and lack of long term success of renewable energy projects in developing countries is technical challenges. This problem is unique because most rural communities lack technical skills especially with regards to high-tech systems such as PV and wind technology. Many rural people have no idea how renewable systems operate and how to tackle even basic repair and maintenance problems. Technical challenges are further compounded by poor planning such as the inability of planners to come up with required strategies to develop such skills locally. Technical challenges in rural areas may also have a socio-cultural dimension. For instance, technicians responsible for maintenance may feel too important to travel long distances to a rural village to perform repairs for people who are not so important. Furthermore, in many rural cultures, the importance of the present could make it difficult to plan and prioritize system maintenance.

Long term economic sustainability of projects also played a major role in project failure. The question still remains how to make renewable energy projects economically viable after project funding is exhausted. A good strategy is the payment of a maintenance fee which worked well in a few cases. However, community involvement is the key to the adoption of a tariff that is considered appropriate; one that is sufficient to ensure economic viability and yet low enough to be affordable by local people.

Based on the identified reasons for failure, some design considerations were proposed to: develop the required skills to deal with technical challenges; develop technically and economically viable solutions; empower rural communities to ensure economic sustainability; and encourage rural communities to make some socio-cultural adjustments to cope with the new technology. In particular, since socio-cultural challenges have great influence on other design considerations, it was proposed that the prevailing socio-cultural environment should be taken into account in project design to prepare such communities for the transition from traditional to modern technology.

Important deductions from this study includes:

- Cost have to be lowered to increase renewable energy penetration;
- Systems need to be simpler;
- Development of technical skills is imperative;
- To achieve cost reduction, promote local economy and industry, system components need to be manufactured locally;
- The socio-cultural environment should be taken into account in project design;
- Entrepreneurship and good business model will increase project sustainability;
- Community participation is key to renewable energy project success in developing.

Chapter 3

Small Wind Turbines in Low Wind Speed Areas

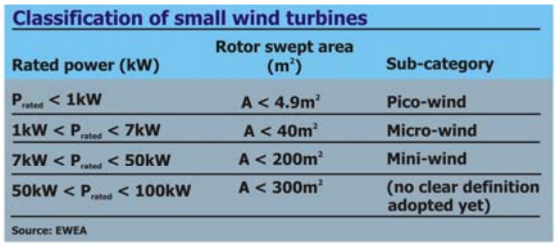
3.1 Introduction

Chapter 2 of this thesis investigated the reasons for the failure of renewable energy systems in developing countries. In this chapter, an overview of the turbines used in small wind power generation and the energy yield from such a system is presented. A survey of existing small wind turbine systems indicates that there exists several possible system configurations. This chapter investigates the best system topologies that are suitable for our application in terms of cost, manufacturability and energy yield. Small wind turbines operate mostly in low and moderate wind speed areas since they are sited where the energy is needed rather than where wind is best. Low wind speed operation of small wind turbines has consequences with respect to the energy yield that can be extracted from the turbine. In order to establish the performance capabilities of small wind turbines in low wind speed areas, a comparison of the energy yield of commercially available small wind turbines is presented in this chapter. The comparison is based on their annual energy yield per swept area and cost per energy produced in a low wind speed climate using measured field data. These criteria were used in order to provide a fair comparison since the turbines do not have the same diameter.

This chapter begins with a description of types and applications of small wind turbines. Next, an overview of generator systems used in small wind turbines and technology of existing small wind turbines are presented to better understand the configurations that are suitable for our application. Finally, a comparison of the energy yield of existing small wind turbines in low wind speed areas is presented.

3.2 Types of small wind turbines

Large wind turbines are popular and are mostly responsible for the continued steady growth of wind technology in the past decade. These MW scale, grid connected turbines are installed in wind farms and in areas with high wind speeds. Small scale wind turbines on the other hand are different: they are mostly used for off-grid applications in remote areas. They also differ from large wind turbines in size, power rating, and types of generators and speed regulation used. Figure 3.1(a) shows a categorization of small wind turbines from a few watts to 100kW.



Classification of small wind turbines

Rated power (kW)	Rotor swept area (m^2)	Sub-category
P_{rated} < 1kW	A < 4.9m^2	Pico-wind
1kW < P_{rated} < 7kW	A < 40m^2	Micro-wind
7kW < P_{rated} < 50kW	A < 200m^2	Mini-wind
50kW < P_{rated} < 100kW	A < 300m^2	(no clear definition adopted yet)

Source: EWEA

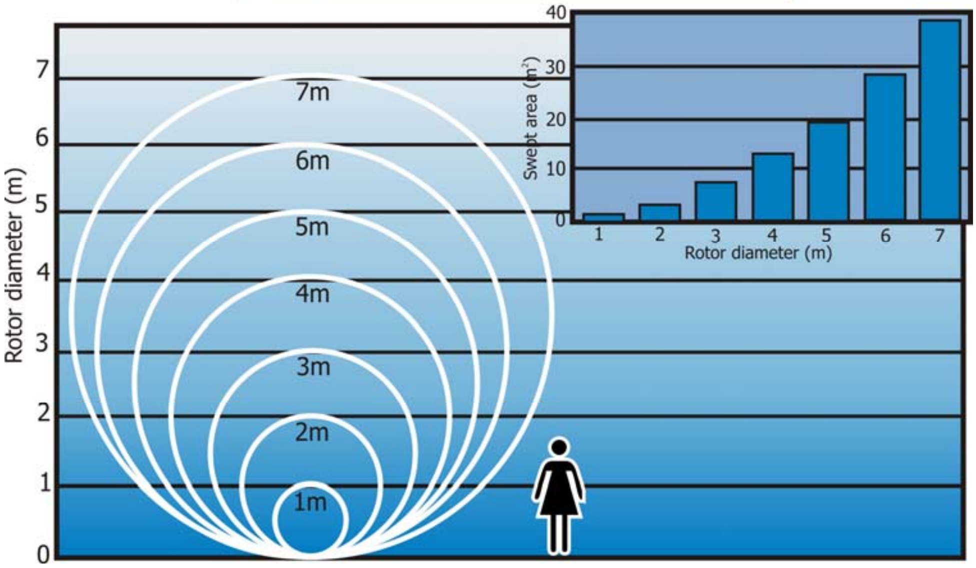


Figure 3.1(a): Classifications and size of small wind turbines

(b)

(c)

Figure 3.1: (b) Fortis Montana, a horizontal axis wind turbine: source- Provincie Zeeland; (c) Turby, a vertical axis wind turbine: source- TU Delft. Both were used at the Schoondijke small wind turbine test trials.

Small wind turbines can be classified based on their physical size (rotor diameter or swept area) and rated power. The pico-wind turbines are generally accepted as those that are smaller than 1kW. A swept area of $40m^2$ was the limit established in the first edition of the International Electrotechnical Commission IEC 61400-2 Standard and is the range intended for the integration of such turbines into the built environment; the $200m^2$ was established in the second edition of the Standard, and includes most small wind turbine applications [8].

Small wind turbines can be categorized into two types: horizontal axis wind turbines and vertical axis wind turbines as shown in Figure 3.1(b) and Figure 3.1(c) respectively. There have been varying claims by both researchers and manufacturers about which turbine type is most attractive in terms of energy yield in low wind speed areas. Vertical axis turbines do not need to be pointed into the wind as it can access wind from all directions. However, the overall efficiency of such a turbine is not very impressive. Horizontal axis turbines have better overall efficiency but they generally have difficulties operating near ground and in areas with turbulent winds because they require more laminar wind flows. In general, the efficiency of small wind turbines is low compared with large wind turbines [18] which invariably leads to comparatively lower energy yield. This low efficiency is in part due to aerodynamics and its operation in low wind speeds, but also due to the lack of optimized designs [8].

Small wind turbines can also be categorized based on the type of system configuration used for different applications. There are three major applications of small wind turbine: mechanical water pumping, electric water pumping, and electricity generation.

3.2.1 Mechanical water pumping

The system description of a mechanical wind pump is shown in Figure 3.2 while examples of small wind turbine applications are shown in Figure 3.3. The farm windmill, shown in Figure 3.3(a), is a mechanical system comprising of multi-bladed high solidity rotors (10 to 24 blades) connected to a positive displacement pump. The high number of blades is necessary to supply the high torque required by the pump for starting. A gearbox is often inserted between the turbine shaft and the crank shaft to achieve gear reduction and increase available torque. The turbine rotors have a peak efficiency of 10-15% at a tip speed ratio of around 1 while system average annual efficiency (wind to water pumped) is around 5–6% [35], [36]. Wind to pump efficiency is lower than turbine efficiency because the pump efficiency further reduces system performance.

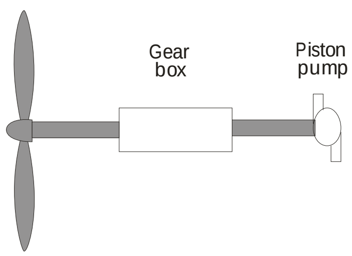


Figure 3.2: Mechanical wind pump system

(a) Mechanical wind pumping [37]

This 18 bladed wind powered water pump on Oak Park Farm, Shedd, Oregon is used to drain excess water from farm land to improve agricultural production. It pumps about 1.4m^3 per minute on an average windy day. The large number of blades ensures that the turbine generates considerable torque. At the tower top, there is gearbox and crankshaft that convert the rotary motion into reciprocating strokes carried downwards through a rod to the pump cylinder below.

(b) Electric wind pumping [38]

This 1.5 kW wind-electric water pumping system is installed at the Oesao Demonstration Farm on the island of Timor in Eastern Indonesia. This part of Indonesia is characterised by a short rainy season but with a water table which is only 2-5 meters below ground level. The turbine was installed to pump water for irrigation so that local farmers can raise higher value crops all year round. The turbine drives a 3-stage surface mounted centrifugal pump (1.5hp, 60Hz, 3-phase, 240VAC) operated at variable voltage and frequency. The pump speed varies with the rotor speed of the wind turbine. It pumps at a peak rate of about 0.18m^3 per minute.

(c) Grid connected electricity [39]

This small wind turbine is mounted on utility pole. Generated electricity from the turbine is connected to the grid via a built in micro-processor controlled inverter.

(d) Hybrid wind-PV systems [40]

This 5kW wind turbine is part of a hybrid system in Senegal comprising the turbine, a 5kW PV, 11kVA diesel generator and 120kWh battery. This hybrid system is used for village electrification.

Figure 3.3: Some applications of small wind turbines

An important distinguishing feature of a wind turbine is the tip speed ratio. The tip speed ratio is a measure of the relation between the rotor blade tip speed and the wind speed. This ratio plays a crucial role in determining the efficiency of the wind turbine. To utilize power in the wind efficiently the rotor has to have suitable rotational speed relative to its size (rotor diameter) and wind speed.

Tip speed ratio of a wind turbine depends on the number of blades: fewer blades implies high tip speed ratio. This implies, for instance, that for turbines with the same rotor diameter, 2-bladed turbine needs a higher rotational speed than a 3-bladed turbine. Optimal tip speed ratio can be calculated for different rotor types as shown in Figure 3.4. The figure shows that a traditional wind mill with 4 rotor blades (Dutch windmill) is most efficient at tip-speed ratio of about 2.5. Optimal tip speed ratios for modern wind turbines are 6.5 and 10 for three-bladed and two-bladed wind turbines respectively. Wind turbines with low tip speed ratios are suitable for low speed applications such as water pumping and other mechanical uses. High tip speed ratio wind turbines are suitable for electricity generation.

The power coefficient C_p is the share of the power in the wind that can be utilized by the rotor. Its theoretical maximum is $C_{p\max} = 16/27$ (≈ 0.593) which means that the rotor of a wind turbine can at most extract 59% of the power in the wind (Betz limit), ignoring aerodynamic and mechanical losses. Practical wind turbines have a C_p value lower than 0.59 and the value also varies for different wind speeds. High speed rotors such as two or three blade rotors having aerodynamically formed blades, rotating at tip-speed ratios of about 4 to 8, have C_p values of about 0.4 to 0.5. Slow running rotors such as the multi-blade American windmill or Dutch four-blade windmills have significantly lower coefficient of performance.

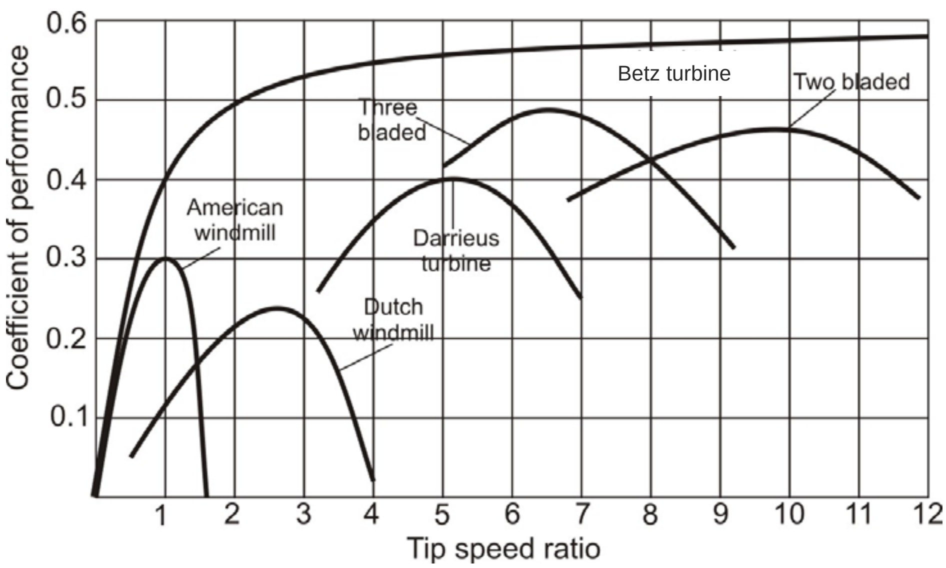


Figure 3.4: Coefficient of performance as a function of the tip speed ratio for various turbine types compared theoretical limit [41].

3.2.2 Electric water pumping

Another type of wind powered water pumping is the use of electricity generating wind turbines to power an electric deep well pump. In this system (Figure 3.5), the turbine is directly connected to a motor which is connected to a centrifugal pump. The advantages of the wind electric system over the mechanical system for water pumping application includes the following.

- It can be sited at a different location than the pump thereby providing the freedom to install the wind turbine at a windy site.
- Average annual system efficiency is double (12-15%) that of mechanical wind pumping system [35]; therefore, wind electric systems can pump twice the amount of water from the same depth
- Larger sized wind electric systems can be used to implement a village water scheme or village irrigation scheme.
- It is a viable alternative solution to diesel powered generators in stand-alone high volume water pumping from deep wells.

3.2.3 Electricity generation

Small wind turbines can be used to generate electricity to charge batteries, to power DC or AC loads and for grid connection. The electricity generated by small wind turbines can be used for either autonomous (off-grid) applications or grid connected applications as shown in Figures 3.6 and 3.7. Off-grid systems are not connected to any larger generating system while grid-connected systems (distributed generation) are connected to a larger distribution (utility) network. The greatest potential for small wind turbines lies in off-grid systems, particularly in developing countries with many remote households far from the nearest grid and where the expected revenue derivable from grid extension is often too small to justify the huge capital investment. The major drawback of such system is that a storage system is required since wind is not present at all times. As a result batteries are included so that excess generated electricity can be stored during periods of high winds and to provide electricity during periods of low and no wind.

Most small wind turbines are of the variable speed direct-drive type employing permanent magnet synchronous generators. To connect such a system to grid the variable frequency output has to be adapted to fit the grid by rectifying the AC output to DC and then converting it back to AC using an inverter in the so-called AC-DC-AC scheme. The main advantages of such a system are that the need for a storage system is eliminated and that revenue can be earned when excess generated electricity is fed to the grid.

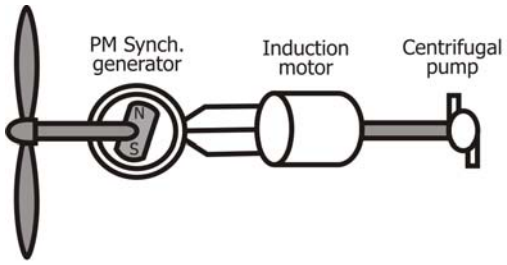


Figure 3.5: Electric water pumping

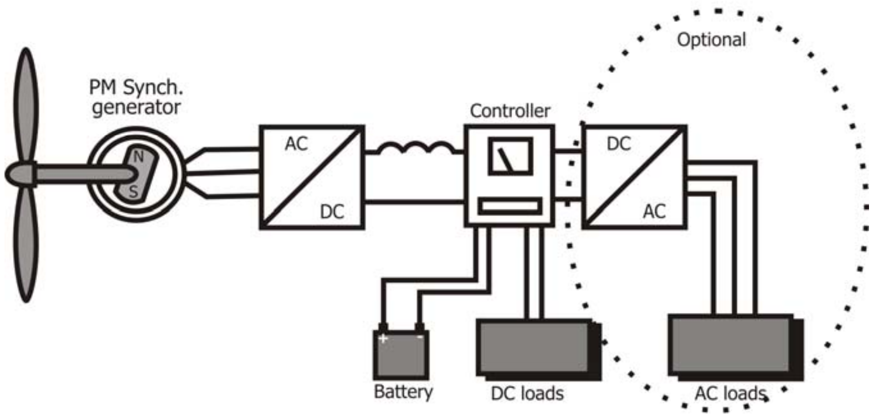


Figure 3.6: Off-grid wind electricity generation

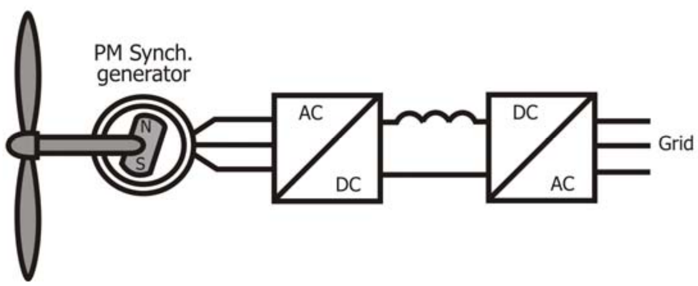


Figure 3.7: Grid-connected wind electricity generation

3.2.4 Hybrid systems

Small wind turbines can be combined with other generation sources such as photovoltaic systems or diesel generators. A hybrid system comprising wind and solar systems leads to a solution with increased availability due to the often complementary nature in the availability of wind and sun. In such a hybrid system, a diesel generator can also be included to supply back up power. Hybrid systems are traditionally used for village electrification but they are finding increasing importance in the telecomm sector where they are used to power mobile phone base stations. In many developing countries, the grid is weak and mostly unavailable leading to low penetration of mobile phone services due to the high cost of operating diesel generators. Mobile phone operators now implement hybrid power solutions to reduce fuel consumption and increase market penetration by extending services to remote areas.

Table 3.1 summarizes the various applications of small wind turbines which can be broadly grouped into off-grid and on-grid applications. The most traditional use of small wind turbines is in isolated (off-grid) applications such as rural electrification, water pumping, telecommunication sites and farms. Small systems of less than 1kW are commonly used as DC systems in which generated energy is stored in a battery and used to supply DC loads. Larger systems of a few kW may be used for electric water pumping, rural electrification (usually hybrid systems) and village square electrification.

Table 3.1: Applications of Small Wind Turbines

Power rating	**Off-grid applications**								**On-grid applications**					
P < 1kW	+		+	+	+	+					+			
1kW < P < 5kW	+	+	+	+	+	+	+		+	+	+	+		
5kW < P < 50kW		+				+	+	+	+	+	+	+	+	
50kW < P < 100kW							+	+				+	+	+
Small wind turbine applications	Battery charging	Water pumping	Street lighting	Water purification	Remote houses	Farms	Village electrification	Mini grid	Residential houses	Health clinic electrification	Building integrated	Charging stations	Light industries	Wind farms

Small wind turbines also have great market potential in grid-connected applications such as residential houses, light industrial loads and even urban environment where they are integrated into the building. Residential grid-connected systems, unlike stand-alone systems, increases the reliability of electricity supply since the turbine can be used when wind is available to supply all or part of the load while the grid is used as back up. A grid-connected turbine is potentially a source of income generation because the user can sell excess generated electricity to the utility company.

3.3 Technology overview

Many agencies and researchers have carried out extensive work on mechanical wind water pumping. One example is the Dutch programme of Consultancy Services Wind Energy Developing Countries based at Eindhoven University of Technology. Although the programme has stopped most of its reports is now merged with the library of DUWIND at Delft University of Technology. Some reports can be found on the website of one of the designers in the programme who has continued on his own [42]. However, such detailed study on mechanical wind water pumping is beyond the scope of this thesis.

Instead, the rest of the thesis will focus on small wind turbines used for electricity generation. Electricity generating small wind turbines can be used for a wide range of applications such as electric water pumping, off-grid and grid-connected systems, among others. Furthermore, electric water pumping has several advantages over mechanical water pumping which were outlined in the previous section.

Table 3.2 shows the characteristics of 29 electricity generating small wind turbines in the range of 100W to 5000W. The table shows that most small wind turbines (26 out of 29 turbines) use permanent magnet synchronous generators while 2 turbines employ induction generators. The advantage of using induction generators is that for grid-connection the use of power electronics can be avoided which leads to cost reduction and increased reliability. Furthermore, as a general tendency, turbine protection against high wind is by furling control. Out of the 29 investigated turbines, 19 turbines used this scheme. Other control schemes employed for the investigated systems are stall control, pitch control and mechanical brakes.

Unlike in photovoltaic generation, there are no universally accepted standard test conditions to which all of the characteristics of the devices are referred [8]. It is the manufacturer who chooses the conditions (rated wind speed) for which to define the rated power of the turbine. Figure 3.8 shows the defined rated wind speeds for the given rated power values by the manufacturers of the investigated small wind turbines. The implication of the large variations in defined rated wind speed values by different manufacturers is that it is difficult to compare parameters related to rated power since they do not refer to the same conditions. There are also no defined standard conditions for large wind turbines either, but the higher maturity of the market for large wind turbines has led to a much lower dispersion [8].

A plot of the rated power shows a somewhat quadratic variation as the rotor diameter increases (Figure 3.9). The rotor diameter, and hence the swept area seems to be a better representation of the power of a small wind turbine than the rated power given by the manufacturer since it gives an indication of the total energy that can be generated by the turbine. As a result, a better representation of the cost comparison of turbines can be shown using the cost per swept area (€/m^2) rather than just cost of the turbine or cost per rated power, as shown in Figure 3.10 using system cost provided by the manufacturers. The figure shows that there is a general trend of lower cost per swept area as the size of the turbine increases.

Table 3.2: Parameters of some commercially available small wind turbines

Turbine	Generator type	Speed regulation	Cut-in [m/s]	Rating	Diam [m]
AC-120 (Aerocraft, Germany), 5 blades	18 pole PM generator	Furling at 15 m/s	3	120W (9m/s)	1.2
Aero4gen-F (LVM, UK), 6 blade rotor	3-phase PM generator	Furling (hinged tail vane) at 20m/s	-	120W (20m/s) at 12/24V DC.	0.87
Superwind 350 (Superwind, Germany), 3 blades	PM generator	Pitch controlled (feathering)	3.5	350W (12.5m/s) at 12/24V DC	1.2
Superwind350 (Superwind, Germany), 3 blades	PM generator	Pitch controlled (feathering)	3.5	350W (12.5m/s) at 12/24V DC	1.2
SOMA 400 (SOMA Power, Australia), 2 blades	3ph PM generator	Tilt up (furling) at 12m/s	4	400W (10m/s) at 12/24/32/36/48/110/120V DC	2
StealthGen (Ecletic Energy, UK), 5 blades	3ph direct drive PMA	Stall regulation	2.6	400W (16.5m/s) at 150V DC. Can be grid-connected	1.1
D-400 (Ecletic Energy, UK), 5 blades	3ph direct drive PMA	Stall regulation	2.6	400W (16.5m/s) at 12/24/48V DC	1.1
Windtalker 400 (Guangshou Hongying Energy, China)	PMG	Furling at 25 m/s	3	400W (12 m/s) at 12/24V DC	1.38
AF 2.4m (Scoraig wind electric, Ireland), 3 blades	Axial flux PM generator	Furling tail at 10m/s	3	500W (10m/s) at 12/24/48V DC	2.4
Cyclon marine (Point.of.com, Germany), 3 blades	PM generator	Furling at 16 m/s	3	600W (12m/s) at 12/24/48V DC	0.68
WT600 (Proven Energy, Scotland), 3 blades	Direct drive PM generator	Above 12m/s blades twist to limit power	2.5	600W (10m/s) at 12/24/48V DC	2.55
Rutland FM 1803 (Marlec, UK), 2 blade rotor.	PM generator	Furling at 15 m/s	2.5	700W (10m/s) at 12/24/36/48V DC	1.8
VK240 (SVIAB, Sweden), 3 blades	3ph synch. PM generator	Side furling, 10 to 20 m/s	2 to 3	750W (11m/s) at 12/24V DC	2.4
Espada (Fortis Wind Energy, The Netherlands), 2 blades	PM generator	Ecliptic hinged vane (furling) at 16m/s	3.2	800W (14m/s) at 12/24/48V DC or 230V AC	2.2
Lakota (Aeromax Corp., USA), 3 blades	3ph PM generator	Load diversion and upward furling	2.7	900W (13m/s) at 12/24/48V DC	2
Airdolphin (Zephyr Corp, Japan)	3ph PM generator	Side furling and stall regulation	2.5	1kW (12.5m/s) at 25V DC	1.8
WS1000 (Windsave, Scotland), 3 blades	1ph PM generator	Furling at 15 m/s	3 to 4	1kW (12 m/s) at 230V AC. Off grid, domestic application	1.75
BWC XL1 (Bergey WindPower Co., USA), 3 blades	3ph PMA direct drive	Auto furl at 13m/s	3	1kW (11m/s) at 24VDC or 120/240V AC	2.5
Whisper200 (Southwest Windpower, USA), 3 blades	PM generator	Side furling	3.1	1kW (11.6m/s) at 12/24/48V DC. Grid connection possible using Windy Boy Inverter	2.7
Passaat (Fortis Wind Energy, The Netherlands), 3 blades	PM generator	Ecliptic hinged vane (furling) at 14m/s	3.0	1.4kW (14m/s) at 24/48/120V DC or 230V AC	3.12
ML1500 (Moratec, Germany), 5 blades	-	-	3.7	1.5kW (11m/s) at 24V DC or 120/230V AC	3.2
Swift (Renewable Devices, Scotland), 5 blades	PM generator	Twin vane furling plus electronic braking mechanism	2.3	1.5kW	2.1
Gusto2kW (Gusto Energy, New Zealand), 3 blades	32 pole, 3ph PM generator	Passive side furling at 17m/s	3.5	2kW (13m/s)	3.2
Tulipo (Tulipower, The Netherlands), 3 blades	8 pole asynchronous generator	Fixed pitch stall control.	3	2.5kW (10m/s) at 230V AC 50Hz	5
Turby (Turby B.V., The Netherlands), 3 blades	3ph PM generator	Braking and shut down	4	2.5kW (14m/s) at 250V AC	2
WT2500 (Proven Energy, Scotland), 3 blades	Direct drive PM generator	Above 12m/s blades twist to limit power	2.5	2.5kW (10m/s) at 24/48V DC; or grid connection at 230V AC @50Hz	3.5
Winglette WO3 (Wingletter Wind Machines, South Africa), 3 blades	Direct drive PMA	Side furling/hinged tail vane		3kW (11.7m/s)	3.6
Westwind (Westwind Turbines, Australia), 3 blades	18 pole, 3ph PM generator	Auto tail furl at 16m/s	3.5	3kW (14m/s) at 48/96/110/120V DC	3.7
Flowtrack 5kW (Flowtrack Pty, Australia), 2 blades	3ph induction generator	hard stall blades	2.5	5kW (10m/s) at 48 or 110 V DC	-

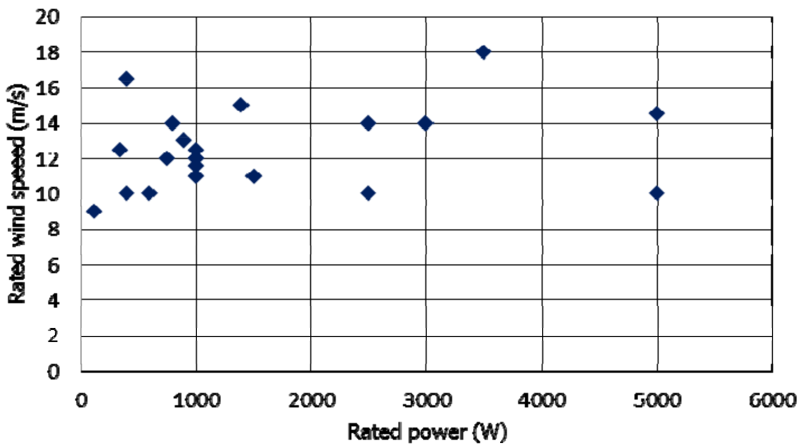


Figure 3.8: Comparison of manufacturers' defined of rated wind speed for given rated power

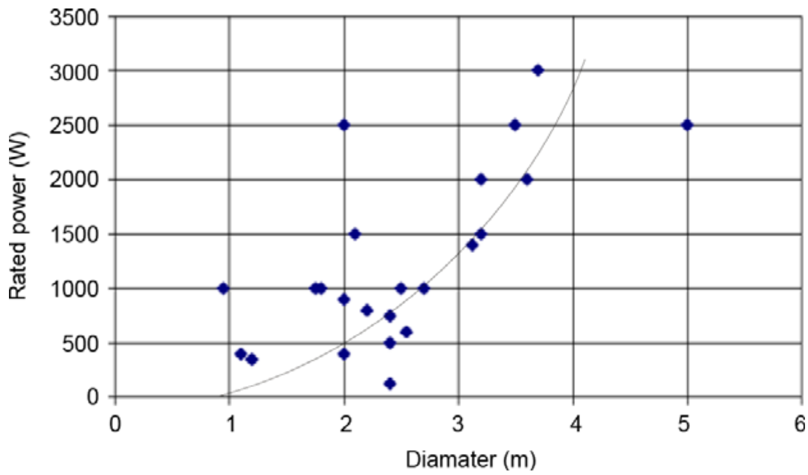


Figure 3.9: Comparison of rated power as a function of rotor diameter

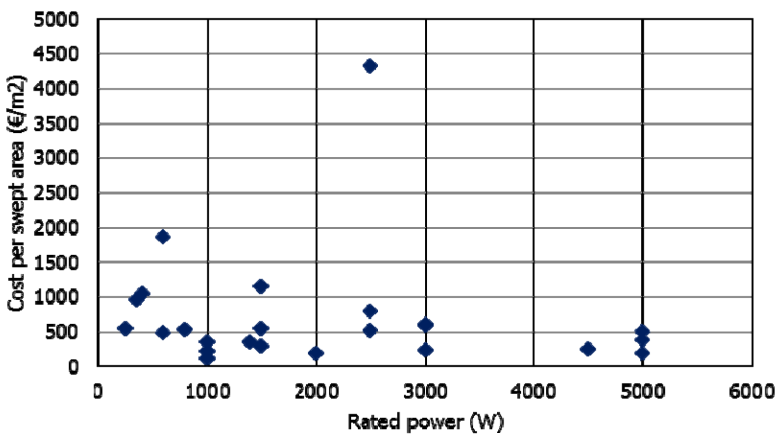


Figure 3.10: Comparison of cost per swept area as a function of rated power

3.4 Energy yield of small wind turbines in low wind speed areas

The objective of this section is to compare six commercially available small wind turbine systems, namely:

1) the 2.5kW Turby;
2) the 5.8kW Fortis Montana;
3) the 1.4kW Fortis Passaat;
4) the 1.5kW Swift;
5) the 1kW Zephyr Air Dolphin;
6) the 0.6kW Ampair.

The comparison is based on their annual energy yield per swept area (kWh/m^2) and cost per energy produced (€/kWh) in a low wind speed climate. These parameters were used so as to provide a fair comparison since the turbines do not have the same diameter. The annual energy yield and cost are calculated for a given low wind speed climate and compared with measured values. This study is important because it has been reported that many small wind turbines are not able to deliver the energy predicted by the manufacturers [43], [44]. It therefore provides a means to verify product performance in terms of actual energy yield delivered by small wind turbines.

The study used data from a field test [45] such as measured annual energy yield, measured average wind speed of the site and cost of the systems and compares the annual energy yield per swept area and cost of generated energy with values calculated using data provided by the manufacturers. At the Technopark test facility in Schoondijke, several small wind turbines were tested in an open field. All six turbines investigated were also tested at this facility.

The section starts with a brief description of the six turbine systems and the resulting coefficient of performance based on manufacturers data. Modelling of the wind climate, annual energy yield and actual coefficient of performance based on measured annual energy yield are presented next. The section concludes with a comparison of the predicted and measured annual energy yield, and cost of generated electricity of the six turbine systems.

3.4.1 Description of investigated systems

The investigated turbines were part of ten small wind turbines tested in a reasonably open field environment (there are some trees and buildings) at the Technopark test facility in Schoondijke (Netherlands). This test is a unique experiment, being probably the first time that several small wind turbines are tested at the same location and under the same wind conditions. The energy yield of the turbines was measured over a period of one year. Among the ten turbines installed at the Schoondijke, the results of six were used in this study. The turbines were selected based on available measured data which showed that in the first year these systems had no downtime. The investigated systems have different turbine specifications which makes for an interesting study. A description of the systems is given below.

- The first is the Turby, a vertical axis turbine which generates no power above rated wind speed [46]. The Turby has a rated power of 2.5kW at 14m/s and a cut-in wind speed of 4m/s. The over speed protection scheme for this system uses two independent detection systems each triggering an independent brake action. Above the rated wind speed the turbine is shut down by short circuiting the generator terminals in order to limit the rotational speed to a low value.

- The second is a furling controlled horizontal axis turbine called Fortis Montana [47]. According to specifications given by manufacturer [47], this system has a rated power of 5.8kW at 17m/s and a low cut-in wind speed of 2.5m/s. It uses a hinged tail vane to turn (furl) the rotor out of the wind when the wind speed is greater than a certain value and to realign it with the wind direction when the wind speed is below a certain value. At very high winds, the generator terminals are short-circuited to limit its rotational speed to as low value as possible. Furling control using a hinged tail vane is very popular among small wind turbines.

- The next system is also a furling controlled horizontal axis turbine called Fortis Passaat [47]. This system has a rated power of 1.4kW at 16m/s and a slightly higher cut-in wind speed of 3m/s compared with the Montana system. It employs the same scheme for power limiting control as the Montana system described above.

- The next system is a furling controlled horizontal axis turbine called Swift [48]. It is a five-bladed turbine system with a rated power of 1.5kW at 12m/s and a cut-in wind speed of 3.5m/s. The Swift system also controls the turbine's rotational speed using its tail vane (furling) in order to limit the output power.

- The next system is a furling and stall controlled horizontal axis turbine called Zephyr Air Dolphin [49], [50]. This system has a rated power of 1kW at 12.5m/s and a cut-in wind speed of 2.5m/s. To limit the power at high wind speeds, the rotation of the turbine is stall controlled until output falls below 600W. To achieve this the power coefficient is degraded by making the turbine rotate on constant speed which causes the turbine blades to stall.

- The last system is a blade pitch controlled horizontal axis turbine called Ampair [51]. This system has a rated power of 0.6kW at a wind speed of 12.6m/s and a cut-in wind speed of 3m/s. In the Ampair system, speed and power regulation is by blade pitch control at wind speeds above 13m/s using three stainless steel blade pitching weights mounted on the hub together with the blades.

Table 3.3: Some stated turbine specifications using manufacturers data

	Fortis Mont.	**Fortis Passat**	**Airdolphin**	**Ampair**	**Swift**	**Turby**
Turbine type	HAWT	HAWT	HAWT	HAWT	HAWT	VAWT
Number of blades	3	3	3	3	5	3
Speed control	Furl	Furl	Furl/stall	Pitch	Furl	Brake/shutdown
Rotor diameter [m]	5	3.12	1.8	1.7	2.08	2
Swept area [m^2]	19.64	7.65	2.54	2.27	3.40	5.3
Rated power [kW]	5.8	1.4	1	0.6	1.5	2.5
Rated wind speed [m/s]	17	16	12.5	12.6	12	14
Cut-in wind speed [m/s]	2.5	3	2.5	3.6	3.4	4.0
Cut-out wind speed [m/s]	n/a	n/a	50	n/a	n/a	14
Output power [kW]*	4	1	1	0.6	1.5	1.6
Calculated Cp [%]*	18.9	12.1	36.4	24.5	40.9	28.5

*At wind speed of 12m/s

Table 3.3 gives some technical specifications of the investigated turbines. Out of the six turbines, one is a vertical axis wind turbine while the rest are horizontal axis wind turbines. There are no standards about what wind speed manufacturers should give the output power of their turbine (rated power). Many small wind turbine manufacturers usually give rated power at different wind speeds as indicated in Table 3.3. Some manufacturers were able to profit from this lapse by showing ‘rated power’ at high wind speed value to make it appear that their turbine has superior performance than their competitors. Therefore, the output power of each system has also been indicated at common reference wind speed of 12m/s by calculating the output power at this wind speed using manufacturer’s power curve. The table also gives the calculated coefficient of performance of the turbines at 12m/s.

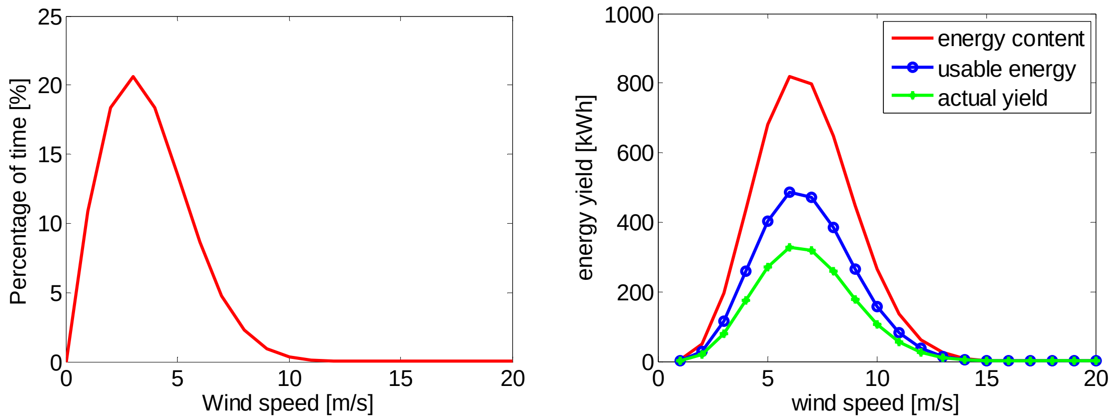
3.4.2 Modeling of wind distribution and energy yield

A. Wind Turbine and Wind Distribution

The energy yield from a turbine system is dependent on the wind speed and wind distribution of the site. The wind variation in most areas can be described by the Weibull distribution as shown in Figure 3.11(a). It gives an indication of what percentage of time a certain wind speed occur in a given site. The Weibull distribution is given by [52]

$$f(v)=\frac{k}{a}\left(\frac{v}{a}\right)^{k-1} e^{-(v/a)^{k}} \quad . \qquad 3.1$$

where v is the wind speed and k is the shape parameter. The scale parameter a is used to scale the distribution for different wind speed regimes depending on the average wind speed (v_{av}). The average wind speed measured during the first year of the Schoondijke Field Test (3.7m/s) is used for the wind distribution given in Figure 3.11(a). The shape of the curve is determined by the shape parameter k which is assumed to be 2.



(a) (b)

Figure 3.11: (a) Weibull distribution of wind at two sites, (b) sample energy yield for a 3m diameter turbine

The available shaft power from a wind turbine is expressed as a function of the wind speed as [52], [53]

$$P = \frac{1}{2}\rho_{air} C_p(\lambda,\theta)\pi r^2 v^3 \qquad 3.2$$

where ρ_{air} is the mass density of air, r is the wind turbine rotor radius, v is the wind speed, and $C_p(\lambda,\theta)$ is the turbine coefficient of performance or the aerodynamic efficiency, which is a function of the tip speed ratio λ (tip speed divided by wind speed) and the pitch angle θ.

The output power produced by the turbine system will be less than this power due to losses in the generator and drive train. Figure 3.11(b) shows the energy yield of a 3m diameter turbine using the wind distribution of Figure 3.11(a). It also depicts the energy content in the wind out of which about 59% may be captured by a wind turbine (usable energy) according to Betz Law. The actual energy yield of the turbine is less than this usable energy because in reality the efficiency of energy conversion by the turbine is less than 59% due to imperfections in blade manufacture which reduces the aerodynamic efficiency of the blades. In large wind turbines, due to the maturity of the technology used for blade manufacture such imperfections are less which makes higher efficiency of conversion possible. The efficiency of conversion (coefficient of performance) of small wind turbines is usually less than 40% [8], [54].

Using the manufacturer's power curve and other characteristics presented in Table 3.3, the coefficient of performance can be calculated as

$$C_p = \frac{2P}{\rho_{\text{air}} A v^3} \qquad 3.3$$

where A is the rotor swept area, and ρ_{air} is the mass density of air, assumed to be 1.225 kg/m^3. Figure 3.12 shows a plot of the turbines' calculated coefficient of performance as a function of wind speed based on specifications provided by the manufacturers.

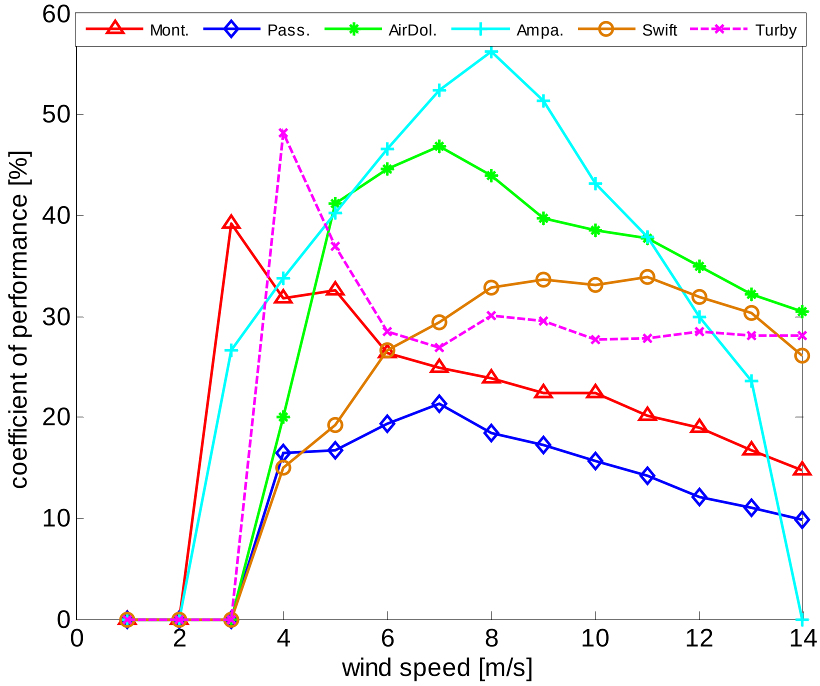


Figure 3.12: Coefficient of performance curves of the turbines versus wind speed simulated using manufacturers' specifications.

Table 3.4: Annual energy yield and cost of investigated turbines

Turbine	Cost [€]	Annual energy yield Calc. [kWh]	Field test [kWh]	Difference [%]
Fortis Montana	18,508	2804	2691	4.2
Fortis Passaat	9,239	674	578	16.6
Zephyr Airdolphin	17,548	516	393	31.3
Ampair	8,925	546	245	122.2
Swift	13,208	419	243	72.4
Turby	21,350	790	266	197.0

Coefficient of performance from measured annual energy yield	$C_{p(Meas.)}$ [%]
Fortis Montana	26.74
Fortis Passaat	14.75
Zephyr Air Dolphin	30.14
Ampair	21.06
Swift	13.95
Turby	9.79

Since most small wind turbines are not able to achieve a coefficient of performance of more than 40% (according to [54] small wind turbines seldom deliver more than 30% of the energy in the wind over any significant period time), Figure 3.12 therefore suggests that some manufacturers may have indicated rather optimistic C_p values. This has some consequences in terms of the energy yield that the turbine is predicted to generate. As a result of this, it became necessary to find a good estimate of the turbine's coefficient of performance using measured data which can be used to predict the energy yield. This will be presented later in this section.

B. Annual Energy Yield

The amount of energy that can be captured by a wind turbine depends on the output power versus wind speed characteristics (power curve) of the turbine and the Weibull distribution of the site. The energy yield over a period of time T is given by [55]

$$E_y = T \int P(v) f(v) dv \qquad 3.4$$

where P is the generated power and $f(v)$ is the Weibull distribution given above. For a time period of 1 year, T is 8760 hours.

To predict the energy yield based on the manufacturer's power curve, the average wind speed measured in the first year of the Schoondijke Test Project is used with the Weibull distribution of the wind shown in Figure 3.11(a). This gives the predicted annual energy yield ($E_{ay(calc)}$). The annual energy yield used in this work were measured at the Technopark Test Facility in Schoondijke where several small wind turbines were tested in an open field. The generated electricity during the first year of the Schoondijke Test Trials gives the measured annual energy yield in kWh/year ($E_{ay(meas)}$).

C. Coefficient of Performance

It is useful to get an indication of the actual coefficient of performance of the turbines because of the reason given earlier. To do this, the measured annual energy yield of the turbines will be used rather than the power curve given by the manufacturers. The following approach is adopted. Again, the measured average wind speed is used to find the Weibull distribution of the wind $f(v)$. By combining Equations 3.3 and 3.4, the annual energy yield can be written as

$$E_{ay} = T \int f(v) \tfrac{1}{2} C_p \rho_{\text{air}} A v^3 dv \qquad 3.5$$

The annual energy yield from Equation 3.5 should be equal to the measured annual energy yield. The coefficient of performance is then calculated as

$$C_{p(\text{meas})} = \frac{E_{ay}}{T \int f(v) \tfrac{1}{2} \rho_{\text{air}} A v^3 dv} \qquad 3.6$$

The energy yield of the turbine is simulated using the $C_{p(meas)}$ values from Equation 3.6 and the Weibull distribution of the site while the annual energy yield is also obtained by integrating the energy yield over the wind speed. It was observed that the annual energy yield obtained using this approach was the same as the measured annual energy yield from the site, thereby confirming the usefulness of the C_p values obtained under this operating condition.

3.4.3 Results, comparison, and discussion

Table 3.4 gives the result of the predicted annual energy yield of the turbines based on manufacturers' data and based on measured data from Schoondijke field test. Details of the field test measurement results can be found in [45], [56]. The cost of the turbine systems presented in Table 3.4 were taken from system cost breakdown of the Project. The table also shows the coefficient of performance from measured annual energy yield ($C_{p(\text{meas.})}$) according to Equation 3.6, which gives an indication of the operating C_p of each turbine in Schoondijke during the first year of the project.

The results presented in Table 3.4 shows that none of the turbines were able to meet the energy yield promised by the manufacturers. In most turbines, large differences exist between measured and predicted annual energy yield, with only a few having differences that could be described as acceptable. This difference between calculated and measured annual energy yield was nearly 200% in one turbine. Compared with the coefficient of performance calculated using manufacturers' specifications, the values in Table 3.4 seems more like what we would expect from a typical small wind turbine operating in a low wind speed climate.

Annual energy yield

The coefficient of performance curves of the turbines were plotted in Figure 3.12 using the manufacturers power curve. Comparison of the results in Figure 3.12 and the differences between measured and calculated annual energy yield presented in Table 3.4 shows that most manufacturers whose C_p values were mostly below 30% had smaller differences in their annual energy yield.

According to Table 3.4, the Fortis Montana and Fortis Passaat systems had the least difference in annual energy yields (4% and 17% respectively). Their C_p values (Figure 3.12) were mostly lower than 30% except at low wind speeds where turbine performance may be difficult to predict accurately.

The Ampair and Turby systems had the largest difference in annual energy yield (120% and 200% respectively). The C_p values of the Ampair system were mostly above 30%. The Turby system however, had fairly reasonable C_p values although this system had the highest difference in annual energy yield of almost 200%. It is possible that the Turby's performance is difficult to predict in low wind speeds due to poor starting, which could account for its low annual energy yield and large disparity between predicted and measured values.

Starting problems commonly occur in small wind turbines, especially at low wind speeds since they are self-starting. The cut-in wind speed of the Turby is 4m/s, which is the highest cut-in wind speed amongst the six turbines (Table 3.3). Bearing in mind that the measured average wind speed at the test site was 3.7m/s, which is below the Turby's cut in wind speed, it is possible that due to low wind speed conditions at the site, the Turby may have found it difficult to start. Even when the wind speed is higher than the turbine's cut-in wind speed, such wind speed need to be sustained for a period of time before the turbine starts generating power [9], [13]. In low wind speed areas this may not be the case as high gusts of short duration occur frequently rather than sustained high winds. Such wind condition where the average wind speed is below the Turby's cut-in wind speed may have led to a frequent *start-stop* condition with negative consequences on its energy yield.

The measured annual energy yield of the turbines is generally poor. The Fortis Montana system generated the highest annual energy yield of 2,690kWh/year which is less than about 3,400kWh/year consumed by an average Dutch household. However, in many developing countries, particularly in rural areas, electricity consumption is low. For instance, Nigeria's electricity consumption per capita in 2008 was only 140kWh/year [57]. Electricity consumption per person in rural areas of Nigeria will be lower than this value. We estimate that less than 0.5kWh per day or 180kWh per year will be sufficient to meet the energy need of a rural household. Based on this, electricity generation from the Fortis Montana system could provide the energy needs of up to 15 rural households.

Annual energy yield per swept area

It is necessary to provide a fair comparison of the annual energy yield for all the turbines since they do not have the same rotor diameter. A useful figure of merit for the analysis of the turbine field performance is then the annual energy yield produced per rotor swept area. This is obtained by dividing the annual energy yield by the rotor swept area. Figure 3.13 shows the annual yield per swept area based on measured field test and calculated values from manufacturers' power curve.

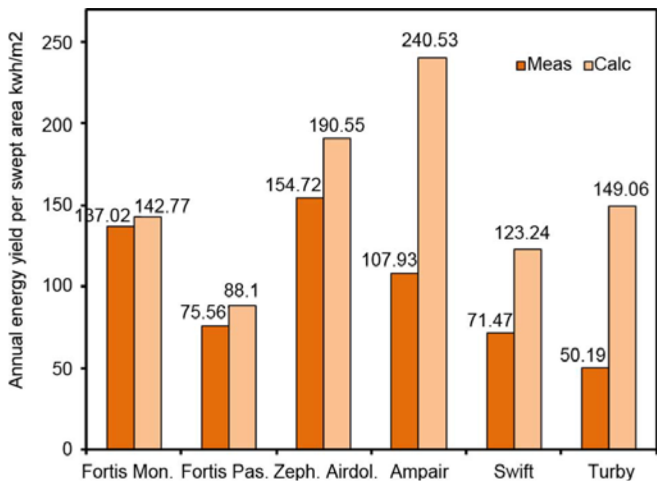


Figure 3.13: Comparison of annual yield per rotor swept area of the systems

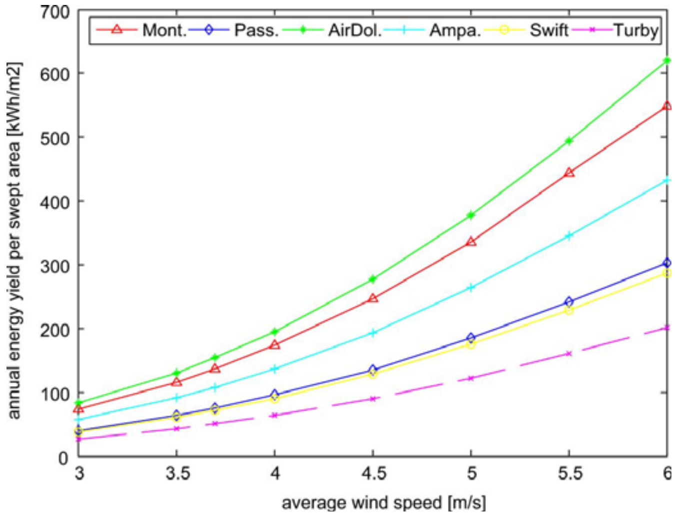


Figure 3.14: Variation of annual yield per rotor swept area with annual average wind speed.

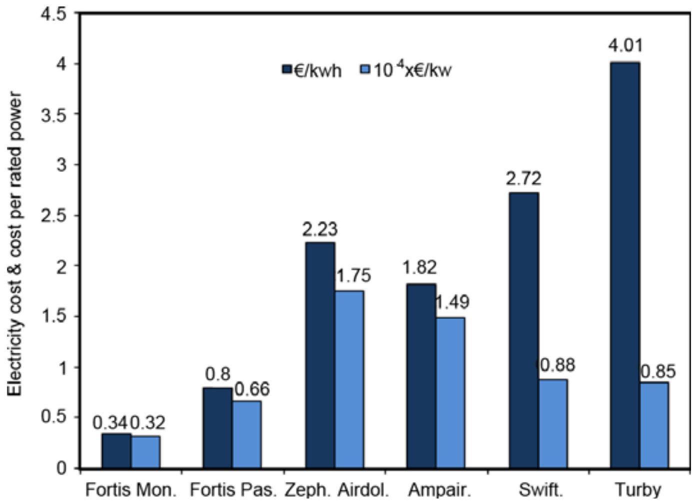


Figure 3.15: Cost analysis of the turbines showing cost per rated power in euro per kW and cost of generated electricity in euro per kWh.

The best performing turbine in terms of kWh generated per swept area is the Zephyr Airdolphin system, generating more than 150 kWh/m^2. The Turby system is the worst performing turbine generating about 70 kWh/m^2. The Fortis Passaat system had the second highest annual energy yield of 578 kWh according to Table 3.4. However, its electricity generation in terms of kWh produced per swept area is only 75kWh/m^2. The Passaat is a 3m diameter turbine yet its energy yield per rotor swept area is a factor of 2 lower than that of the Airdolphin which is a 1.8m diameter turbine. Therefore, the use of generated energy per swept area rather than just the generated energy is preferred in the comparison of energy yield of small wind turbines.

The annual energy yield per swept area has been plotted for different average wind speeds as shown in Figure 3.14. It has been assumed that the sites have the same shape parameter value of k = 2. This plot was generated using the $C_{p(\mathrm{meas})}$ values obtained from measured annual energy yield as explained in the previous subsection. It gives an indication of the annual energy yield each turbine is predicted to generate at other sites thereby providing a comparison of small wind turbine performance for different average wind speed conditions. It has been assumed that each turbine will operate at the same C_p as obtained from the previous section.

Cost comparison

The actual cost of the turbine systems used in the Schoondijke Test Project are given in Table 3.4. The cost of generated electricity can be estimated as the system cost divided by the total energy yield in the turbine's lifetime. In this analysis, it was assumed that the turbines have a life-time of at least 20 years and that during this life time they will operate with the same efficiency as during the test period. Additional cost for repair and maintenance have been neglected.

The cost of generated electricity in euro per kWh can then be calculated as

$$c = \frac{Ce}{T \times E_{ay(\mathrm{meas})}} \qquad 3.7$$

where Ce is the actual system cost, T is the turbine's lifetime and $E_{ay(meas)}$ is the measured annual energy yield as indicated in Table 3.4. A comparison of cost of generated electricity (€/kWh) is shown in Figure 3.15 However, it must be pointed out that the life time of a small wind turbine depends partly on the design and manufacturing process. Furthermore, cost of repair and maintenance could become a major cost determining factor over the turbine's lifetime.

In performing a cost efficiency analysis of the turbines, it is desirable to have systems with low €/kWh. Therefore, the most cost efficient turbines according to Figure 3.15 are the Fortis systems; their electricity generation costs were €0.34 per kWh and €0.8 per kWh for the Montana and Passaat systems respectively. The least cost efficient turbine is the Turby whose cost of electricity generation is about €4 per kWh. The graph should be viewed as indicative because in reality other variables which were not taken into account will come into play. For instance, some manufacturers may have paid extra attention to robustness in their design in order to achieve high reliability. Over the assumed lifetime of the turbines, maintenance cost and downtime would be low (compared with other systems) thereby increasing the competiveness of such systems in terms of €/kWh.

Generally, the cost of the systems is considered high and perhaps even prohibitive especially for developing countries where small wind turbines are considered to have its greatest potential. The cost of generated electricity and cost per rated power of the most cost effective turbine were €0.34/kWh and €3,200/kW, compared with €0.05/kWh and €1,300/kW [8] for large wind turbines.

Figure 3.15 also shows the cost per rated power. It is common to use cost per rated power for the cost analysis of small wind turbines. However, since there are no universally accepted rated wind speed for which the rated power should be defined, a cost analysis based on this parameter could be misleading. The results of Figure 3.15 shows that the cost per rated power of the Swift and Turby systems were less than the Air Dolphin and Ampair systems. However, the cost of generated electricity of the latter systems were actually lower than that of the former. This is partly due to the lack of a standardized wind speed value for the definition of the turbine's rated power. The large variation in the rated wind speed value of the turbines (see Table 3.4) means that the specific parameters related to rated power cannot be compared, as they do not refer to the same conditions [8]. The cost of generated electricity (€/kWh) is a better figure of merit for performing cost analysis of small wind turbines.

Figure 3.16 shows the variation of annual energy yield per swept area and cost per kWh produced with respect to turbine diameter. It has been claimed in [58] that the turbines that perform best are simply the largest ones. This suggests that turbines of higher diameter generally performed better than those with smaller diameter. The analysis in [58] was based on annual energy yield of the turbines instead of the annual energy yield per swept area. The plot of the annual energy yield per swept area and cost per kWh produced against the turbine diameter suggests that this claim may not be entirely correct.

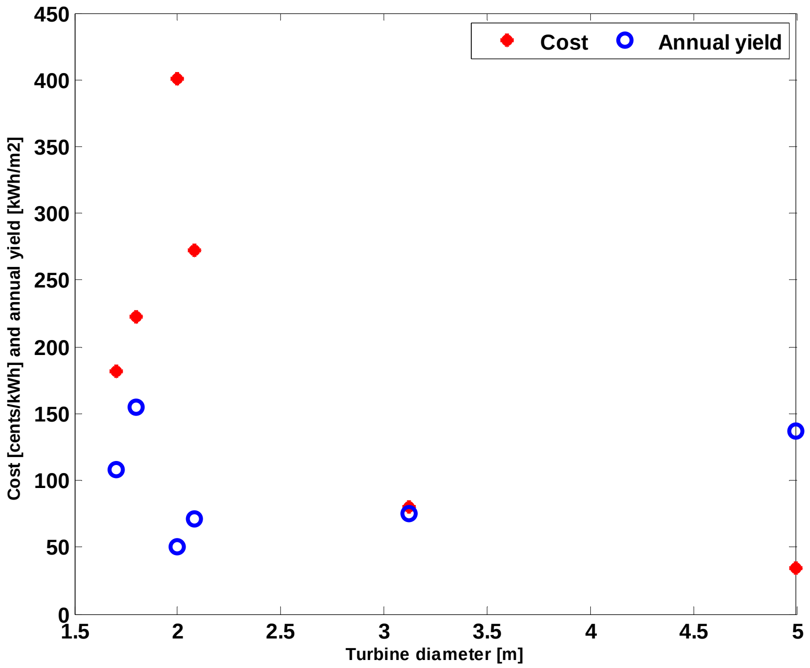


Figure 3.16: Variation of annual energy yield and cost as a function of turbine diameter

With regards to cost per kWh produced, turbines of large diameter generally performed better having lower €/kWh than small diameter turbines. On the other hand, with regards to annual energy yield per rotor swept area, many small diameter turbines performed better than large diameter turbines. The Airdolphin, which is a 1.8m diameter turbine generated twice the annual energy yield per rotor swept area of the Passaat system which is a 3m diameter turbine. However, above turbine diameter of 3m, large diameter turbines performed better, having both low €/kWh and high kWh/m^2.

This study has shown that small wind turbines operate mostly under low wind speed conditions. This is evident by the measured average wind speed of 3.7m/s and the inability of the turbines to meet the annual energy yield predicted by the manufacturers suggesting that many manufacturers may have indicated rather optimistic energy yield for their turbines. The difference between measured and predicted annual energy yield may have been as a result of the difference between the wind conditions in manufacturers test facility and real life test. This can be further illustrated by the high rated wind speed values used by manufacturers (e.g. 17m/s for the Montana) which the turbine may never experience for a sustained period of time.

Furthermore, the turbines that performed well in terms of annual energy yield per rotor swept area (high kWh/m^2) were those with low cut-in wind speeds, for instance, Airdolphin (2.5m/s) and Fortis Montana (2.5m/s). Turbines with high cut-in wind speeds (such as the Turby – 4m/s and Swift – 3.4m/s) did not perform very well having low kWh/m^2. It is possible that turbines with high cut-in wind speeds found it difficult to start under such low wind speed condition which led to their low annual energy yield per swept area.

The inability of the turbines to deliver the energy yield predicted by the manufacturers also raises the issue of standards used in small wind turbine industry. The internationally accepted standards relevant to the small wind turbine industry is the International Electrotechnical Commission (IEC 61400) standards, specifically the IEC 61400-2, IEC 61400-11 and IEC 61400-12 [8], [59]. However, they are not much used in practice [8], [59]. In addition, there was further uncertainty about exactly what should be measured and reported, when conducting tests (power and acoustic) [59]. Such ambiguity and lack of proper standards is illustrated by the large differences between the performance predicted using manufacturers data and that obtained through actual measurements. Such a consistent overestimation of the energy yield obtainable from the turbine is also an indication of the low maturity of small wind turbine industry.

3.5 Conclusions

This chapter presented an overview of turbines used in small wind power generation and the energy yield from such a system. First a survey of different types of small wind turbines was conducted to highlight possible applications that can be implemented for a given system configuration. In this first part of the chapter, it was shown that the most traditional use of small wind turbines is for autonomous (off-grid) applications such as electrification of remote communities, water pumping, remote telecommunication base stations and farms. These applications are typically found in rural areas of developing countries, which shows that the greatest potential of small wind turbines is its application in remote areas, where a hybrid system (with photovoltaic or diesel or both) can be implemented for increased availability.

In the second part of the chapter, we presented a comparison of the performance of six commercially available small wind turbine systems under low wind speed condition. The annual energy yield predicted using the manufacturers power curve was compared with measured annual energy yield from a field test. The actual coefficient of performance (C_p) of the turbines was determined using measured annual energy yield. The annual energy yield obtained using this C_p value is the same with actual measured value thereby confirming the usefulness of the C_p values obtained under this operating condition. Since the turbines are of different sizes, the comparison was based on the annual energy yield per swept area (kWh/m^2) and cost per generated electricity (€/kWh) in a low wind speed site.

Comparison of the annual energy yield showed that most systems failed to meet the performance stated by the manufacturers. In at least two systems, calculated annual energy yield was higher than measured values from field test by more than a factor of two.

Furthermore, large diameter turbines generally had lower cost per generated electricity than small diameter turbines. On the other hand, many small diameter turbines showed higher annual energy yield per rotor swept area than large diameter turbines. However, above 3m diameter, large diameter turbines performed better, having both low cost per kWh and high kWh per area.

The energy yield per unit area is indicative of the turbine's efficiency of energy conversion while the cost per generated electricity indicates the cost effectiveness of the turbine. However, it has to be stated that in terms of overall performance of a turbine the energy yield per swept area is less important than the cost of energy per kWh. As earlier stated, the energy yield of a turbine can be increased by increasing its rotor diameter which is a common practice when designing a wind turbine for low speed sites. In addition, the cost per generated electricity is usually the optimization criteria used by designers.

The second part of the chapter therefore, highlighted the need for manufacturers of small wind turbines to pay attention to low wind speed operation of their systems since small wind turbines operate mostly under such wind conditions. Low wind speed operation of small wind turbines has consequences in terms of the energy yield of the turbines due to difficulties in turbine starting. The higher the cut-in wind speeds the more the effect of low wind speed operation on the annual energy yield. Turbines that performed well in terms of annual energy yield per rotor swept area (high kWh/m^2) were mostly those with low cut-in wind speeds while turbines with high cut-in wind speeds did not perform very well.

It also highlighted another important issue regarding the need for better standardization of small wind turbine testing conditions such as rated wind speed, temperature and pressure. The large differences between the performance predicted using manufacturers data and that obtained through actual measurements is an indication of the low maturity of small wind turbine industry. Manufacturers should not just show power curves of their turbines but should also indicate whether the power curve was based on actual measurements or predicted using an assumed coefficient of performance. Such standardization should also include making sure that manufacturers indicate the test condition under which performance tests were carried out. This is necessary to ensure that users of small wind turbines buy products with confidence.

Chapter 4

Comparison of PM Generators

4.1 Introduction

The study of existing systems was presented in Chapters 2 and 3. The key lessons learnt in these chapters are: 1) maintainability of the system should be considered when small wind turbines are implemented in rural areas; 2) the cost of current small wind turbine systems is high; and 3) the energy yield of small wind turbines is low. In Chapter 3 it was shown that the cost of generated electricity of small wind turbines compared with large wind turbines was sometimes higher by a factor of 100. This is partly due to low wind speed operation of small wind turbines and its attendant starting problems with negative consequences on the energy yield. Chapter 2 also highlighted the problem of system maintainability due to lack of skills in rural areas.

In addressing these problems, the remaining chapters of this thesis will focus on the generator used for small wind turbines, which is a key component of the turbine. Lowering the generator cost will significantly lower the total cost of the turbine thereby increasing its applicability. Furthermore, turbine starting can be significantly improved by eliminating cogging in the generator thereby improving its energy yield.

There are also other challenges to small wind turbine deployment such as the design of a suitable control system that will work well for turbines installed in all types of wind climate. The Dutch Research and Development programme of Consultancy Services Wind Energy Developing Countries did some useful work in this area.

This chapter performs a comparison of different generators to find the configuration that satisfies the generator requirements developed based on our research objectives. The requirements of the desired generator are presented in section 4.2 based on the analysis in Chapters 2 and 3. Section 4.3 gives an overview of the different generator choices that can be used for our application by highlighting their strengths and weaknesses. Based on the results of this section, some generator configurations will be selected for further analysis and comparison. The required manufacturing processes for selected generator configurations are presented in section 4.4 which will be used as basis for comparing their manufacturability and manufacturing cost as presented in section 4.5. In section 4.6 a conclusion is drawn by describing the selected generator and motivation for this choice. The design and performance verification of selected generator will be presented in Chapter 5.

4.2 Generator requirements

The requirements of the desired generator can be specified based on the analysis presented in Chapter 2 and Chapter 3. The important deductions from the study in Chapter 2 which are relevant for the generator requirements are:

1) Cost of current systems need to be lowered to make them affordable and applicable in developing countries; and
2) The system need to be built such that it can be manufactured and maintained by people with basic technical skills or skills for maintenance need to be developed.

One approach which can be implemented to address the first problem (and to some extent the second) is to lower the manufacturing cost of the generator using local resources (local skills and materials) since the generator contributes significantly to the total turbine cost. To achieve this, systems need to be simpler so that people with basic technical skills can build them. By building small wind turbine generators locally, growth of the local industry can be stimulated thereby increasing local technical capability for system operation and maintenance.

The important deductions from the analysis in Chapter 3 which are relevant for the generator requirements can be also be summarized as follows:

1) The cost of current small wind turbines systems is between €3,000 to €17,500 per kW (compared with €1,300 per kW for large wind turbines), which is considered prohibitive for most people living in developing countries;
2) The measured energy yield from the turbines is low and most small wind turbines were not able to generate the energy yield promised by their manufacturers.

The first deduction from Chapter 3 corroborates the first deduction from Chapter 2 thereby making this a strong problem that need to be addressed in this thesis. One reason for the low energy yield of the turbines investigated in Chapter 3 is the low wind speed operation of small wind turbines. Small wind turbines 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 [10].

Based on these, the following are specified as requirements for our generator.

1. Low cost compared with average cost of existing systems as presented in Chapter 3. The target is to achieve a reduction in generator cost such that it becomes cheaper or at least matches the cost for large wind turbines.
2. Manufacturability in small workshops. In this context, manufacturability 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. A generator is therefore considered to have good manufacturability if:

- many of its components can be built in small workshops,
- its components can be built using easily available materials,
- the manufacturing process is short and uncomplicated,
- the cost of its construction, including materials cost is lower.

3. Good operation in low wind speed. To fulfil this requirement the desired generator should have low cogging torque and good efficiency. Since small wind turbines mostly operate in low wind speed areas, generator operation at the rated speed is mostly rare. Therefore good efficiency is not just required at the rated speed but particularly at reduced speeds (for instance 50% of rated).

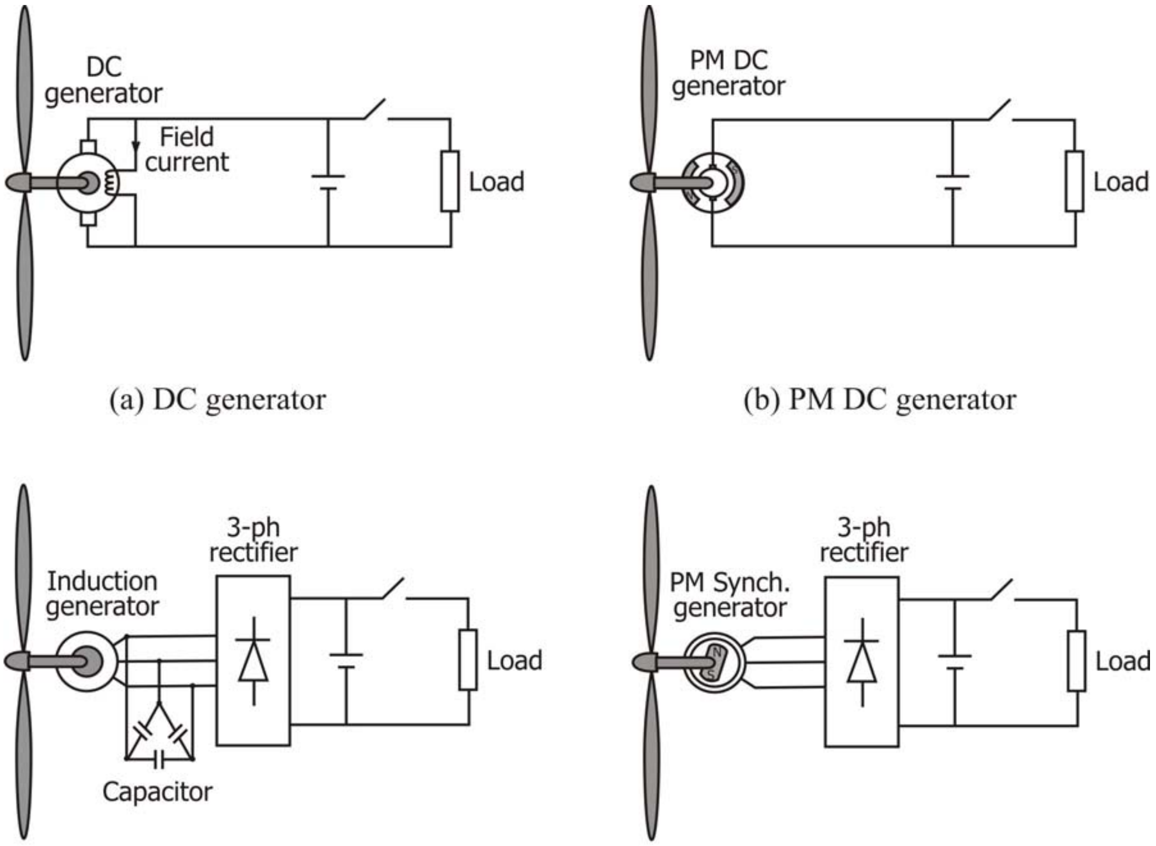
4.3 Overview of generator systems for small wind turbines

This section presents an overview of generator topologies used in small wind turbines by outlining key features, advantages and disadvantages of each system. Several types of generators can be coupled to small wind turbines: DC or AC types, synchronous or asynchronous, and with permanent magnets or electrical field excitation. The choice of generator depends on a wide range of factors such as application (e.g. stand alone or grid connected), the type of load, cost, manufacturability, and turbine speed, among others.

4.3.1 Wound field DC Generators and Permanent magnet DC generator

Almost all the wind turbines in the 1930s used DC generators mostly for battery charging application. An example is the Jacobs wind chargers of the 1930s and 1940s which were popularly used in the US to power a radio, few light bulbs, and occasionally for other electrical appliances. In the 1930s, it is common for all household appliances to be operated using DC supply. Such appliances nearly all disappeared with the coming of grid-connected electricity but started reappearing in recreational vehicles in the 1970s for a 12 V DC system. The generator consists of a rotor or *armature* and a field winding on the stator. The armature current is taken out of the generator via brushes connected to a set of electrical contacts (*commutator*). The major drawback of DC generators is that the brushes wear out and have to be replaced frequently. These types of generators are not very popular nowadays (only few small wind turbines of 200W to 500W capacity use DC generators).

Wound-field DC generators can be replaced by permanent magnet DC generators to eliminate the need for field current and hence field winding copper losses. The major drawback is again the wear of brushes required to transmit the power. This problem is eliminated when permanent magnet (PM) synchronous generators are used since they have no brushes. Different types of permanent magnet synchronous generators will be presented in more details in subsequent sections of this chapter.



(a) DC generator (b) PM DC generator

(c) Induction generator (d) PM synchronous generator

Figure 4.1: Overview of some small wind turbine generator systems for battery charging application.

4.3.2 Induction generators

Induction generators were the most widely used small wind turbines in the 1980s because they are easily available, robust and inexpensive. Furthermore, due to their use in a wide range of industrial appliances, their technology is very familiar, its maintenance and replacement parts are easily available. For its operation, the induction generator needs some amount of reactive power to establish exciting or magnetizing current which must be supplied externally either by the grid (for grid connected application) or by a bank of capacitors connected across its terminals (for stand-alone applications) [60], [61]. When the generator shaft is driven by a prime mover residual magnetism induces a small EMF in the stator windings at a frequency proportional to the rotor speed thereby establishing some circulating current through the capacitors. If the capacitors are of sufficient value the voltage builds up from this initial value, its final value being limited by saturation of the machine [60]. Voltage build up occurs much more readily at no-load [60] which can be achieved by placing a switch in series with capacitor bank and load.

Traditionally, most induction generators used for wind generating systems are grid connected where the induction generator is made to rotate at a speed of about 1500 rpm [62] – [67]. In both off-grid and grid-connected applications, a gearbox is required to adapt the low rotating speed of the turbine shaft to the high speed required by the generator. The use of gearboxes will lead to some drawbacks such as:

- they are a source of heat losses due to friction which reduces system efficiency;
- the friction from gearboxes creates additional noise;
- they need oil and regular maintenance which reduces overall system reliability.

In addition, induction generators require electrical excitation which must be provided by external sources in off-grid applications. Due to these reasons, induction machines are no longer the popular choice for generators used in off grid small wind turbines.

4.3.3 Synchronous generator with electrical excitation

To eliminate the drawbacks associated with gearboxes, it is desirable to implement a direct-drive topology in which the gearbox is removed by connecting a low speed generator directly to the turbine shaft so that it rotates at the same speed as the turbine rotor. Electrically excited synchronous generators can be used for direct-drive wind turbines. This type of generator has a DC excited rotor field winding and a three phase stator winding. As in all electric machines with field windings, the generator efficiency is reduced due to the field winding losses. In addition, a source for DC excitation of the field windings need to be provided which may pose a challenge for autonomous (off-grid) small wind application.

To increase generator efficiency and eliminate the need for field winding excitation, permanent magnet synchronous machines are generally the preferred choice of generator for small wind turbines. For small wind turbines which are sited mostly in low wind speed areas, high generator efficiency (reduced losses) is desirable in order to improve the energy yield from such a system. Two main types of permanent magnet generators systems are used for small wind turbines, namely, 1) radial flux PM generators and, 2) axial flux PM generators. These two generators types will be described in more detail in the next sections.

4.3.4 Radial flux PM generator

Among PM machines, the radial flux type is mostly used for small wind turbine application. The radial flux PM machine configurations found in literature which are used for small wind turbine application are of two types (as shown in Figures 4.2 and 4.3):

- slotted inner rotor [68] - [70], and
- slotted outer rotor [68], [71], [72].

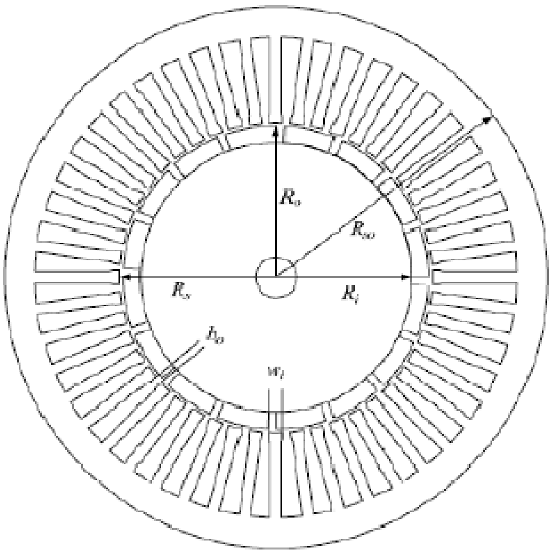


Figure 4.2: Slotted radial flux machines with inner rotor configuration [68]

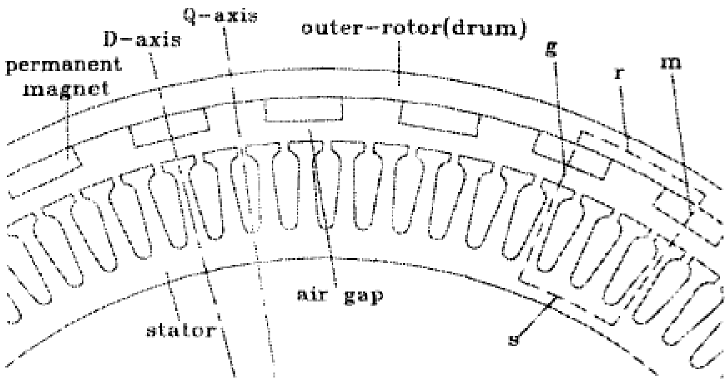


Figure 4.3: Slotted radial flux machines with outer rotor configuration [71], [72]

Slotted inner rotor RFPM

The inner rotor type shown in Figure 4.2 is the conventionally used configuration for radial flux machines. It has surface mounted permanent magnets at the outer circumference of the rotor which rotates inside stationary stator windings, with slots at the inner circumference of the stator. With respect to small wind turbine application, the major advantage of having an external stator (inner rotor) is that the stator is exposed to the winds which could aid cooling of its windings. However, compared with the outer rotor structure, connecting the turbine to the rotor of such a machine may not be easy.

Slotted outer rotor RFPM

As shown in Figure 4.3, the slotted outer rotor RFPM machine configuration has wound stator coils placed in slots. The magnets are evenly placed along the inner circumference of the rotating rotor drum which encircle the stator. While the generator is running, the centrifugal force of the magnets applies pressure to the outer rotor core, decreasing the risk of magnet detachment. Having the rotor outside also improves the cooling of the magnets which reduces the risk of demagnetization [70]. Perhaps the greatest advantage of the outer rotor configuration is that turbine blades can be easily bolted to the generator rotor in a direct-drive topology. For these reasons the outer rotor radial flux PM machine is mostly used for small wind turbine application.

4.3.5 Axial flux PM generator

The technology for making stator slots in radial flux PM machines is well-known in the industry and therefore widely used by many generator manufacturers. However, stator slots will require specialized equipment to manufacture which are most likely not available in many developing countries especially rural areas. Therefore, such specialized manufacturing process of making slots is not suitable for generator construction in small workshops. The manufacture of slots is even more difficult in axial flux PM machines which can potentially increase its manufacturing cost. For this reason axial flux PM machines are not as popular as the radial flux type but are generating increasing interest among researchers [73] – [76]. Various axial flux PM machine topologies have been proposed for wind generator applications, namely:

- single sided with one rotor and one slotted stator [77];
- double sided with slotless toroidal wound (TORUS) stator [78], [79];
- double sided with slotless air cored stator (coreless) [73], [75], [76];
- multi-stage configuration [80].

This section will examine the suitability of these axial flux PM machine configurations for small wind turbine application.

Single-sided AFPM generator

Figure 4.4 shows a single sided axial flux PM generator with stator windings placed in slots while the rotor has surface mounted permanent magnets. This generator has a simple structure with only one rotor and one stator disk. However a drawback of this configuration is that there appears an uncompensated attractive force between the rotor and stator. Such attractive forces must be dealt with using some special bearings. The rotor disk has to be also sufficiently thick in order to avoid excessive deflection [77]. As a result the single sided configuration is not very popularly used for small wind turbine application.

Figure 4.4: Single-sided axial flux machine with one PM rotor disk and slotted stator [77].

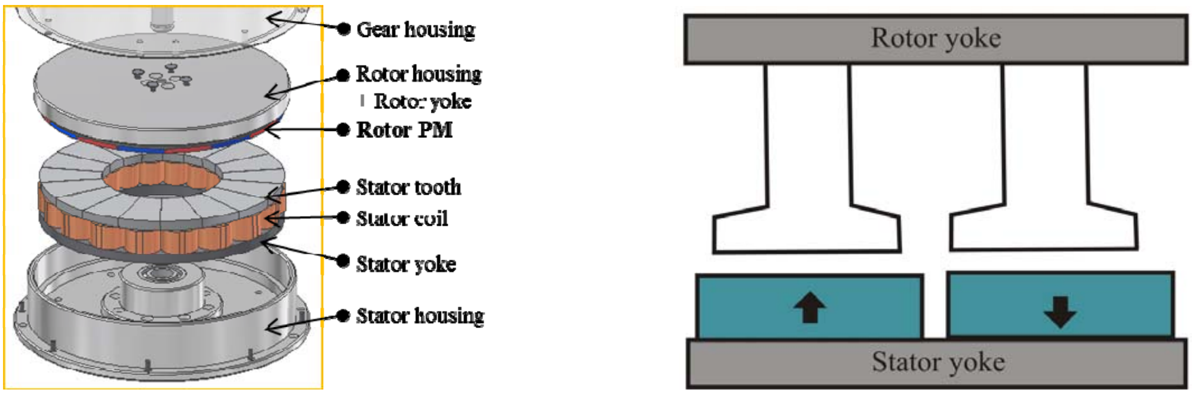


Figure 4.5: Single-sided axial flux machine with PM rotor and slotted stator [81].

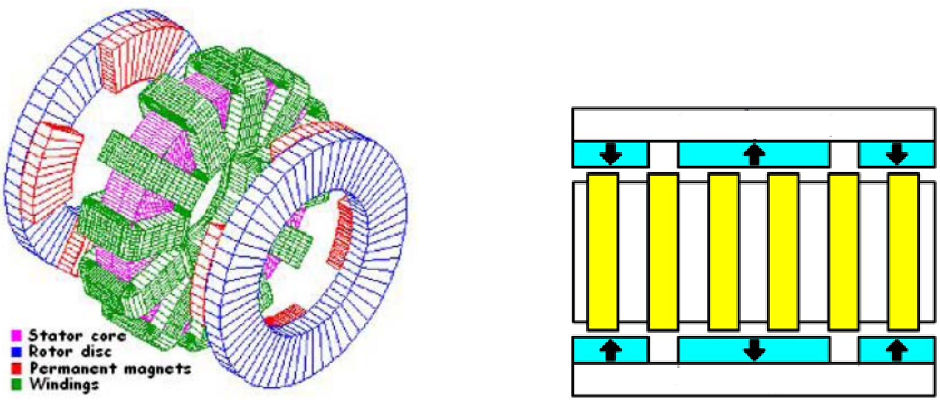


Figure 4.6: Double-sided AFPM machine with torroidal stator and two outer rotor disks [79].

Double-sided AFPM generator with toroidal stator

The mechanical concerns due to the high axial attractive force between the stator and rotor can be counterbalanced by adding an additional stator or rotor. The double air gap system in such a configuration causes the total axial force to be small [77]. One of such configuration is the double sided AFPM configuration with two rotor disks and one toroidally wound stator (TORUS).

This machine structure has a relatively simple construction due to the absence of stator slots. The rotor has surface mounted permanent magnets while the stator windings are wound on a laminated steel ring. The absence of stator slots eliminates cogging which makes it easier for the turbine to turn especially, at low wind speed. The outer rotor structure ensures easy coupling to the turbine. The disadvantages of this configuration for our application are:

- The machine has large air gap due to the absence of stator teeth. As a result a large amount of magnet material is required [78] and hence increased cost;
- If the machine is manufactured in the workshop, it may be difficult to maintain a constant air gap;
- Stator manufacture could be problematic as it may be difficult to place windings on the stator ring.

Double sided AFPM generator with air cored stator

Another type of AFPM machine topology with double air gap system is the configuration which is similar to the TORUS machine but with air cored stator. Just like the TORUS, this machine configuration has two rotor disks and one stator disk. However, there is no iron in the stator of this machine, instead the windings are placed in the air gap and epoxy encapsulated. Due to the absence of stator iron, the flux travels from the north-pole of one rotor disk through the air gap to the south-pole of the other disk and returns by travelling circumferentially around the rotor back iron. In the TORUS machine, flux from the north-pole of a rotor disk travels through the air gap to the stator ring and returns by travelling circumferentially around the stator ring to the south-pole of the same rotor disk. Therefore, in the machine with air cored stator, the north-pole of one rotor directly faces the south-pole of the other rotor as shown in Figure 4.7 while in the TORUS, the north-pole of one rotor directly faces the north-pole of the other rotor as shown in Figure 4.6.

The machine with air cored stator has the same advantages as the TORUS machine such as elimination of cogging and easy integration to turbine due to outer rotor configuration. In addition the absence of iron in the stator eliminates stator iron losses and increases generator efficiency. Furthermore, the epoxy encapsulated stator windings are easier to manufacture in small workshops. The air cored machine also has the first two disadvantages described for the TORUS machine. In addition, the use of epoxy leads to poor cooling of the windings compared with having iron which is a better conductor of heat.

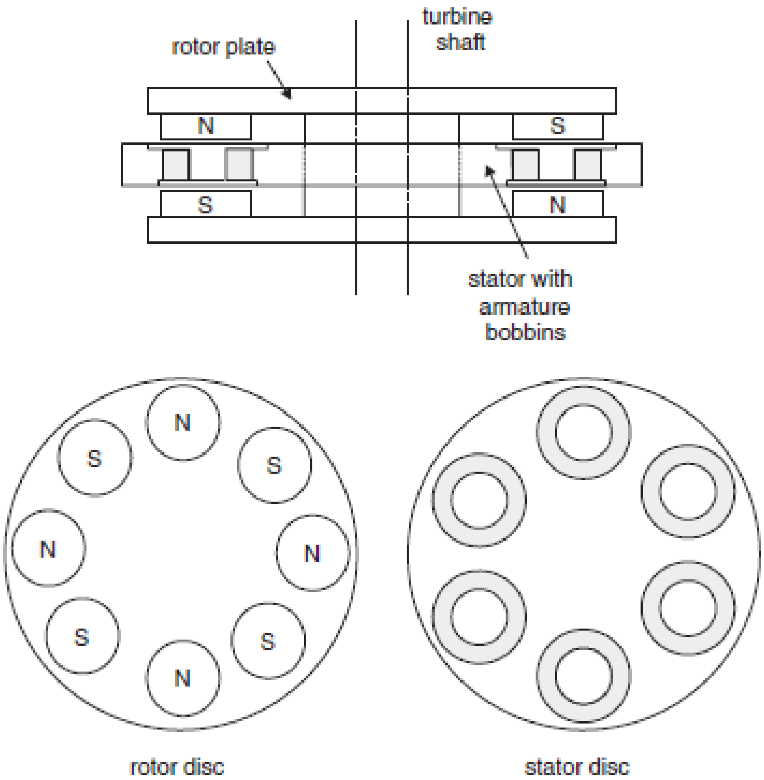


Figure 4.7: Double sided AFPM machine with air cored stator and two rotor disks having circular coils and circular PMs [73].

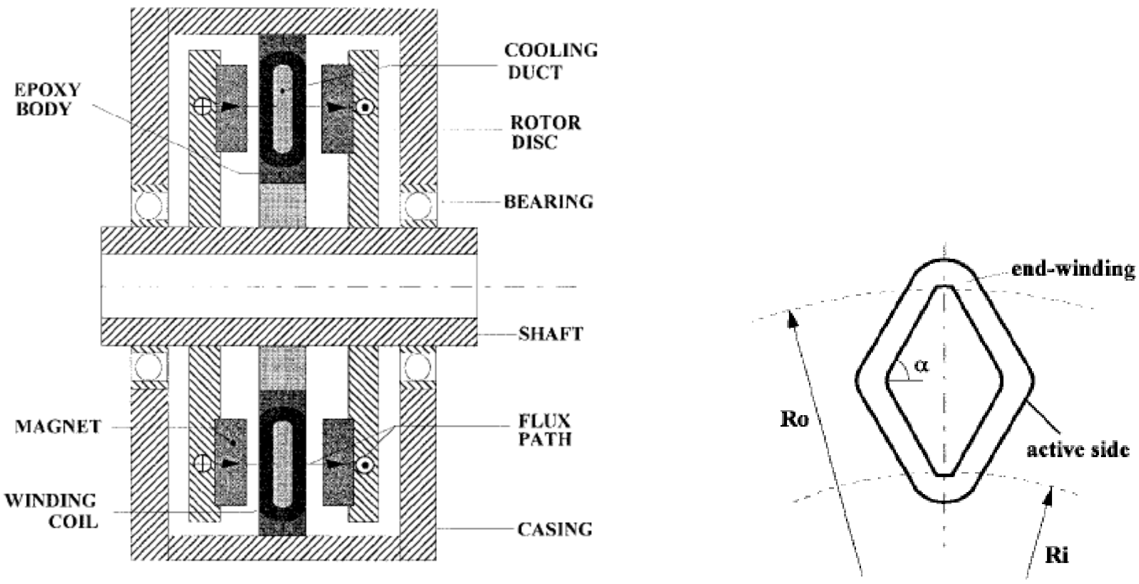


Figure 4.8: Double sided AFPM machine with air cored stator and two rotor disks having rhomboidal coils and rectangular PMs [82].

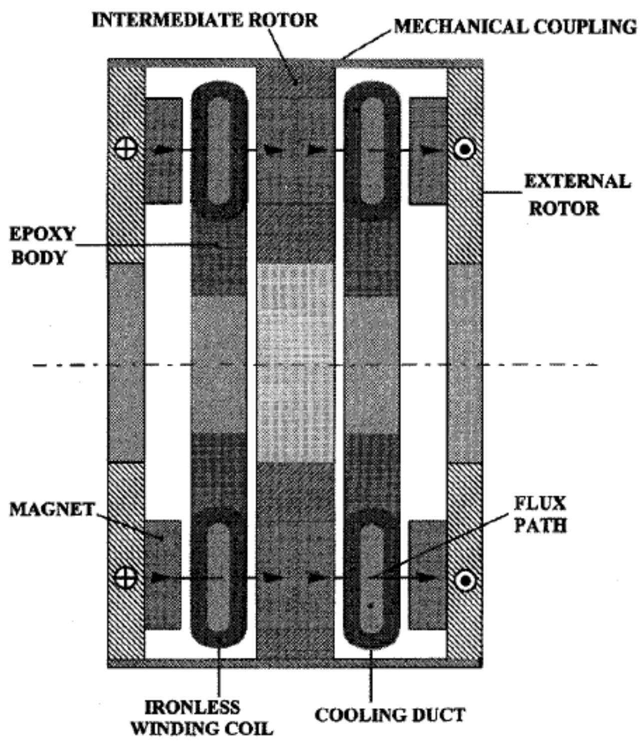


Figure 4.9: Multi-stage AFPM machine with two stator and three rotor disks and having air cored stator [83].

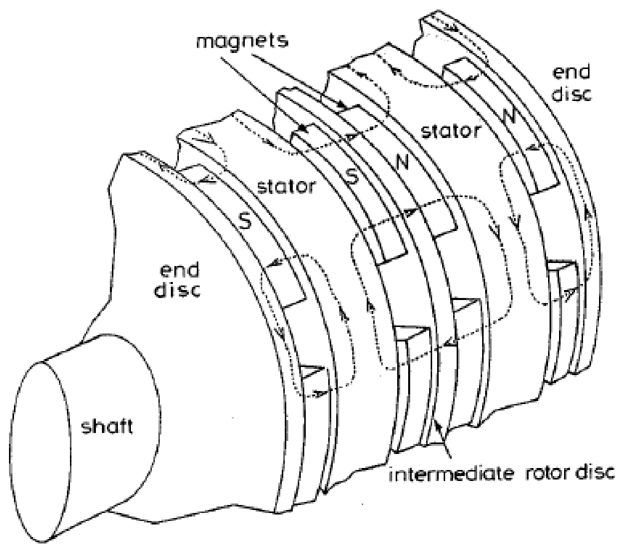


Figure 4.10: Multi-stage AFPM machine with two stator and three rotor disks with iron cored stator [80].

Multi-stage AFPM generator

In certain applications where a large power output is required but with a limitation on the available diameters, then the required power can be achieved using a multi-stage configuration. Figure 4.9 shows a slotless two-stage AFPM machine with water cooled rhomboidal shaped stator windings. This prototype AFPM machine rated 215Nm at 1100 rpm was described in [83] for direct-drive wheel motor application. Figure 4.10 also shows multi-stage AFPM with two iron cored stator disks which was proposed in [80] but not presented in sufficient detail. One of the challenges for the multi-stage configuration as highlighted in [80] is the structural stability of the machine due to the increased number of disks that must be integrated carefully. In addition, having multiple rotor and stator disks increases manufacturing complexities which is exacerbated when the generator is built in small workshops. Multiple rotor disks also leads to increased magnet materials that are used and hence increased cost of generator.

4.3.6 Selected generator configurations

The advantages of permanent magnet generators over generators with electrical excitation have been highlighted. PM generators will give lower losses (higher efficiency) compared with synchronous generators with electrical excitation. In addition, if the electrically-excited synchronous generator is used in off-grid application, a source for DC excitation of the field windings need to be provided. For these reasons, permanent magnet machines are preferred for our application. Due to its manufacturing complexities and structural challenges, multi-stage AFPM machines are not considered attractive for our application.

The configurations selected for further consideration are:

- conventional slotted radial flux PM generator;
- slotted single sided axial flux PM generator;
- TORUS;
- double sided axial flux PM generator with air cored stator.

In the next sections, the generators' manufacturing processes are presented followed by comparison of their manufacturability using some criteria drawn based on research goals.

4.4 Manufacturing processes

Four permanent magnet generator topologies were selected for further consideration. The conventional slotted radial flux PM generator can have outer rotor or inner rotor. It is assumed that the rotor of the generators have surface mounted permanent magnets such that the manufacturability of the rotor is the same for all configurations. As a result, comparison of stator manufacturability is sufficient to represent a comparison of generator manufacturability.

The stator of slotted machines (radial flux and axial flux types) can be made using iron laminations or soft magnetic composites (SMC). Therefore, manufacturability of the stator depends mostly on the choice of material used such as laminations, SMC, toroid or air cored. The selected generator types can then be described as the following:

- **Type I:** slotted stator with laminations;
- **Type II:** slotted stator with SMC;
- **Type III:** torroidal wound stator;
- **Type IV:** air cored stator.

In order to compare manufacturability of theses generator types the processes required for the manufacture of each generator type has to be made clear.

4.4.1 Manufacture of slotted machines with laminations

The processes required for the stator manufacture of radial flux PM and axial flux PM machines having slotted stator with laminations can be summarized by the block diagram shown in Figure 4.11. The manufacturing process of the slotted machine type with laminations begins with cold-rolling the electrical steel sheets (silicon iron) into thin strips. Rolling is a metal forming process in which metal stock is passed through a pair of rolls. The process is termed cold-rolling if the temperature of the metal is below its recrystallization temperature.

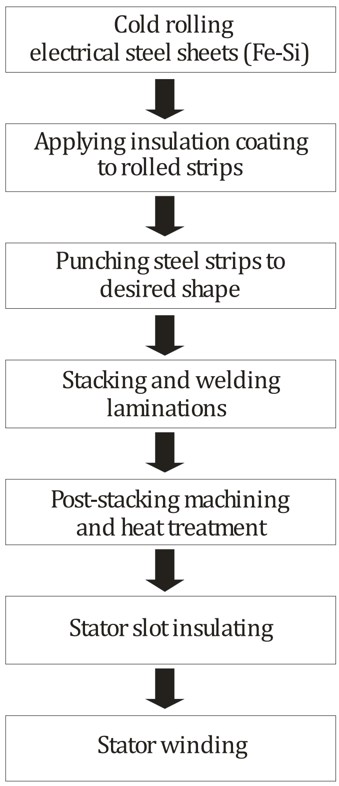


Figure 4.11: Block diagram summarizing the manufacturing processes of slotted stator with electrical steel laminations

The rolled strip is usually coated with insulation to increase the electrical resistance between laminations and hence reduce eddy current losses, to provide resistance to corrosion, and to act as lubricant during punching. The strips are then shaped by cutting to the desired shape using methods such as punching or laser cut. Punching can be done using a machine press or stamping press in a single stage operation where every stroke of the press produces the desired form on the sheets or through a series of stages. Once the sheet is punched to the desired shape, it is stacked, pressed and welded together to form a core. Apart from welding, the sheets can also be secured together via another process called interlocking. During the punching process, dimples are automatically placed in each strip. A punched depression in a strip is interlocked by a protrusion from the strip above. Post machining and heat treatment are performed to relieve the residual stress and material deformation (burrs) introduced during punching process in order to obtain good core performance.

The next step after the stator core is manufactured is slot insulating in which insulating materials are placed in the slots using slot insulating machines. Slot insulating can be achieved by coating with epoxy or placing laminate material such as polyester film in the stator slots. It is assumed that the PM machine is equipped with concentrated windings in order to take full advantage of the perceived simplified manufacturing associated with concentrated winding. The coils are therefore wound around the teeth using winding machine equipped with a needle.

4.4.2 PM machines with Soft Magnetic Composite (SMC)

Soft magnetic composites consists of fine iron powder coated with a small amount of binder material which also serves to insulate the particles from one another. The electromagnetic and mechanical properties of the finished SMC will depend not only on the iron power but also on the type of mix (added binder) and the process, such as cold or warm compaction [84]. The type of mix will also determine the maximum heat treatment temperature. The insulation between the iron particles gives SMC a high electrical resistivity and hence low eddy-current losses. However, during the moulding process (compaction) mechanical stress is introduced in the iron particles which deteriorates magnetic properties of the SMC and hence produces high hysteresis losses [84], [85].

Iron losses in SMC consist of hysteresis losses and eddy current losses. Hysteresis losses increase linearly with frequency while eddy current losses increase with approximately square of frequency [81], [86]. Generally, SMC materials have higher stator iron losses compared with conventional silicon-iron (Fe-Si) laminations at low frequencies where hysteresis losses are dominant. However, the iron losses of SMC becomes comparable with conventional silicon-iron (Fe-Si) laminations at higher frequencies where eddy current losses becomes dominant [84] – [87]. In the frequency range of fifty to a few hundred Hz which is the interesting range for most electrical machines, iron losses are generally higher in an SMC material than in silicon-iron (Fe-Si) laminations [84], [87].

Although punched silicon-iron laminations used in radial flux machines are popular, the use of SMC materials is gaining interest due to certain unique advantages. SMC can be moulded under pressure to a wide range of shapes which is highly advantageous in realizing new machine design topologies with unconventional and innovative shapes. It has been reported that the moulded construction offer a simplified manufacturing process and cost reduction compared with punching laminations [84], [85], [87]. One of the main disadvantages of axial flux PM machines with laminations is the difficulty in the manufacture of slotted topology. The use of SMC can open opportunities for increased use of slotted AFPM machine for various applications. Some PM machines found in literature utilizing SMC materials and their applications are presented in Table 4.1. The reported efficiency values is an indication that machines with SMC are generally less efficient compared with machines with laminations.

Table 4.1: Some PM machines utilising soft magnetic composite materials

	[81]	[87]	[88]	[85]
Application	Human power	3 phase motor	Wind	Wind
Configuration	Single-sided	Single-sided	Double-sided outer rotor	Double-sided inner rotor
Number of poles	16	4	6	14
Outer diameter (mm)	35.5	110	80	122.2
Air gap length (mm)	0.6	6.5	0.8	1.5
Speed (rpm)	2000	1000	600	428
Power (W)	50	52 (at 24V DC)	100	220
Efficiency (%)	88	52	48	72

4.4.3 Manufacture of slotted machines with SMC

The manufacturing process for the stator of PM machines with soft magnetic composite materials can be summarized as shown in Figure 4.12. The iron particles are premixed with binder material and then moulded to the desired shaped under high pressure (compaction). Heat and temperature is applied to reduce the residual mechanical stress introduced by the moulding process. The stator slots are formed by compaction to the desired slot geometry as shown in Figure 4.13.

The SMC stator core can be split to form the tooth and the core back which can be produced separately and then bonded together as shown in Figure 4.14. Splitting the stator core into two sections enables a preformed coil to be placed over the tooth before the tooth is inserted into its core back using high temperature epoxy glue [89]. This technique has the advantage of yielding a high fill factor of about 64% [89], [90]. The slot fill factor can also be improved by making rounded edges on the stator teeth. Rectangular conductors were used to wind the coils in [91] and the reported slot fill factor was 74%. The slot fill factor in [89] increases from 64% to 78% after pressing the coils by applying pressure.

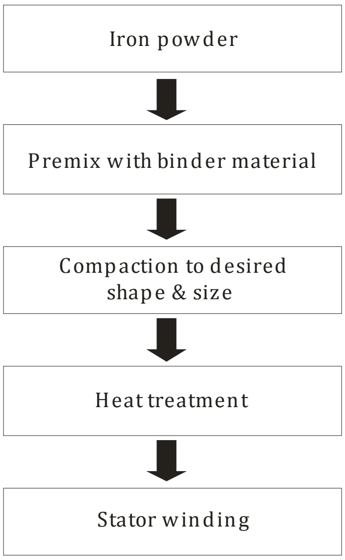


Figure 4.12: Block diagram for the manufacture of slotted stator with SMC.

(a) [92] (b) [87]

Figure 4.13: Examples of slot geometry formed by compaction from SMC moulds.

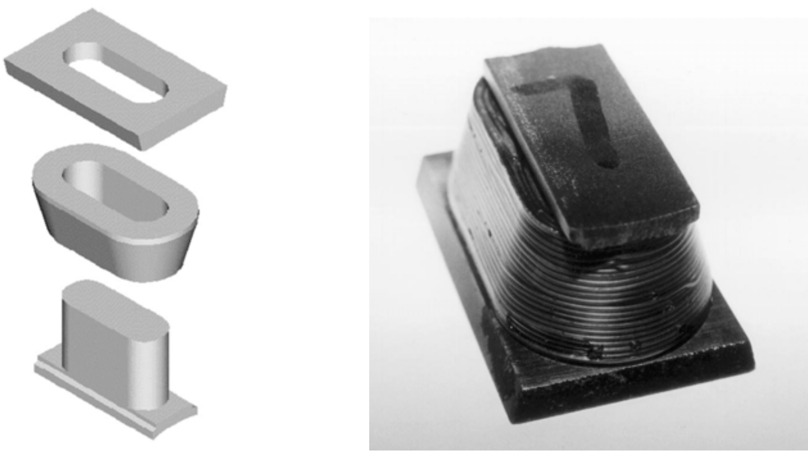


Figure 4.14: Components of tooth section: left photo (top to bottom) comprises core back, preformed coil and tooth while right photo shows finished tooth section [89].

4.4.4 Manufacture of machines with toroidal wound stator

The manufacturing process for the stator of a TORUS machine is similar to that of slotted stator machines with electrical steel laminations and is summarized in Figure 4.15. Just like in the machine with laminations, the manufacturing process begins with cold-rolling silicon steel materials into thin strips and then coating the strips with some insulation. The cores are wound to the desired shapes after slitting using core winding machines. The winding machine stops automatically when pre-decided dimension is reached. The start and finish ends are then firmly welded to complete the core shape. To relief the internal stresses and obtain good performance, stress-relief annealing is carried out on the cores by heating it and keeping it at a certain temperature (annealing temperature) followed by controlled cooling. Winding coils around a toroidal core is not easily done using a winding machine. In most cases, the coils are wound manually around the core and held firmly using glue such as epoxy.

Winding and placing the coils on the toroid can be made simpler if the core is split into two. In this case, the core can be made using soft magnetic composite materials. This allows for each semi-circular core to be inserted into preformed coils and joining the two core parts using glue. This method can reduce manufacturing complexity and cost through the use of a simpler winding machine or manual winding onto the core.

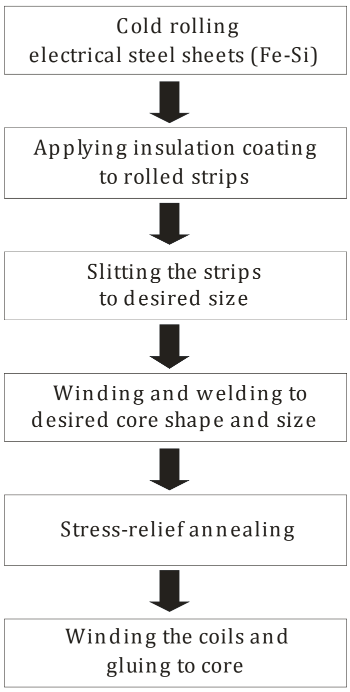


Figure 4.15: Block diagram for the manufacture of toroidal wound stator (TORUS).

4.4.5 Manufacture of machines with air cored stator

The manufacturing process for the stator of air cored PM machine is summarized by the block diagram of Figure 4.16. It is observed from the figure that the manufacturing process of this type of generator is radically different and shorter compared with the other processes described in previous sections. The starting point is making the stator mould where the coils will be arranged for casting. Since the stator of this type of generator is air cored, nonmagnetic materials (for instance epoxy resin) with permeability close to that of air are used for coil support. The coils are preformed, arranged in the mould and connected in a proper manner as shown in Figure 4.17 (left photo) to give a three phase configuration. The coils can be wound manually or using a simple coil winder which can be constructed easily. Finally, the polyester epoxy mixture is made according to manufacturer's specifications and poured to make the stator cast. After several hours, the stator manufacture is completed as shown in Figure 4.17 (right photo).

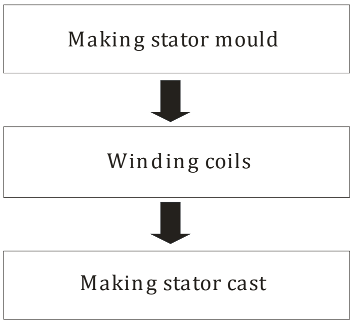


Figure 4.16: Block diagram of required processes for the manufacture of air cored stator.

Figure 4.17: Manufacture of air cored stator: left photo shows arrangement of coils in a mould while right photo shows the completed stator.

4.5 Comparison of manufacturability

A major requirement for our generator as given earlier in this chapter, and indeed a strong objective of this thesis, is manufacturability of the generator. Therefore, having presented the processes required for the manufacture of the generators, this section compares their manufacturability. Manufacturability of a design is difficult to analyze because it depends on many factors which are not easy to quantify. The first task in this section is therefore to define the criteria for comparing manufacturability.

Several models attempt to quantify the manufacturability of a design. The Boothroyd-Dewhurst index builds an estimate of design manufacturability relative to factors such as assembly complexity and number of parts [93]. The problem with such model is that assembly complexity are not easily quantifiable especially if the assembly line is different for each product. Other models attempt to quantify manufacturability using activity-based costing or process-based costing in which a product's manufacturing operation is decomposed into small steps and the cost of manufacture can be considered as a compilation of costs incurred at each manufacturing process or task [93], [94]. Each step in the manufacturing process is assigned cost according to the time, equipment and human resources it consumes such that a product requiring more processing steps, time and labour resources will cost more than a product requiring less of these. This method could be interesting if the labour requirements of each step and other resources are modelled accurately. However, the use of such models for comparison of manufacturability is beyond the scope of this thesis.

Instead, this thesis compares the manufacturability of a generator design using the following four criteria:

- availability of equipment and skills;
- availability of materials;
- manufacturing complexity;
- manufacturing cost.

These criteria were drawn based on the goals of the thesis to increase the penetration of small wind turbines in rural areas of developing countries. One of such goals is to develop a generator concept that is manufacturable in small workshops using materials that are easily available. A candidate generator configuration that can meet this goal is one whose design is simple such that its components can be built by people with basic technical skills in order to reduce cost and enhance maintainability. A generator design will therefore be considered to have good manufacturability if it can be built using materials, skills, tools and equipment that are easily available in many locations.

In the previous section, the manufacturing processes of four types of permanent magnet generator configurations were presented. They are: slotted stator with laminations, slotted stator with SMC, torroidal wound stator (TORUS), and air cored stator. It was also assumed that the manufacturability of the rotor is the same for all configurations (i.e. they all have surface mounted PMs) such that comparison of stator manufacturability is sufficient to represent a comparison of manufacturability of the entire generator.

4.5.1 Laminated stator core

The conventional method of manufacturing laminated stator core is by punching the entire section of the core in piece. In this method, the centre piece left after punching is not useful resulting in large wasted iron material. Segmented stator core method in which the core is split into segments of 120^o or segments of 60^o can be employed to reduce the amount of iron waste. The segments need to be welded together which increases the required manufacturing equipment and hence manufacturing cost.

The major equipment required for this manufacturing method are:

- cold rolling machine;
- punching press;
- welding machine;
- heat treatment; and
- coil winding machine.

These equipment are most likely not available in small workshops and will require huge investments to be setup. Skilled operators are also required for equipment operation and maintenance which may not be available in many areas. Although, the manufacturing method is well known in the industry, the cost of establishing the needed equipment is high. This leads to the conclusion that for our application this type of generator has low manufacturability.

4.5.2 Soft magnetic composite stator core

The large quantity of wasted iron materials in laminated stator core and the resulting increase in cost makes soft magnetic composite materials a good alternative for cost reduction. SMC is also well adapted for innovative stator designs and concentrated winding around the teeth since it is possible to produce the teeth and stator back separately. The fabrication of SMC based stator is by machining a solid block of SMC to the required shape and size. The block of SMC is produced by mixing iron powder with binder (insulation) and then compressing the mixture in a die under high pressure. Compared with punching, machining slots from SMC block is easier as simpler tools can be used unlike using a punching press.

The major equipment required for this manufacturing method are given as:

- mixing machine;
- compacting press machine;
- heat treatment;
- machining tool;
- coil winding machine.

Compared with conventional iron lamination, the equipment and manufacture of SMC stator core are simpler and cheaper [88] – [90] thereby making it a low cost option. The efficiency obtained when SMC material is used is low resulting in lower energy yield if the machine is connected to a small wind turbine. The conclusion drawn is that for our application this type of generator has some potential for good manufacturability.

4.5.3 Toroidal stator core

Toroidal cores are made by winding silicon steel strips to desired core size. The coils can be wound around the toroid using a winding machine equipped with a needle or manually. Coil winding can be made simpler and cheaper by splitting the core into two semi-circular cores.

The major equipment required for this manufacturing method are:

- cold rolling machine;
- splitting tool;
- strip winding and welding machine
- heat treatment; and
- coil winding machine.

The equipment, manufacturing complexity and cost associated with this method are comparable to that of laminated stator core. Therefore, it is also concluded that the equipment are most likely not available in small workshops, huge investments are required for setup, and required skills for equipment operation and maintenance may not be available in many areas. Based on these, this type of generator also has low manufacturability for our application.

4.5.4 Air cored stator

Air cored stator can be manufactured by casting preformed coils in epoxy resin mixture. The coils can be manually wound using a simple and easily built winding tool. The fabrication of air cored stator requires no special equipment. The mould for casting is made from cut sheets of wood using simple wood cutting tools which can be found almost anywhere. It is concluded that for our application this type of generator has high manufacturability.

Comparison of manufacturability of the four types of stator core is summarized in Table 4.2. The laminated and toroidal stator cores are the generators with the least manufacturability due to their low rating in terms of availability of equipment, skills for equipment operation, and complexity of manufacturing in small workshops. The air cored stator has the highest manufacturability due to its high rating in terms of the criteria mentioned above. The table also shows that SMC based stator core has the potential to be a low cost option. The equipment required for the manufacture of SMC stator core is considered to be potentially available compared with equipment for laminated or toroidal core manufacture. For instance, the tooling required for machining slots from SMC blocks can be found in small workshops.

Table 4.2: Manufacturability of different types of stators

Criteria	Laminated	SMC	Toroidal	Air cored
Availability of equipment & skills	- huge investment for equipment - most equipment not available in small workshops - low availability of skills	- huge investment for equipment - low availability of skills ± some equipment are available in small workshops	- huge investment for equipment - most equipment not available in small workshops - low availability of skills	+ very low investment for equipment + only basic skills are required + tools are available in small workshops
Availability of materials	± silicon steel + copper	± iron powder + copper	± silicon steel + copper	+ epoxy resin + copper
Manufacturing complexity	- low possibility for manufacturing in small workshops	± some possibility for manufacturing in small workshops	- low possibility for manufacturing in small workshops	+ high possibility for manufacturing in small workshops
Manufacturing cost	- very high if built in small workshops	± potential for low cost	- very high if built in small workshops	+ low if built in small workshop

4.6 Conclusions

In this chapter, several generator concepts that can be used for small turbine application have been presented. The advantages of permanent magnet excitation over wound rotor with electrical excitation have been highlighted. Electrically excited generators have field windings which leads to reduced efficiency due to losses in the field windings. In addition, a source for DC excitation of the field winding need to be provided which may pose a challenge for autonomous (off-grid) small wind application. For these reasons permanent magnet synchronous machine is the preferred choice of generator for small wind turbines.

A generator considered suitable for our applications is expected to meet certain requirements. These were stated as:

1. *Low cost compared with average cost of existing systems as presented in Chapter 3.*
2. *Manufacturability in small workshops using simple manufacturing processes and easily available materials and tools.*
3. *Good operation in low wind speed, that is low cogging torque and good efficiency.*

Cost reduction and manufacturability are identified as being crucial requirements for a generator used in this application. Therefore, four PM generator configurations were selected for comparison of manufacturability and cost of manufacturing. These generator configurations were further simplified to give the following generator types:

- **Type I:** slotted stator with laminations;
- **Type II:** slotted stator with SMC;

- **Type III:** torroidal wound stator;
- **Type IV:** air cored stator.

The criteria for comparison were developed based on the goals of the thesis to increase the penetration of small wind turbines in rural areas of developing countries. One of such goals is to develop a generator concept that is manufacturable in small workshops using materials that are easily available.

The axial flux PM generator with air cored stator has the highest manufacturability due to its high rating in terms of availability of equipment, skills for equipment operation & maintenance, availability of materials, simplicity of manufacturing in small workshops and low manufacturing cost. The non-slotted (air cored) structure of this configuration makes it suitable for manufacture in small workshops since the complication of making stator slots are eliminated. In addition, this type of configuration also eliminates stator iron losses and cogging which improves generator efficiency and makes it easier for the turbine to start at low wind speeds. Its outer rotor structure simplifies integration to turbine as blades can be bolted to generator rotor.

The selected generator which is considered suitable to meet the stated generator requirements is the axial flux machine configuration with air cored stator disk and two surface mounted PM outer rotor disks. In the next chapter of the thesis, the design of this type of generator configuration will be presented. Measurement tests conducted on a manufactured prototype will also be presented to verify generator performance.

Chapter 5

Design of axial flux PM generator with air cored stator

5.1 Introduction

Chapter 4 of this thesis compared four types of permanent magnet generators, that is, two slotted permanent magnet generator configurations with laminations and with soft magnetic composite material, and two slotless configurations with toroidal wound stator and with air cored stator. The criteria for comparing the generators were cost of manufacturing and manufacturability, which were used based on thesis goal of developing a generator concept that is manufacturable in small workshops using materials that are easily available. The conclusion of Chapter 4 is that the axial flux permanent magnet generator with air cored stator is the most suitable for this application.

Most small wind turbines are directly connected to the generator (direct drive configuration) in order to avoid the drawbacks associated with the use of a gearbox. With respect to our application, the three main disadvantages of gearboxes which favour a direct drive configuration are:

- they are a source of heat losses due to friction which reduces system efficiency,
- the frictional torque in a gearbox leads to starting problems, and
- they need oil and regular maintenance which reduces overall system reliability.

Small wind turbines operate mostly in low wind sites which affects the energy yield from the turbine negatively. Therefore, good system efficiency is desirable for increased energy production. Starting problems in small wind turbines also has an influence on the energy yield as they are usually self-starting. Before a wind turbine can start, the torque produced by the wind acting on the blades must be high enough to overcome some resistive torque present in the turbine system, such as the frictional torque in the gearbox and drivetrain as well as cogging torque in the generator. If this resistive torque is high the turbine might not be able to start at low wind speeds which further reduces the energy yield obtainable from the turbine. Furthermore, in autonomous off grid applications where a small wind turbine is sited in a remote area, it is desirable to have a system which requires less maintenance in order to increase system reliability. For these reasons, a direct drive configuration is selected for this research.

The concept of manufacturing small wind turbines in small workshops using air cored axial flux permanent magnet generator was popularized by High Piggott [95]. The High Piggott turbine is a 3-bladed vertical axis wind turbine of small rating (usually less than 5 m rotor diameter), directly connected to the generator for battery charging application. The blades are made from shaped wood using simple workshop tools to achieve blade twist and increase aerodynamic efficiency. They can also be made from composite materials [96]. The turbine tower can be made using wooden or iron poles with guyed wires. Although the blade manufacture leads to a low cost solution, long man hours are required to carve the wood to desired twisted shape. To reduce the hours spent on wood carving, the blades can also be made from popular plastic materials such as polyvinyl chloride used for drainage pipes as presented in [97].

The axial flux PM generator concept implemented in this Chapter uses vehicle wheel hub bearing. The use of this type of bearing was also proposed by Hugh Piggott in [95]. Although the use of this component has the advantage of low cost and ease of availability, it is also a potential source of losses in the system thereby degrading generator performance. In this thesis, the loss contribution from the vehicle hub bearing is quantified and separated from other no-load losses. Due to the choice of air cored stator, eddy currents losses are produced in the stator conductors in addition to stator copper losses, since the windings are directly exposed to the magnetic field from the permanent magnets (no stator teeth). In this chapter, the eddy current losses that occur in this generator are also quantified. This chapter therefore, investigated the effects of the hub bearing and other design choices on generator performance.

The objective of this chapter is to present the design of an axial flux permanent magnet generator with air cored stator for small wind turbine application which is capable of meeting other research objectives introduced in previous chapters of this thesis. The chapter highlights the generator structure, design choices and the effects of such choices on efficiency and energy yield, design equations used, and measured generator performance.

This chapter is structured as follows. First, the generator structure and design choices are introduced. Simple models are developed for generator design, modelling of losses and performance prediction. The manufacture of the rotor, stator and other components of the test setup used for generator performance verification is presented. Measurement tests conducted on the manufactured generator are reported and discussed. The manufactured generator prototype presented in this chapter was not based on optimised design rather it was developed based on dimensions of available materials. The chapter, therefore concludes with an optimized design and some design improvements that can be made.

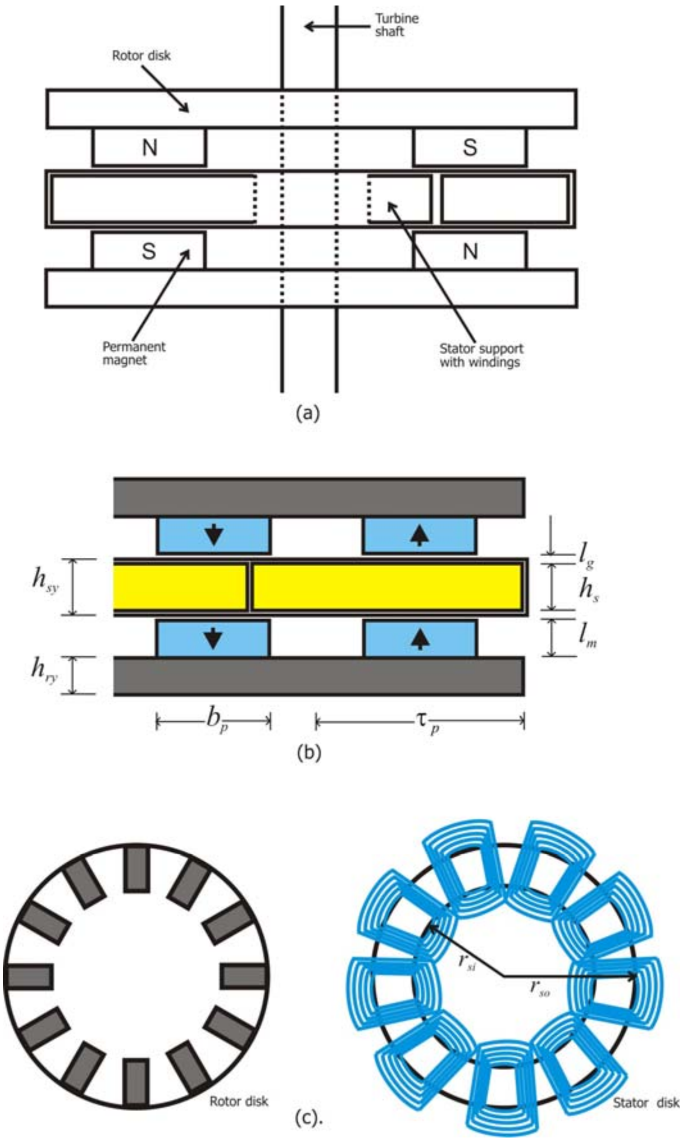


Figure 5.1: Generator concept: (a) schematic; (b) cross section; (c) rotor and stator disks.

5.2 Generator topology and design choices

Figure 5.1(a) shows a cross section of the layout of an axial flux PM generator with coreless stator winding. The machine configuration consists of the following components: two rotor disks, permanent magnets, stator support, stator housing, windings, and bearing. The two rotor disks are on both sides of the stator disk. The axially magnetized PMs are glued to the surface of each steel rotor back iron in an N-S-N-S arrangement such that the magnets on one rotor disk are directly aligned with an opposite pole on the other disk. In this way, the completed rotor disks attract each other.

Figure 5.1(b) shows two pole pitches of the axial flux PM generator having four poles per three coils. The flux lines are indicated by thick arrows in Figure 5.1(b). Since the stator has no iron, the flux driven by the magnets will travel axially through the air gap from one rotor disk to the other and completes its path by returning circumferentially around the rotor back iron to the next magnet. The machine therefore has a large effective air gap comprising the physical gap on both sides of the stator, magnet length and the winding thickness.

The effective air gap is defined as

$$l_{geff} = 2l_g + \frac{2l_m}{\mu_{rm}} + h_{sy} \tag{5.1}$$

where l_g is the physical gap between magnet and stator disk, l_m is the magnet length in magnetization direction, μ_{rm} is the relative recoil permeability of the magnets and h_{sy} is the stator thickness or axial thickness of the winding plus core material as defined in Figure 5.1(b).

One of the disadvantages of this type of machine is that it is difficult to maintain a constant air gap due to the two rotor disks on both sides of the stator. Figure 5.2 shows how the effective air gap of the generator is kept constant using spacers tapered at both ends. Bolts are passed through the spacers to connect the two rotor disks together and to the hub bearing.

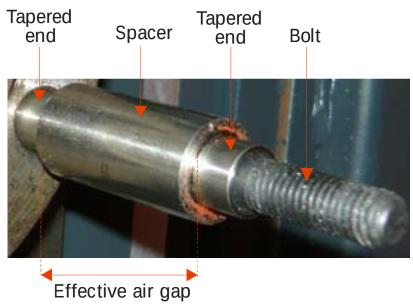


Figure 5.2: Spacer for maintaining constant air gap. The rotor disks are connected together and to the hub bearing by passing a bolt through the spacer. The tapered end ensures that the distance between the disks remain constant.

5.2.1 Measures for cost reduction

The manufacture of a generator that will meet the requirements set out in this research requires careful selection of generator configuration, materials and manufacturing method. The materials were selected based on two major criteria: availability, and cost. To fulfil these criteria often means that the generator efficiency has to be sacrificed. The following are the measures implemented to achieve cost reduction.

1. Generator configuration
   - Coreless stator.
   - Preformed coils were used which were formed using a simple winding device. This eliminates the need for a winding machine (needle winding machine).
   - Surface mounted PM rotor disks
2. Materials selection.
   - Use of available magnet size rather than optimized dimensions. This reduces manufacturing cost by eliminating the need to manufacture special magnet sizes.
   - Use of vehicle hub bearing rather than off the shelf units or manufacture of a new bearing. Such bearings are easily available and at low cost. However, the penalty for using this component is the possibility of increased mechanical losses due to bearing friction. The loss contribution from this component (bearing loss) is quantified in this chapter.
3. Generator manufacture
   - Generator was manufactured in a small workshop using basic tools.
   - Once the bearing is selected, suitable size of steel disks can be cut to form the rotor disks. The permanent magnets are glued to disk surface.
   - The stator is manufactured by encapsulating the preformed coils in epoxy to make a cast. This is a much simpler and low cost manufacturing process compared with making lamination punching for stator which will require specialized equipment and skills.
   - Assembly of generator components is easier since there are no axial magnetic forces between the rotor and stator.

Some key materials used in the construction of the generator are shown in Table 5.1 with their properties. The most difficult choice of material proved to be the generator hub bearing required to link the shaft with the two rotor disks and also to keep the stator rigid. This is a key component in the prototype manufacture because once this is decided then the dimensions of other components can be deduced. For instance, the stator inner diameter must be greater than the hub bearing diameter. The stator winding support material is polyester resin mixed with fiber glass. This material has the same permeability as air, and yet strong enough to hold the windings in place. Therefore, casting the windings using a mixture of these materials yields a stator with air gap winding.

Table 5.1: Materials used for manufacture and their properties

Generator unit	**Material**	**Properties**
Stator disk	polyester resin	permeability of air, low processing time, up to 15^{o}C application temperature
Stator conductor	copper	Magnesol® UN-180, solderable enamelled round wire, temperature class 180^{o}C
Stator housing	aluminium alloy	nonmagnetic, good thermal conductor, lightweight, malleable
Rotor disk	steel	high permeability, high strength, cheap & available
Bearing	vehicle wheel hub bearing	cheap, high strength, high torque capability.
Permanent magnets	N42 NdFeB	max temperature 80^{o}C; at 20^{o}C; B_r = 1.3T

5.2.2 Available tools and skills

The choice of this configuration encourages generator manufacture in small workshops using basic tools and skills. The following are the tools that were used for the generator manufacture.

1) Steel cutting tool for shaping the rotor disk to the required size.
2) Wood shaping tools to make stator mould.
3) Drilling machine to make suitable holes on rotor disk and hub bearing.

Tools and skills for cutting steel are easily found in many parts of the world. A guillotine steel cutter or a welding machine can be used for this purpose. This also true for wood shaping and drilling tools, as well as the needed skills for such tasks.

A major concern for the manufacture of this generator is the availability of permanent magnets which is often an issue of politics and cannot always be guaranteed. This thesis dealt with this problem in part by using magnets that are mostly available rather than using specially manufactured magnets. The cost of PMs can also become too high due to the same reason thereby significantly affecting its low cost objective. In the event that PMs are not available, an automotive alternator could provide a low cost alternative for this application. This concept will be presented in the next chapter.

5.3 Generator dimensions and characteristics

This section describes how the main dimensions of the generator are determined. The dimensions obtained in this section will be used in the analytical design of the generator which will be presented later. The relations between the generator dimensions and generator parameters are calculated in simple and conventional ways.

The following assumptions were used in the design calculations.

1) The magnetic flux density crosses the air gap perpendicularly. In AFPM machines with magnetic core there are negligible leakage fluxes as the magnetic flux is guided by the yoke. However, since the winding of a coreless machine is in air, there are leakage flux paths due to fringing. The air gap flux density will then be less than the magnet flux density.
2) The effects of space harmonics of the magnetic flux density distribution in the air gap are neglected; only the fundamental is considered to contribute to power.

From Ampere's law

$$\oint_{Cm} \vec{H}.d\vec{l} = \iint_{Sm} \vec{J}.d\vec{A} \tag{5.2}$$

The flux traverses l_m four times, so that

$$2H_g l_g' + 4H_m l_m = 0 \tag{5.3}$$

$$l_g' = 2l_g + h_{sy} \tag{5.3a}$$

where H_g and H_m are respectively the magnetic field intensity in the air gap and magnet, l_m, l_g and h_{sy} have been defined earlier in Equation 5.1.

The BH characteristics of the magnet is given by

$$B_m = \mu_0 \mu_{rm} H_m + B_{rm} \tag{5.4}$$

where B_{rm} is the remanent flux density of the magnets, μ_0 is the permeability of free space and μ_{rm} has been defined in Equation 5.1. The BH characteristics of the airgap is given by

$$B_g = \mu_0 H_g \tag{5.5}$$

Continuity of magnetic flux implies that

$$B_g = B_m \tag{5.6}$$

Combining the above equations we can write

$$\frac{B_g l_g'}{\mu_0} + \frac{2l_m \left(B_g - B_{rm}\right)}{\mu_0 \mu_{rm}} = 0 \tag{5.7}$$

The air gap flux density due to the magnets can then be written as [98]

$$B_g = \frac{2B_{rm} l_m}{\mu_{rm} l_{geff}} \tag{5.8}$$

where l_{geff} is the effective airgap earlier defined in Equation (5.1).

The flux density is assumed to cross the air gap perpendicularly so that we obtain a rectangular space distribution of the flux density. The rectangular space distribution can be expressed as a Fourier series, therefore the amplitude of the fundamental space harmonic can be written as [98]

$$\hat{B}_{gm} = \frac{2l_m}{\mu_{rm} l_{geff}} B_{rm} \frac{4}{\pi} \sin\left(\frac{\pi b_p}{\tau_p}\right) \tag{5.9}$$

where τ_p is the average pole pitch, b_p is the magnet width. It is assumed that only the first space harmonic gives a contribution to power. The effect of other space harmonics of the air gap flux density is neglected. The average pole pitch is calculated as

$$\tau_p = \frac{\pi\left(r_{si} + r_{so}\right)}{2p} \tag{5.10}$$

where r_{si} and r_{so} are respectively the stator inner and outer radii as defined in Figure 5.1(c).

From Faraday's Law, the no-load phase voltage induced in the stator coils (as a function of time) can be written as

$$e(t) = N_s \frac{d\phi}{dt} \tag{5.11}$$

where N_s is the number of turns of a stator phase. The RMS value of the electromotive force (EMF) induced by this flux density in the stator phase winding is [53], [98]

$$E_p = \sqrt{2} k_w N_s l_s r_s \omega_m \hat{B}_{gm} \tag{5.12}$$

where ω_m is mechanical angular speed of the rotor, k_w is the winding factor, l_s and r_s are the stack length and average stator radius given by

$$l_s = \left(r_{so} - r_{si}\right) \tag{5.13}$$

$$r_s = \tfrac{1}{2}\left(r_{so} + r_{si}\right) \tag{5.14}$$

The RMS value of the EMF voltage can then be written as

$$E_p = \frac{\sqrt{2}}{2} k_w N_s \left(r_{so}^2 - r_{si}^2\right) \omega_m \hat{B}_{gm} \tag{5.15}$$

5.4 Modelling of losses

To estimate the efficiency and performance of the generator, the losses that occur in the generator need to be considered. The loss components can be grouped into two

$$P_{loss} = P_{stator} + P_{rotor} \tag{5.16}$$

where P_{stator} and P_{rotor} are the stator and rotor losses. It was earlier stated that a coreless stator configuration will eliminate stator iron losses. Therefore, for this generator structure there are only winding copper losses in the stator of the generator. The prediction of the stator and rotor losses will be presented next.

5.4.1 Stator copper losses

The major part of the winding losses is the resistive losses in the copper, which depends on the load, resistance of the windings and temperature of the windings. Therefore, to predict the copper losses the length of the conductor has to be known. It is assumed that the end turns are half circles with diameter equal to τ_{co} and τ_{ci} or the coil spans at the outer and inner stator diameter as shown in Figure 5.3. The length of the outside and inside end turns can be estimated as

$$l_{to} = \frac{2\pi \frac{\tau_{co}}{2}}{2} \tag{5.17}$$

$$l_{ti} = \frac{2\pi \frac{\tau_{ci}}{2}}{2} \tag{5.18}$$

The length of a conductor phase winding is then estimated as

$$l_{Cus} = N_s\left[2(r_{so} - r_{si}) + \tfrac{1}{2}\pi(\tau_{co} + \tau_{ci})\right] \tag{5.19}$$

The coil resistance is dependent on the length of the conductor and its cross sectional area. Large end windings increases the overall length of the conductor and hence the resistance. Therefore, to increase generator efficiency, the end windings should be kept small since stator copper losses contribute significantly to the overall generator losses.

The stator copper losses is given by

$$P_{Cus} = 3I_s^2 R_s \tag{5.20}$$

where I_s is the RMS value of the phase current. The phase resistance R_s is given by

$$R_s = \rho_{Cu}\frac{l_{Cus}}{A_{Cus}} \tag{5.21}$$

where ρ_{Cu} and A_{Cus} are the resistivity and cross sectional area of the conductor. The cross sectional area of the conductor is a function of the available area for a coil and the number of turns of conductors per coil

$$A_{Cus} = k_{fill}\frac{b_s h_s}{N_c} \tag{5.22}$$

where k_{fill} is the conductor fill factor, b_s is the coil width, h_s is the coil axial height and N_c is the number of turns per coil. The fill factor takes into account the percentage of the coil area filled with conductors. Compared with round wires, the use of rectangular wires can lead to significant increase in the fill factor thereby reducing the coil resistance. However, round wires are cheaper and easily available, making it attractive for this application. Furthermore, the use of rectangular wires could lead to possible increase in the eddy current losses in the coil.

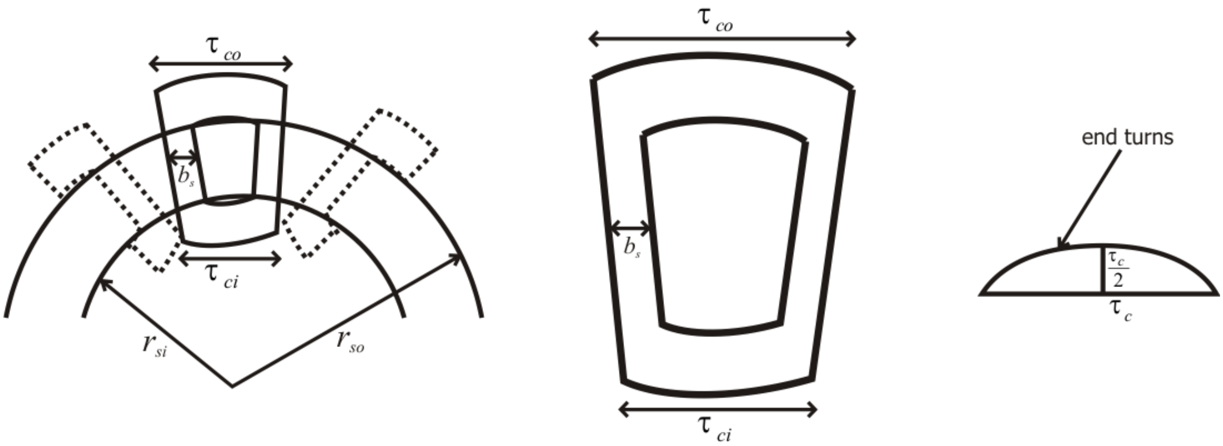


Figure 5.3: Coil dimensions at stator inner and outer diameter and end turns of one coil.

5.4.2 Stator eddy current losses

In coreless machines eddy currents are also induced in the stator conductors since the stator windings are exposed to the magnetic field from the permanent magnets [73], [82], [99], [100]. These induced eddy currents will produce eddy current losses in the stator conductors. In slotted axial flux PM machines, eddy current losses in the stator windings are generally ignored since the magnetic flux penetrates through the teeth and yoke and only small leakage flux penetrates through the slot space with conductors [99].

The eddy current losses from this effect is given by Carter [101]

$$P_{eddy} = \frac{1}{32}\left(\omega \hat{B}_{gm} d\right)^2 \frac{2N_c l}{\rho_{Cu}} \frac{\pi d^2}{4} \tag{5.23}$$

where d is the diameter of the copper wire, l is the length of wire exposed to the magnetic field.

The loss due to eddy currents in stator conductors depends mainly on the wire cross section, the waveform of the flux density and frequency. As earlier stated round wires are less prone to eddy currents compared with rectangular wires [82]. The eddy current loss in the above equation is inversely proportional to the resistivity. The use of conductors with high resistivity is one way of reducing such losses. However, this is not very practical as the copper losses also increases. In addition, the eddy current loss also varies with the conductor diameter to the fourth power. As a result, multi-stranded (Litz) wires can be employed to reduce eddy current losses to a negligible value [82], [100]. However, the use of Litz wires will lead to increase in manufacturing cost. As the peak flux density is usually low, the frequency is low and the wire diameter is relatively small eddy current loss in this generator will not be significant. The eddy current losses in the stator conductors are quantified using measurement tests and calculation as presented Section 5.6.4 (Figure 5.15).

5.4.3 Rotor losses

The rotor losses are mainly due to friction as a result of rotation of the rotor disks (mechanical losses). The major components of the mechanical losses are windage losses and bearing losses. Windage losses are modeled as being proportional to the cube of the speed

$$P_w = C_w \omega^3 \tag{5.24}$$

where C_w is a constant which depends on the dimensions of the rotor disk, friction coefficient of the rotating disk which can be estimated as shown in [102] and air density. The bearing losses on the other hand is estimated to vary proportionally with speed [102] as

$$P_b = C_b \omega \tag{5.25}$$

where C_b is the bearing coefficient which is provided by the manufacturer. The bearing used is a recycled vehicle hub bearing, which is cheap and easily available but has possibility of increased losses. The values of C_w and C_b were determined experimentally at 300 rpm using measured no-load losses as shown in Table 5.2. Details of no-load measurements are presented in Section 5.6.4.

5.5 Mass of active materials

The mass of active materials consist of mass of permanent magnets, copper and iron. The mass of copper can be estimated from the calculated length of a conductor phase winding and the copper cross sectional area as

$$M_{Cu} = 3\rho_{mCu} l_{Cus} A_{Cus} \tag{5.26}$$

where $\rho_{m\mathrm{Cu}}$ is the mass density of copper.

There are no iron in the stator; therefore the total mass of iron is the mass of the rotor disks which is estimated using the rotor dimensions as

$$M_{Fe} = 2\rho_{mFe} h_{ry} \pi \left(r_{ro}^2 - r_{ri}^2\right) \tag{5.27}$$

where $\rho_{m\mathrm{Fe}}$ is the mass density of iron and h_{ry} is the thickness of rotor disk. The inner radius of the rotor r_{ri} is defined by the diameter of hub bearing and shaft assembly as indicated in Figure 5.4. That is, the inner diameter of the rotor disk cannot be larger than the bearing outer diameter (D_{bo}) since the rotor disks have to be connected together using bolts through the bearing. Furthermore, the inner diameter of the rotor disk cannot be smaller than the bearing inner diameter (D_{bi}) since this part of the bearing has to fit into this space as shown in Figure 5.4.

Table 5.2: Measured rotor loss constants at 300 rpm

Windage loss constant (C_w)	6.45 x 10^2
Bearing loss constant (C_b)	1.56

The total magnet mass is estimated from the actual magnet surface area and the magnet length as

$$M_m = 2\rho_{mm} l_m \pi \left(r_{so}^2 - r_{si}^2\right)\frac{b_p}{\tau_p} \tag{5.28}$$

where ρ_{mm} is the mass density of magnet. The actual surface area of the magnets is calculated as the total available surface area for magnets multiplied by the magnet width to pole pitch ratio. A factor of 2 is included in the calculation of the mass of iron and mass of magnets because there are two rotor disks.

5.6 Experimental results

Measurements tests are necessary to determine generator performance and to study its operational behaviour. The results of the measurement tests can then be used to make further design improvements and optimisation. To test the generator performance it is necessary to build a dedicated test setup to enable generator performance to be measured at a wide speed range. One requirement of a suitable generator for this application as given in Chapter 4 of this thesis, and also a major objective of this thesis, is manufacturability in small workshops. To achieve this, a prototype axial flux generator was built in the workshop which is used for the measurement tests reported in this section. The section starts with a description of the test setup, including rotor manufacture, stator manufacture, and integration of generator components to test bench.

The main measurement tests conducted are: no load tests to determine back EMF voltages, no-load losses (separation of no-load losses) and rotor loss constants (windage and bearing loss constants); and load tests to determine output power (voltage and current) and generator efficiency. Results of these measurements are also presented.

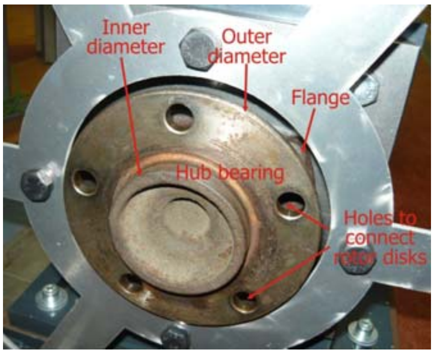
5.6.1 Test setup

Rotor manufacture

The rotor components consists of the rotor disks, permanent magnets and the bearing assembly. For this prototype, the bearing used is a recycled vehicle hub bearing, which is a low cost and easily available component but has possibility of increased losses. To determine the penalty for using such a bearing, its loss contribution (bearing loss) will be quantified through measurement tests.

The hub bearing has two major components: the component that connects to the rotor (hub) and the other that connects to the stator (flange). Suitable holes need to be drilled on these parts to enable the use of conventional bolts and nuts as shown in Figure 5.5 and Figure 5.4. The hub bearing also comes with a stub shaft which is welded to a long shaft.

The rotor disks were cut from steel plate to design dimensions once the hub bearing has been selected. Holes are drilled on the two rotor disks to allow bolts from the hub bearing to connect the rotor disks together. The magnets are glued to the disk surface with the aid of a template specifically designed for this purpose. The PM mounting template guides the magnets to pre-marked locations on the disks ensuring that they are not a threat to people. The completed rotor disk is shown in Figure 5.6.



(a)

(b)

(c)

Figure 5.4: Photo of rotor: (a) hub bearing assembly showing outer and inner diameter, (b) hub bearing with bolts inserted, and (c) one rotor disk connected. The holes connect the bearing to the two rotor disks. The flange can be seen partially obscured behind the hub bearing (Figure 5.4(a)). It connects the stator via the housing to a rigid frame. The shaft (not seen) is at the back side behind the frame.

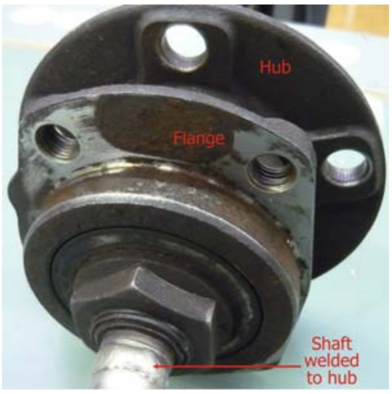


Figure 5.5: Photo of the hub bearing. The flange connects to rigid frame in the test setup while the hub bearing connects the two rotor disks.

Figure 5.6: Photo of completed rotor disk. The hub connects the two rotor disk via the holes drilled on the disks and hub.

Stator manufacture

The stator consists of the windings, winding support and stator housing. The coils are made by turning the handle of a coil winder designed to accommodate the desired size and shape of stator coils. Special attention is paid to keep the same number of turns per coil and to identify the *start* and *stop* end of each coil. The coils are continuously arranged at intervals to pack as much conductor as possible (high fill factor) and to reduce the length of end windings. One of the measures adopted to achieve possible reduction in the length of end windings was to arrange them at the inner stator diameter instead of the outer diameter. Figure 5.7 (a) shows a preformed coil, while Figure 5.7 (b) shows the completed stator connected to test setup.

The coils are weighed to check for consistency. A heavier coil (or otherwise) could be an indication of a higher number of turns or loose arrangement of the coils during winding. The measured weight of the coils is shown in Table 5.3. The number of turns of each phase is 174 and each coil contains 58 turns. Later, the coils are connected inside the stator mould to give a three phase configuration. Finally, the polyester epoxy mixture is made according to manufacturer's specifications and poured to make the stator cast. After several hours, the stator manufacture is completed as shown in Figure 5.7(b).

The stator housing comprises a front and back disk on both sides of the rotor and a circular plate connecting the two disks as shown in Figure 5.8. The front and back disks were designed to have as less material as possible as shown in Figure 5.8 (only one disk is shown). The circular plate also has holes along its surface to aid stator cooling. The stator housing is important because it connects the stator to a rigid frame in order to keep it steady and also to maintain a constant air gap at both sides of the stator. It also acts as protection against possible detachment of the permanent magnets as the rotor turns.

(a)

(b)

Figure 5.7: Photo of stator: (a) preformed formed coil, end windings were arranged at inner diameter, (b) completed stator connected to setup, behind the stator is one rotor disk and hub bearing with spacers attached.

Table 5.3: Measured weight of the coils

Coil	**Weight (g)**
1	341
2	336
3	339
4	341
5	338
6	336
7	337
8	341
9	336
Total	**3045**
Ave. weight	***338***

Figure 5.8: Stator housing and cover to protect against possible PM detachment.

Figure 5.9: Photo of prototype axial flux PM generator after manufacture and assembly.

Generator integration

A photo of the completed AFPM generator is shown in Figure 5.9 while Figure 5.10 shows a schematic overview of the manufactured generator in which the most important parts are indicated. The main challeneg in the generator integration is maintaining a constant gap between the rotor and stator. The effective air gap was first kept constant using spacers which are tapered on both ends as shown earlier in Figure 5.2. Bolts are passed from the hub bearing through the spacers to connect the two rotor disks via pre-drilled holes (Figure 5.4).

The tapering on the spacer is to ensure that a constant effective air gap is maintained between the rotor disks. The tapering is longer on the back end than on the front end. On the back end the tapering length is approximately equal to the rotor disk thickness plus the axial thickness of the bearing. On the front end the tapering is approximately equal to the rotor disk thickness. This is to ensure that the disks can snugly fit on both ends without going beyond the tapering. The stator is kept approximately mid-way between the two rotor disks using nuts and washers attached to bolts from the front housing, through the stator and to back housing. This keeps the stator steady as the rotor turns while maintaining the required air gap length on both sides of the stator.

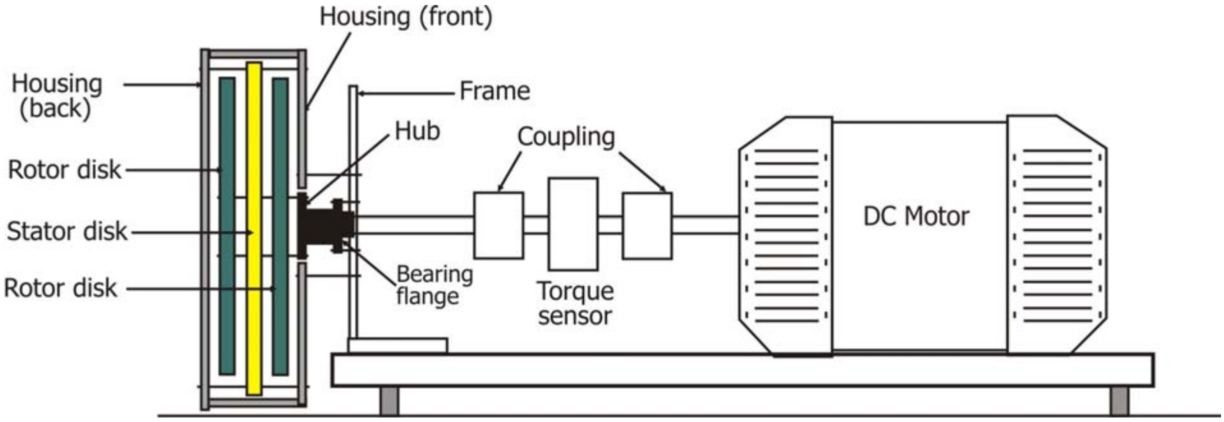


Figure 5.11: Schematics of generator integration to laboratory test setup

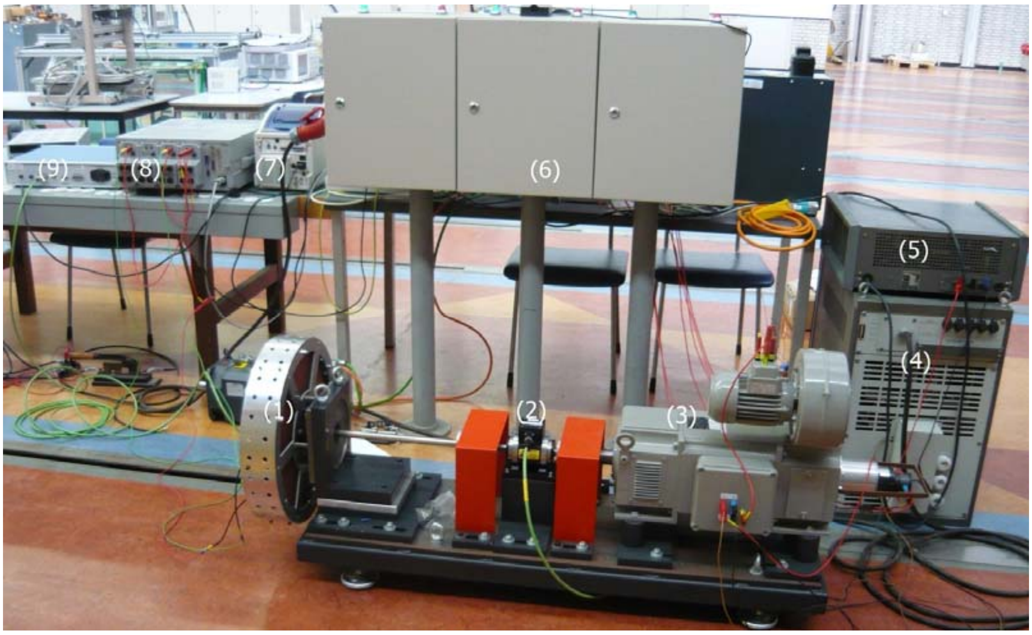


Figure 5.12: Photo of laboratory generator test setup, showing (1) axial flux PM generator with stator housing, (2) torque sensor, (3) DC machine, (4) & (5) DC power supply, (6) grid, (7) oscilloscope, (8) power analyser and (9) speed and torque display.

5.6.2 Resistance and inductance measurement

At the completion of the generator manufacture, the first set of measurement tests conducted were the measurement of all phase resistances and inductances. This serves as a way to check for inconsistencies during manufacture. Significant differences between measured and calculated values of phase resistance and inductance or large differences between phases may indicate a manufacturing error.

The phase resistances were measured immediately after the stator manufacture, when the generator is at rest and the terminals are open. The phase resistances were measured between two terminals at a time and the average of the three resistance measurements is the measured value of the resistance, R_L, from line to line. The phase resistance is calculated as half the measured resistance across two phases for a star-connected phase windings. The measured phase resistance at room temperature is given in Table 5.4.

The phase inductances were also measured when the generator is at rest and the terminals are open using an impedance (LCR) meter. The impedance meter measures the phase inductance at relatively high frequency (1kHz). The measured phase inductances were found to be approximately 0.88mH as shown in Table 5.4.

Table 5.4: Measured phase resistances and inductances

Phase A	Phase B	Phase C
Phase resistances at 21^{o}C		
0.31 Ω	0.31 Ω	0.31 Ω
Phase inductances		
0.88mH	0.88mH	0.88mH

5.6.3 Back-emf measurement

The generator back-emf (no-load voltage) is determined from open circuit test. In this test, the generator is driven over a wide speed range by the DC machine while the line voltages are measured for each speed as shown in Figure 5.13. Figure 5.14 shows the generator back EMF voltage waveform measured at 410 rpm. The measured waveform is quite sinusoidal in accordance with the predicted EMF. At 41 Hz the measured peak value of 50V is about 5% higher than the peak EMF value predicted from design calculations.

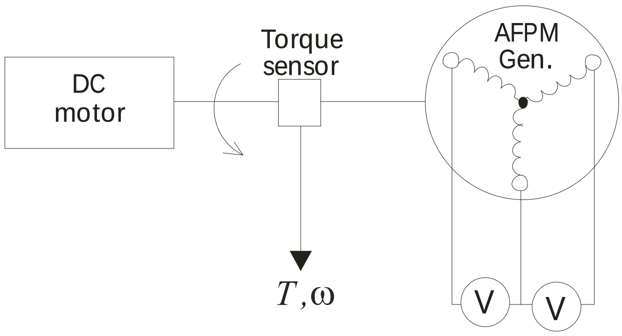


Figure 5.13: Axial flux PM generator no-load test arrangement. The measured voltages, torque and speed are represented by V, T and ω respectively.

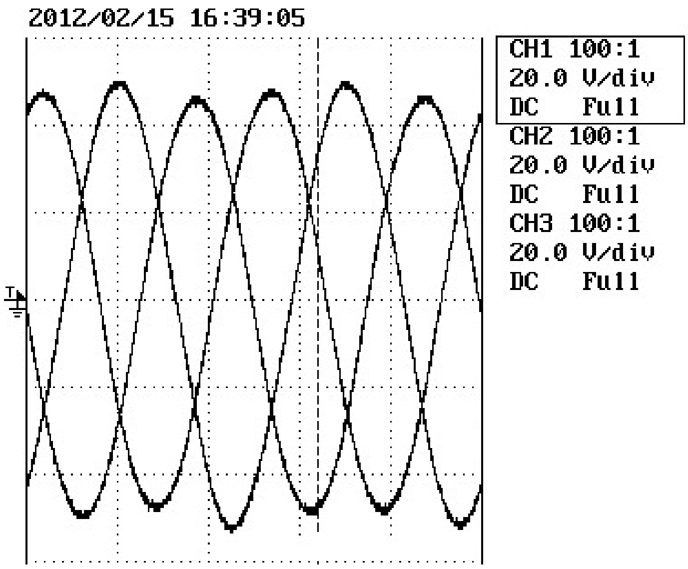


Figure 5.14: Measured back EMF voltage waveform of prototype generator at 41 Hz

5.6.4 No-load losses

The no-load losses are the losses that occur in the generator when it is not loaded and these were also determined during the no-load tests. The major components of the no-load losses for this type of machine are:

- windage (air friction) losses;
- bearing losses;
- and eddy current losses in stator conductor.

The axial flux PM generator under test has no iron in the stator (coreless configuration), so that the no-load losses in this case are mostly losses from the hub bearing and frictional losses due to air resistance. In addition, eddy currents are also induced in the stator conductors. In slotted axial flux PM machines, eddy current losses in the stator windings are generally ignored since the magnetic flux penetrates through the teeth and yoke and only small leakage flux penetrates through the slot space with conductors. However, in slotless and coreless machines, the stator windings are exposed to the magnetic field from the permanent magnets leading to eddy current losses in the stator conductors.

It is desirable to separate the no-load losses in order to determine the contributions of the various components and the rotor loss constants (bearing loss constant and windage loss constant). To separate these losses the following approach is adopted.

1) Measure the no-load power (torque and speed) with only hub bearing to determine bearing losses.
2) Measure the no-load power (torque and speed) with hub bearing and rotor disks to determine bearing and windage losses.
3) Finally, measure the no-load power (torque and speed) with hub bearing, rotor disks and stator to determine bearing, windage and stator eddy current losses.

The plot in Figure 5.15 shows a comparison of the measured no-load losses with design predictions using Equations (5.23) to (5.25). It is clear that by far the major contributor to no-load losses in this generator is the hub bearing. The bearing loss constitutes about 90% of the total no-load loss at 300 rpm. This is an important result as it shows that a heavy penalty is paid by using the vehicle hub bearing which is cheap but very inefficient. It also shows that using a more efficient bearing will improve the performance of the generator. Figure 5.15 shows that eddy current loss due to stator conductors are low at low speeds but becomes slightly significant at higher speeds. At 300 rpm, measured stator eddy current loss is only 4 W or about 7% of total no-load losses. The air friction loss is low even at higher speeds.

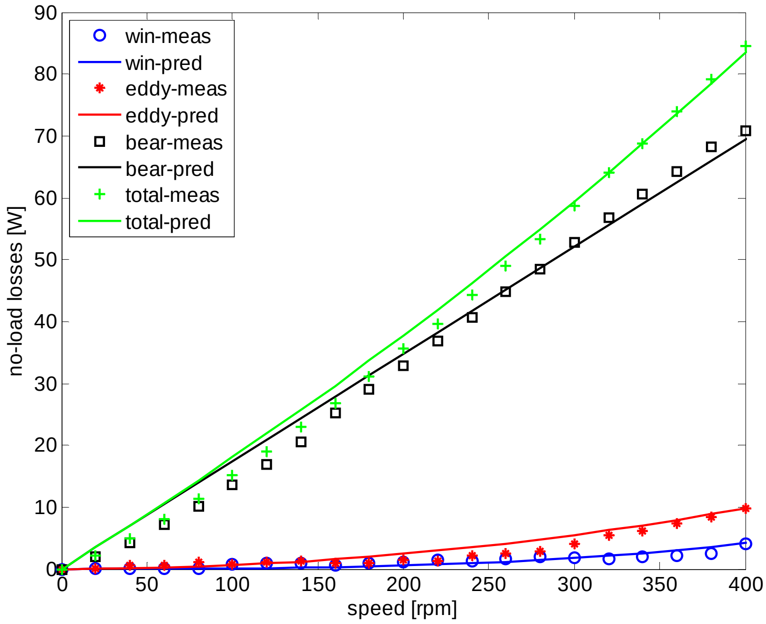


Figure 5.15: Measured and predicted no-load losses of the AFPM generator at various speeds

Table 5.5: Measured no-load loss components at 300rpm

	Bearing	**Stator eddy current**	**Windage**	**Total no-load**
Measured loss (W)	49	4	2	55
Contribution (%)	89.1	7.3	3.6	100

5.6.5 Load test and efficiency

Load tests were carried out using resistive load as shown in Figure 5.16. During the load test, the generator speed is kept constant while the load resistance is varied. The generator output current and power are also given in Figure 5.17 and Figure 5.18 respectively.

A plot of the generator efficiency with generated output power at constant speeds is also shown in Figure 5.19. As the load increases to rated value the output power also increases while the voltage remains nearly constant. As the load increases further, the voltage begins to decrease at a faster rate thereby reducing the power until nearly no power is generated at near short circuit. Figure 5.19 shows that at a speed of 300 rpm, the generator is able to achieve an efficiency of about 80%. Furthermore, as generator speed increases, the efficiency remains nearly constant at its maximum value for some time as the output power increases (increasing load).

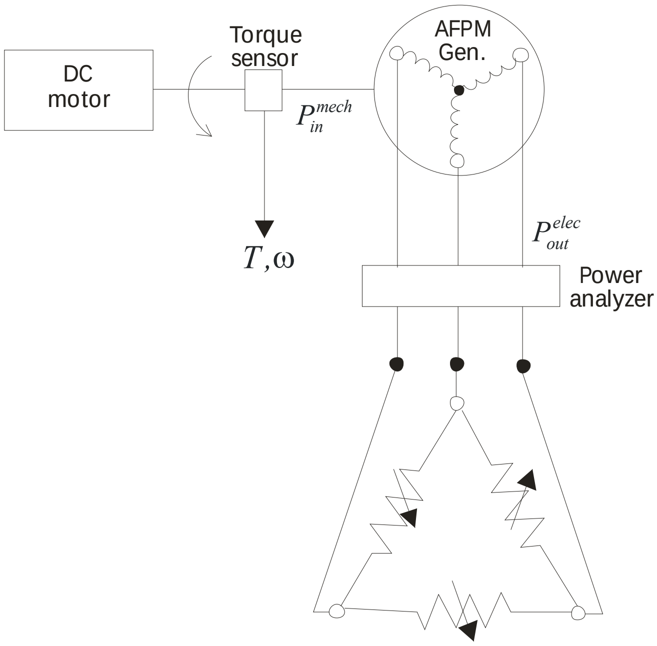


Figure 5.16: Axial flux PM generator load test arrangement. The power analyser measures the electrical output power (current and voltage) while the input power (torque and speed) is measured by the torque sensor. The load resistance is connected in delta.

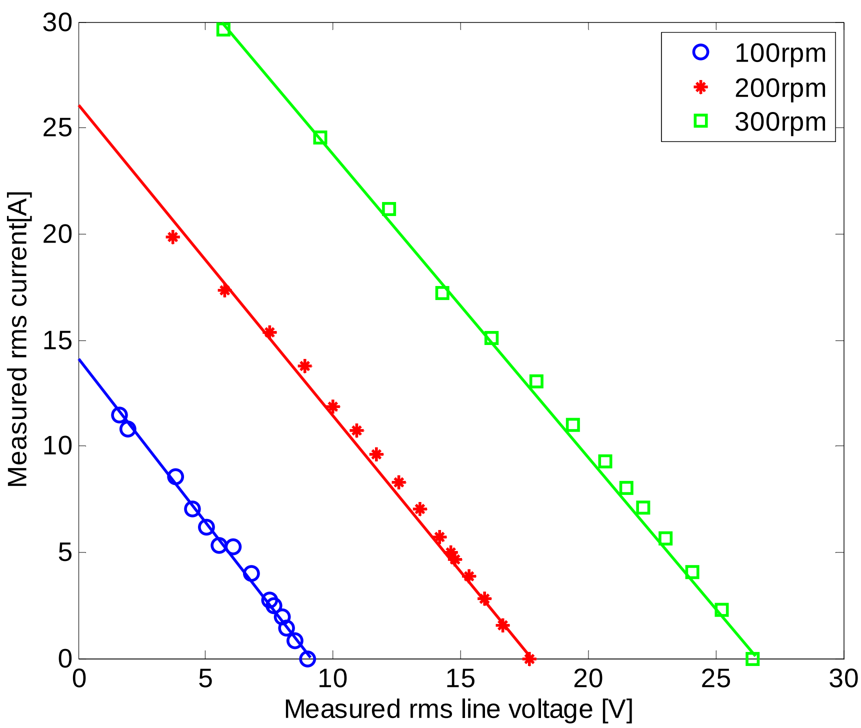


Figure 5.17: Measured output current variation with voltage at speeds of 100, 200 and 300rpm.

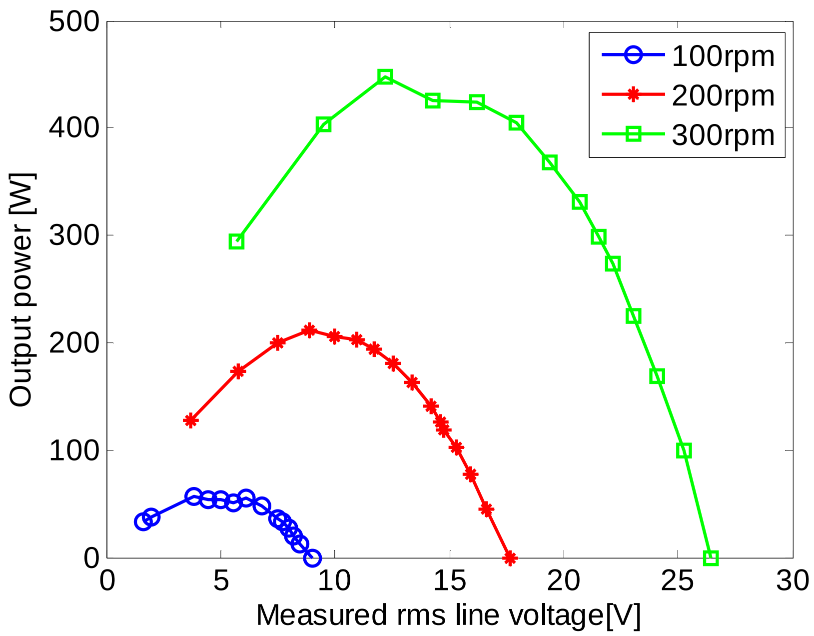


Figure 5.18: Measured output power variation with voltage at speeds of 100, 200 and 300rpm.

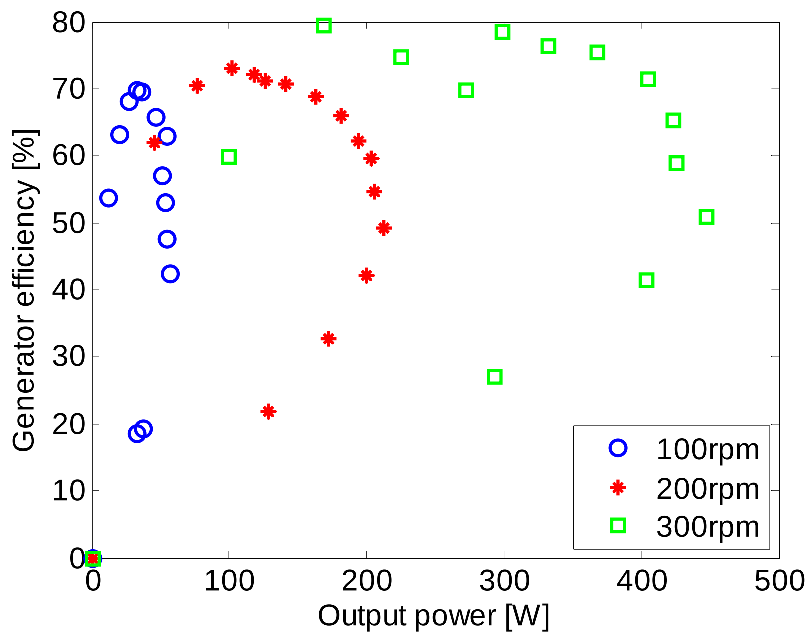


Figure 5.19: Measured generator efficiency variation with output power at speeds of 100, 200 and 300rpm.

The generator efficiency is obtained as.

$$\eta = \frac{P_{out}}{P_{in}} = \frac{\sqrt{3} V_L I_L \cos(\phi)}{T\omega} \tag{5.29}$$

The measured generator maximum efficiency increases from about 70% at 100rpm to 80% at 300rpm. If a more efficient hub bearing had been used, generator efficiency would have improved. At 300 rpm the generator attains maximum efficiency of 80% while delivering an output power of about 300W. The input power at this operating point is 375W (300W/0.8). If the bearing losses were to reduce by half at 300rpm (that is from 49W to 24W), then output power increases to 325W while the efficiency increases to about 87% (325/375).

5.6.6 Design improvements

The measurement tests and experimental results conducted on the prototype axial flux PM generator suggest that possible improvements can be made to this machine for better performance. These are:

1) The use of a more efficient bearing. The penalty paid by the use of this vehicle hub bearing is a bearing loss of about 50W (about 90% of no-load losses) at 300rpm. The parameters that influence bearing losses in vehicle hub bearings are investigated in Section 5.8 to determine how loss reduction from this component can be achieved to improve generator efficiency.
2) The use of stator conductors with smaller diameter. At the initial stage, it was thought that stator eddy current losses might be significant due to the air cored stator. However, from the experimental results, stator eddy current loss was only 4W (about 7% of no-load losses) at 300rpm. Since the losses vary with the diameter of stator conductor to the fourth power, the use of wires with smaller diameter can reduce such losses.
3) Optimising generator dimensions. Generator dimensions and parameters can be varied in order to optimize the design and achieve a given target such as cost minimization. For instance, low pole width to pole pitch ratio (b_p/τ_p) was used in the design of the prototype generator because this ratio was imposed by the adoption of a particular magnet dimension due to availability. A consequence of using a low value of b_p/τ_p is that due to the low magnet width, the flux density in the air gap is small and hence the voltage is also small. In addition, the stator inner diameter was limited by the mechanical limitations imposed by the diameter of the hub bearing component. Once the inner diameter is selected, outer diameter then had to be selected to satisfy certain practical difficulties such as sufficient space to arrange the coils.

Optimization of the prototype generator is presented in the next section.

5.7 Optimization

Generally, in optimization problems, such as optimization of electric machines, some criteria need to be maximized or minimized using input variables which are functions of the criteria. The prototype axial flux PM generator developed in the earlier part of this thesis was not optimized. Its design and manufacture was guided by availability of materials rather than optimized dimensions. Since this generator is proposed for application in small-scale wind power generation in developing countries, generator cost is a major issue. High cost of small wind turbines was earlier identified as a major reason for the low penetration of current systems in such areas. Therefore, a low cost solution is important for this application and forms the focus of the implemented optimization.

In this section, the optimization of the axial flux PM generator is presented using the dimensions calculated earlier as a starting point. The optimization is based on a criteria that minimizes the cost of active materials while achieving a certain required efficiency. In order to implement this, the following parameters are used as variables in the optimization process.

- Magnet length in magnetization direction, l_m.
- Magnet width to pole pitch ratio, b_p/τ_p
- Stator outer diameter, r_{so}
- Coil height, h_s
- Coil width to coil pitch ratio, b_s/τ_s

The optimization focuses on minimizing the cost of active materials while achieving a certain required efficiency by minimizing the following criterion:

$$C = \left(C_{Cu}M_{mCu} + C_{Fe}M_{mFe} + C_m M_m\right) + 0.01e^{(1000\eta_0 - \eta)} \qquad 5.30$$

where C_{Cu}, C_{Fe} and C_m are respectively the costs per kg of copper, iron and permanent magnet as shown in Table 5.6. The criterion ensures that while the optimization program is trying to minimize the cost of active materials, a very high penalty is imposed if the generator efficiency η is lower than the required efficiency η_0.

Table 5.6: Cost of active materials as at Oct. 2011.

Material	**Cost (€/kg)**
Magnesol Grade 1 round copper wire	15
Iron steel	3
N42 grade NdFeB permanent magnet	40

The optimization program calculates the cost of active materials of several generators using the equations developed in this chapter and Table 5.6. The optimization program is a MATLAB®-based program `fminsearch`, which finds the minimum of a multivariable function starting at an initial estimate. The program identifies the generator dimension with the least cost of active materials at a given efficiency. This is repeated for several set efficiencies.

The results of the optimization are shown in Figure 5.20 to Figure 5.23. In Figure 5.20, a plot of cost of active materials and stator outer diameter of the axial flux PM generator for different set efficiency is shown. The plot of mass of the active materials (magnet, copper and iron) and stator outer diameter for different set efficiency values is shown in Figure 5.21 while Figure 5.22 shows a plot of cost of active materials and optimized efficiency values. A plot of stator outer diameter and optimized efficiency values of the axial flux PM generator is also shown in Figure 5.23.

In each plot, each point is an optimized generator (least cost machine) for a given generator efficiency. From the plots, it can be observed that the cost of active materials can be reduced by reducing the generator efficiency, stator outer diameter and amount of active material. That is, lowering designed generator efficiency favour light and low cost generator solutions. Furthermore, cost reduction and efficiency improvement are more significantly improved at lower generator diameters. For instance, if the diameter increases from 222mm to 233mm (5% increase), the cost increases from €121 to €132 (9.1% increase) while the efficiency also improves from 79.9% to 82.7% (3.5% increase). However, when the diameter increases from 290mm to 305mm (5% increase), the cost increases from €196 to €218 (11.2% increase) while the efficiency also improves from 89.8% to 90.7% (1% increase).

A plot of the mass of active materials and stator outer diameter at different set efficiency values is shown in Figure 5.21. The mass of permanent magnet is kept as low as possible by the optimization program due to its high cost compared with other components of the active materials. Due to the same reason, the mass of iron is kept as high as possible due to its lower cost per unit mass as shown in Table 5.6. If the optimization target was to minimize the mass of active materials, the optimized solution may not be the least cost.

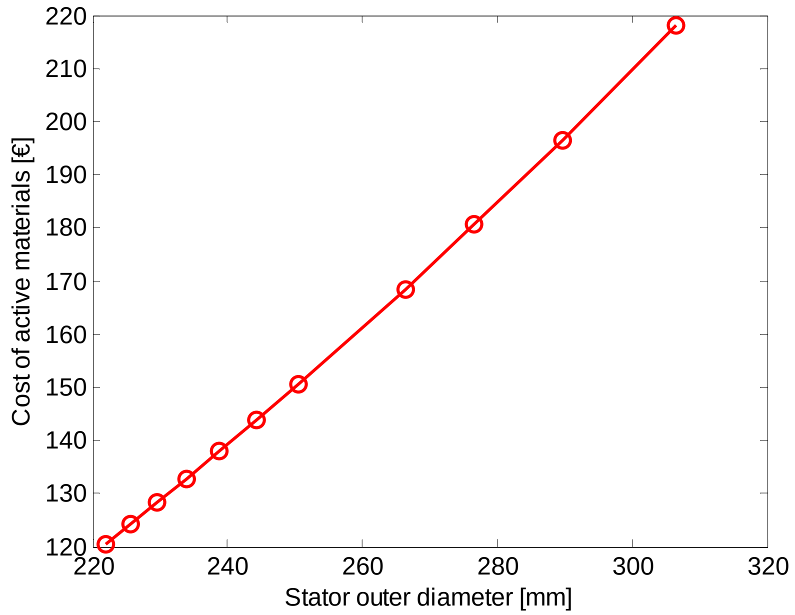


Figure 5.20: Cost of active materials and stator outer diameter of axial flux PM generator optimized at different set efficiency values. The optimization target is to minimize the cost of active materials.

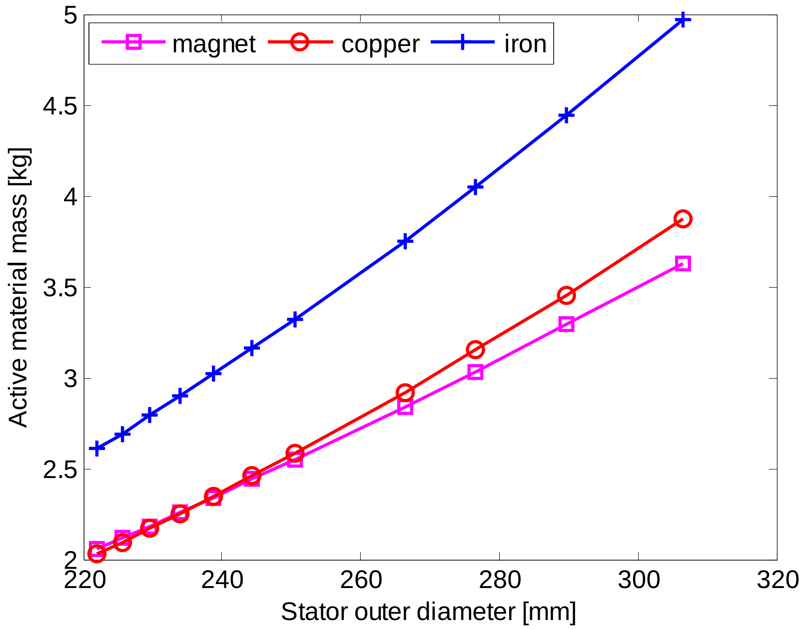


Figure 5.21: Mass of active materials and stator outer diameter of axial flux PM generator optimized at different set efficiency values. The mass of active materials consists of mass of PM magnet, copper and rotor back iron.

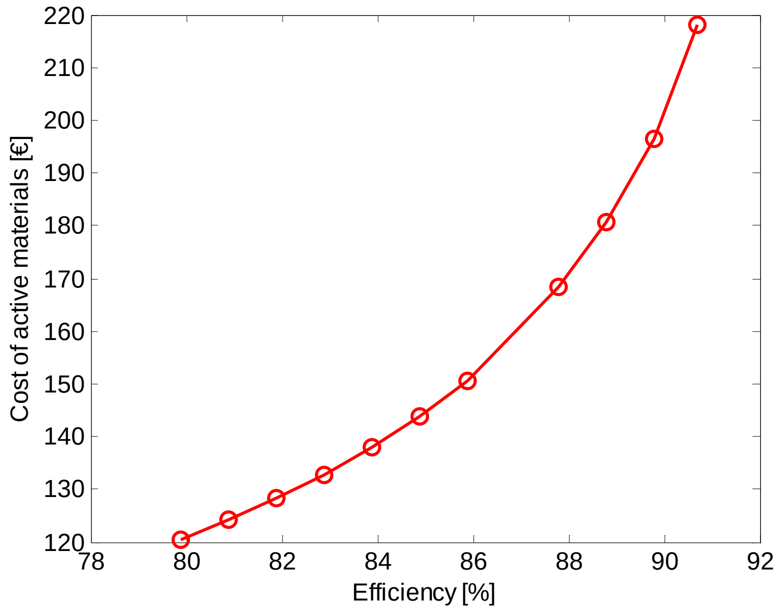


Figure 5.22: Cost of active materials of axial flux PM generator and optimized efficiency values. The cost of active materials consists of cost of PM magnet, copper and rotor back iron.

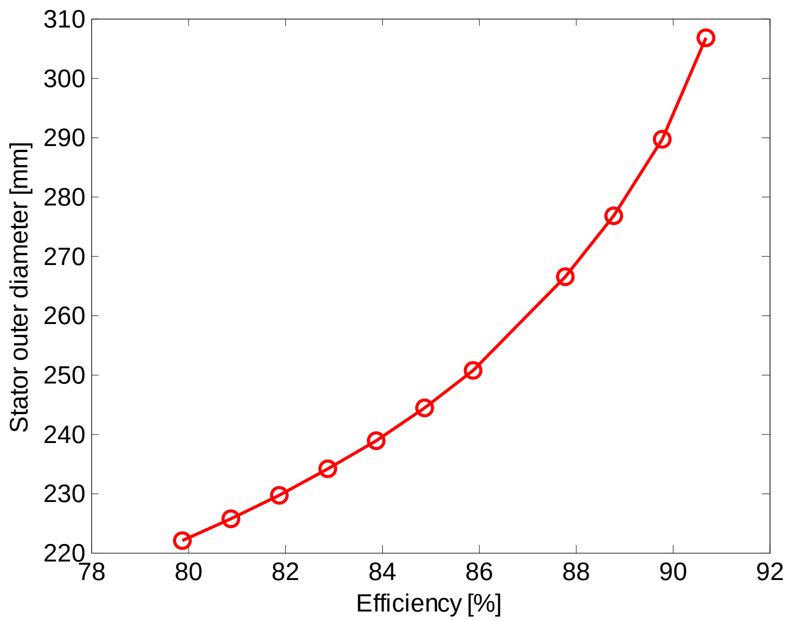


Figure 5.23: Stator outer diameter and optimized efficiency values of axial flux PM generator.

Table 5.7: Properties of manufactured prototype and optimized axial flux PM generator

Property	Prototype (meas.)	Optimized
Mass of active materials (kg)	12.03	7.71
Cost of active materials (€)	147	138
Mass of magnet (kg)	2.21	2.34
Mass of copper (kg)	3.045	2.35
Mass of iron (kg)	6.77	3.02
Magnet width (mm)	25	41.7
Magnet with to pole pitch ratio	0.3	0.6
Magnet length in magnetization direction (mm)	10	18.7
Effective air gap (mm)	38	53
Number of coils	9	9
Number of turns of a stator phase	168	168
Output power (W)	405	430
Speed (rpm)	300	300
Outer diameter (mm)	165	119
Output line-line voltage (V)	18	28.6
Phase current (A)	7.5	8.7
Efficiency (%)	72	84

Table 5.7 gives a comparison of the properties of manufactured prototype and optimized axial flux PM generator. The table shows that the optimized generator is lighter (used less active materials), cheaper and more efficient than manufactured prototype. At set efficiency of 84%, the optimized generator is 36% lighter, 12% more efficient and 6% cheaper than the manufactured prototype generator.

5.8 Bearing losses in vehicle hub bearing

Bearings are widely used in many applications to reduce friction between two components in motion. Bearings generally contribute to the total frictional losses in a given system (bearing losses). It has been reported that nearly one-third of the energy used in industrialized countries goes to overcome friction [103], [104]. Lubricants are usually used to reduce friction in bearings.

In the manufactured axial flux PM generator prototype presented in this chapter, a vehicle wheel hub bearing was used. Wheel bearings allow wheels to turn freely over thousands of miles reducing the friction between the wheel and the spindle it sits on. The choice of this component for our application was motivated by its low cost and availability in many areas of developing countries for automotive application. However, this component contributed about

90% of the total no-load losses at 300 rpm thereby significantly reducing generator efficiency. This section attempts to reduce the loss contribution of the hub bearing by investigating the parameters that influence bearing losses.

Table 5.8 shows the parameters of the vehicle hub bearing used for the manufactured prototype generator. The hub bearing has a hub flange for fixing the wheel and brake rotor attachments, and another flange for fixing the unit to the suspension. For our application, the hub flange connects the two rotor disks while the other flange connects the stator housing and stator disk to a rigid frame. The measured torque to overcome bearing friction at 300rpm is 1.6Nm resulting in a bearing loss of 49W.

The bearing loss can be estimated as being proportional to the speed as presented earlier in Section 5.4.3

$$P_b = T_{fri}\omega \tag{5.31}$$

where T_{fri} is the frictional torque, and ω is the bearing rotational speed in rad/s. For most normal operating conditions the total friction torque can be estimated with sufficient accuracy as load dependent (applied force) using a constant coefficient of friction [105]

$$T_{fri} = \mu F \frac{d}{2} \tag{5.32}$$

where T_{fri} is the bearing friction torque calculated at the bearing bore (inner) radius $0.5d$ [105], μ is the frictional coefficient and F is the applied force. The bearing loss depends on the running speed of the bearing, the applied force and the bearing bore. The friction coefficient depends on the type of bearing, load, lubrication, speed, and other factors [106] and can be estimated for different bearings for normal operating conditions using [105]. Therefore, if the friction coefficient, applied force and speed are the same for certain bearings (that is, the bearings are of the same design), then the bearing loss will depend on the bearing bore (inner) diameter. The larger the bearing bore, the higher the bearing loss. The friction torque is then given by

$$T_{fri} = k \frac{d}{2} \tag{5.33}$$

where $k = \mu F$ is a constant.

Table 5.8: Parameters of the bearing used for the prototype generator

Description	Dodge Ram van 1996
Bearing bore (inner) diameter	64 mm
Outer diameter	140 mm
Rotational speed	300 rpm
Friction torque (measured)	1.6 Nm
Bearing loss (measured)	49 W

Figure 5.24 gives a plot of the bearing loss variation with inner diameter using Equations 5.31 and 5.33. The friction coefficient and the applied force is assumed to be the same as in the hub bearing used for the manufactured prototype such that the bearing loss varies only with varying inner diameter. A bearing with half the inner diameter (about 30mm) of the unit used for the manufactured prototype generator will reduce the bearing loss by half (that is, calculated bearing loss is about 24W) as shown in Figure 5.24.

The generator attains maximum efficiency of 80% at 300rpm while delivering an output power of about 300W while the input power is 375W (300W/0.8). If the bearing loss reduces to 24W, then output power and efficiency will increase to 325W and 87% (325/375) respectively. Therefore, the existing bearing can be replaced with a front wheel hub bearing from Opel Astra G Estate (2002 model), with bearing inner diameter of 29.5mm [107], [108] to reduce the bearing losses from 49W to about 24W.

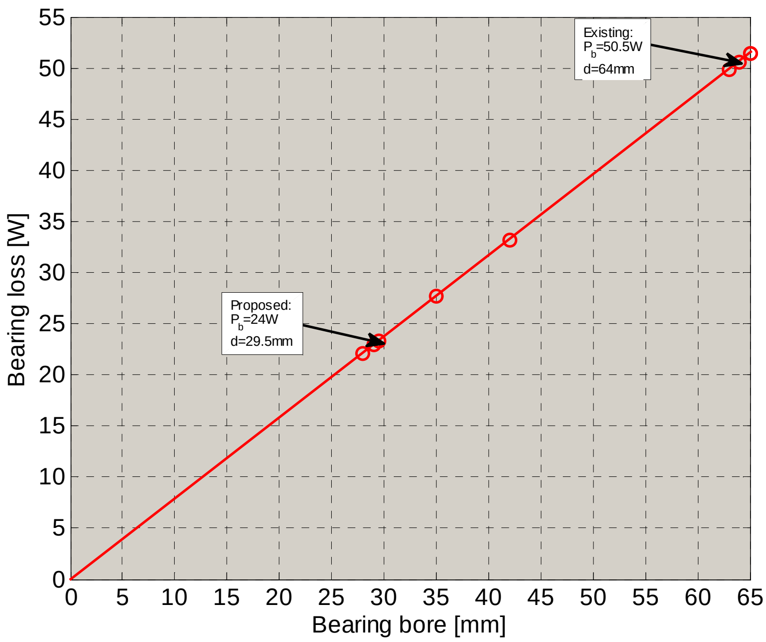


Figure 5.24: Bearing loss variation with inner diameter. Reducing the bearing diameter by 50% will reduce the bearing losses by the same margin.

5.9 Conclusion

The design, manufacture and performance results of an axial flux permanent magnet generator has been presented in this chapter. The design choices made and the effect of these choices on efficiency and performance were highlighted. One of such choices is the use of vehicle hub bearing which is cheap but inefficient. The eddy current loss introduced by the use of coreless axial flux PM machine configuration as well the loss due to the choice of bearing were quantified through measurement tests. The following are the concluding remarks from this chapter.

- The loss contribution due to the bearing was experimentally determined and separated from other no-load loss components. It was shown that the penalty paid by the use of this type of bearing is a bearing loss of about 50W (about 90% of no-load losses) at 300rpm.
- The use of a hub bearing with smaller inner diameter is proposed to reduce the bearing losses. If the bearing loss reduces by half, the generator efficiency will improve from 90% to about 87% at 300 rpm.
- On the other hand, the measured windage loss was determined to be just 2 W at 300 rpm.
- The loss contribution due to eddy currents in stator conductors was also quantified through measurement and separated from other no-load losses. The loss contribution due to stator eddy currents is not significant: at 300 rpm measured eddy current loss is just 4W which is about 7% of the total no-load losses. This is due to the low peak flux density in the air gap, low frequency and relatively small wire diameter.
- Possible improvements to the performance of the prototype axial flux PM generator were highlighted. One of such improvement is optimization of the design since the development of the prototype generator was guided by availability of materials rather than optimized dimensions. The optimized generator is 36% lighter, 12% more efficient and 6% cheaper than the manufactured prototype generator.

Chapter 6

Automotive alternator

6.1 Introduction

In chapter 5 of this thesis we presented the design, manufacture and performance verification of an axial flux permanent magnet (PM) generator suitable for small wind turbine application. The market for permanent magnets can sometimes be a subject of politics leading to a situation where the availability of PMs cannot be guaranteed at all times. The objective of this chapter is to present a concept to increase available generator options for small wind turbine application using claw pole automotive alternators.

Adriaan Kragten [42] has worked on adapting an induction motor equipped with PMs as small wind turbine generator. This concept, although low cost, also require PMs which may not be available. Automotive alternators can provide an alternative to PM generators for small wind turbine application because of the following reasons.

- Low cost: due to the high volume of alternators manufactured yearly for automotive application, they are inexpensive.
- Availability: alternators can be found in most parts of the world.
- Maintainability: in automotive application, alternators have been found to have high robustness even when they are used in harsh operating conditions.
- They are designed specifically to generate electricity for battery charging.
- Availability of skills: even in remote rural areas, skills for this technology are available albeit for automotive application. Using this as a starting point it would be possible to utilize existing skills and make the required transition to wind turbine application. Therefore, this concept has a very important advantage for our application in terms of acceptance and available technical skills.

The feasibility of automotive alternator as small wind turbine generators have been proposed in [11], [109] – [112]. Menet [109] proposed the use of automotive alternator for a vertical axis (Savonius) wind turbine. Automotive alternators usually operate at relatively high rotational speeds (>1000 rpm) whereas small wind turbines usually run at lower speeds (<1000 rpm). A gear system is an obvious choice to increase the speed input to the alternator. In the study conducted by Menet [109], a gear system was considered unsuitable due to the low efficiencies of Savonius turbines. Instead, the alternator was modified by rewinding with copper wire having half the diameter of the original conductor. In addition, the number of conductors per stator slot was increased by a factor of 4. The estimated output power delivered by this system was approximately 7A (at 12V DC) at a speed of 386 rpm (corresponding to a wind speed of 10m/s). Due to the low power generated from this turbine, the cost per generated power is comparatively high. The estimated cost of this wind turbine “in a supposed series fabrication” was €350 [109], equivalent to €4,375 per kW of generated power, compared with €2,500 to €6,000 per kW for current stand-alone small wind turbines [113].

The work of Fernandez *et al* [110] proposed to utilize the alternator output to feed an arrangement of a step-up chopper and a three-phase inverter controlled by a digital signal process (Texas Instrument) to provide a three-phase voltage output. However, the authors concluded that the cost effectiveness of this scheme as a wind driven generator for developing countries need to be evaluated. In this chapter, this claim is further investigated.

In [111], WindPro2004 Wind Turbine simulation platform was used to implement a small wind turbine coupled to a vehicle alternator. Matching of the turbine rotor characteristics with alternator was achieved using a gear ratio of 1:4. Under experimental conditions, the authors claimed an energy yield of 18.75kWh per month for a 2.3m diameter turbine in a site with average wind speed of 4.8m/s. The energy yield from a vehicle alternator coupled to a specific wind turbine is evaluated in this chapter and compared with commercially available systems.

In [112], experimental work on a vehicle alternator coupled to a small wind turbine using a belt and pulley system at gear ratio of 1:3 was conducted. Information about the rating of the alternator used for this experiment was not provided. This system generated an output of about 100W (at 13V DC) at alternator speed of 1080 rpm equivalent to wind speed of 8.5m/s). Furthermore, the cut-in wind speed was found to be too high (6.35m/s) which makes such a system unsuitable for most areas. The poor performance of this system probably led the author to conclude that a vehicle alternator is not suitable for small wind turbine application.

In this chapter of the thesis, the feasibility of using automotive alternator as generator for a small wind turbine is evaluated. To do this, an analysis of the alternator system is necessary. Models are developed to describe the performance of the alternator which are validated through measurements results. Optimization of alternator performance by the selection of suitable turbine parameters and gear ratio is shown to be an effective method of achieving good matching of the turbine characteristics with alternator. The energy yield from the alternator integrated to a specific turbine is presented and compared with values for commercially available systems earlier presented in Chapter 3. Some design improvements are also presented to increase output power generation and efficiency.

6.2 Claw pole automotive alternator system

The claw-pole alternator is perhaps the oldest type of three phase synchronous electrical machine. The first one was used in 1891 to generate electricity for the first three phase transmission line from Lauffen to Frankfurt/Main Germany [114]. After this, claw-pole alternators disappeared and it was not until early 1960 that it reappeared for electric power generation in vehicles. Today the alternator is the most common generator used in vehicles where millions have been sold for this application.

Despite the relatively low efficiency of the Lundell alternator, for many years this machine remained the best compromise between efficiency and cost. The Lundell alternator was designed based on a 14 V DC voltage output in order to charge 12 V batteries. However, as new loads are being added to the automotive power system, a new 42 V DC output voltage system is being proposed to handle the increasing power demand of vehicles [115].

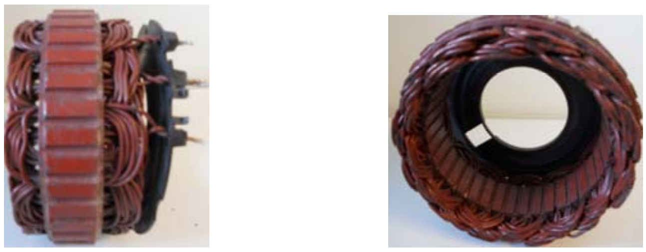


Figure 6.1: Stator of automotive alternator showing the teeth and slots. The stator has laminated core with copper wires inserted in slots.

(a) Rotor (b) Power electronics

Figure 6.2: Rotor and power electronics control of automotive alternator. The field windings in the rotor are made of fine wire and enclosed the rotor claws made of solid iron. The power electronics consists of diode rectifier and inbuilt regulator.

Automotive alternators are three phase synchronous generators with an internal diode rectifier and voltage regulator. The main parts of a typical claw pole alternator from Delco Remy is shown in Figure 6.1 and Figure 6.2. The stator core is uniformly laminated with windings placed in slots. The stator has three-phase star or delta connected AC windings, typically single layer with number of slots per pole per phase (q = 1). The windings are machine-inserted in the slots, with slot filling factor of about 0.3 to 0.32 [116].

As shown in Figure 6.2, the rotor consists of claws made of solid iron that surround a ring shaped DC-excitation field windings. Power is transferred to the DC excitation field windings on the rotor via copper slip-rings and carbon brushes. Bearing and rotor shaft on opposite side (drive end side) complete the rotor assembly. In automotive application, the generator is driven by the internal combustion engine (ICE) through a belt transmission.

The AC generated by the Lundell alternator is rectified through an inbuilt three phase diode bridge rectifier and connected to the battery. A 14V DC system is currently being used, but the 42V DC system is being proposed as the new standard for automotive applications due to increasing load demand in today's vehicles [116], [117]. The output voltage is normally maintained at 14V DC (for 14V battery system) by an internal regulator that samples the battery voltage and adjusts the field current accordingly. The regulator maintains the desired voltage by varying the duty-cycle of the pulse width modulated (PWM) voltage applied to the field winding. As the electrical load in the vehicle increases, more current is drawn from the alternator and the output voltage decreases. The regulator detects this drop in voltage and increases the voltage by increasing the duty cycle to increase the field current, and vice versa when there is a decrease in electrical load.

The alternator system is therefore a three-phase AC synchronous generator used to supply a constant voltage load for battery charging via a three-phase diode bride rectifier. This system can then be likened to a three phase permanent magnet generator with diode rectifier which are commonly used for battery charging in autonomous (off-grid) small wind turbine applications. Analysis and performance of such a system will be presented in the next sections.

6.3 Analysis of alternator with three-phase rectifier and constant voltage loads

It is surprising that despite its widespread use, the analysis of the operational characteristics of the system shown in Figure 6.3 has attracted little interest in literature. In this section an analysis of the output characteristics of three-phase diode bridge rectifier with constant voltage loads is given. The system comprises a three-phase voltage source with series inductance and resistance representing the synchronous generator back EMF, inductance and resistance, while the constant voltage load represents the battery and connected system loads. On one hand, three-phase rectifier circuits with constant current load are analysed in sufficient details in standard textbooks such as [118].

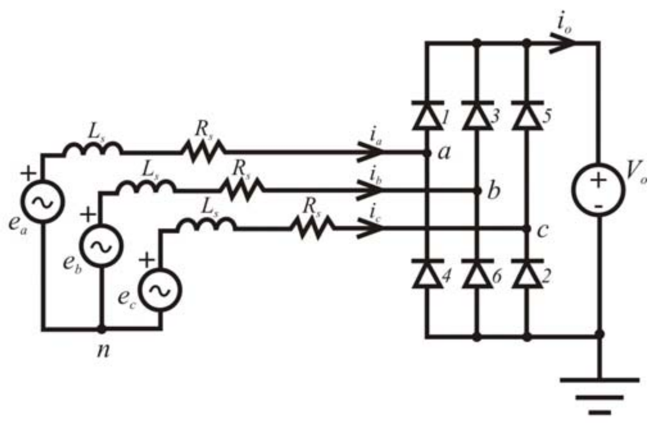


Figure 6.3: Three-phase diode bridge rectifier with a constant voltage load and ac-side inductance and resistance

On the other hand, the system with constant voltage load is hardly analysed [119]. When they are treated, low values of inductance are often assumed such that the bridge operates in discontinuous conduction mode (DCM) [119]. Higher inductance values, required for continuous conduction are usually not considered. The reason for the little apparent lack of interest in the circuit with constant voltage load operating in continuous current conduction mode could be because most variable speed motor drives are based on pulse width modulated voltage source inverters supplied from a DC link voltage. The DC link voltage is often obtained from a 3 phase mains voltage with diode bride rectifier and a large output capacitor to keep the DC link voltage constant. With a large output capacitor, the ac line currents at the input of the bridge rectifier are often discontinuous.

The analysis presented in this section assumes that the inductance L_s is large enough to ensure continuous ac-side conduction. Continuous conduction mode (CCM) is defined with respect to the ac line currents to mean that the ac line currents i_a, i_b, and i_c vary continuously and do not remain at zero for some part of the cycle.

6.3.1 Commutation process and waveforms

Figure 6.3 shows a three-phase rectifier with a constant voltage load. The voltage source of the diode bridge rectifier is supplied from a star-connected three-phase set of sinusoidal voltages e_a, e_b, and e_c with angular frequency ω:

$$e_a = \sqrt{2}E_s \sin(\omega t) \tag{6.1}$$

$$e_b = \sqrt{2}E_s \sin(\omega t - 2\pi/3) \tag{6.2}$$

$$e_c = \sqrt{2}E_s \sin(\omega t + 2\pi/3) \tag{6.3}$$

where the amplitude of the voltages is given by $E_m = \sqrt{2}E_s$.

Due to the series inductance L_s, there is a phase shift so that each AC line current lags its respective voltage by an angle ϕ. Figure 6.4 shows a typical current and voltage waveforms of the 3-phase diode bridge rectifier with constant voltage load in continuous conduction mode.

To generate the waveforms of Figure 6.4 a simulation model of Figure 6.3 was implemented in Matlab SIMULINK platform. The stator resistance and inductance are assumed to be 0.08Ω and 180μH respectively, which are typical values for claw pole alternators used in vehicles. Figure 6.4(a) shows the waveforms for source voltage amplitude of 20V at a frequency of 180 Hz equivalent to a shaft speed of 1800 rpm for a 12 pole alternator while Figure 6.4(b) depicts the waveforms for voltage amplitude of 60V at a frequency of 540Hz (5400 rpm). From the waveforms of Figure 6.4, it can be observed that when the inductance is large enough, continuous conduction mode is achieved while the ac line currents are close to sinusoidal.

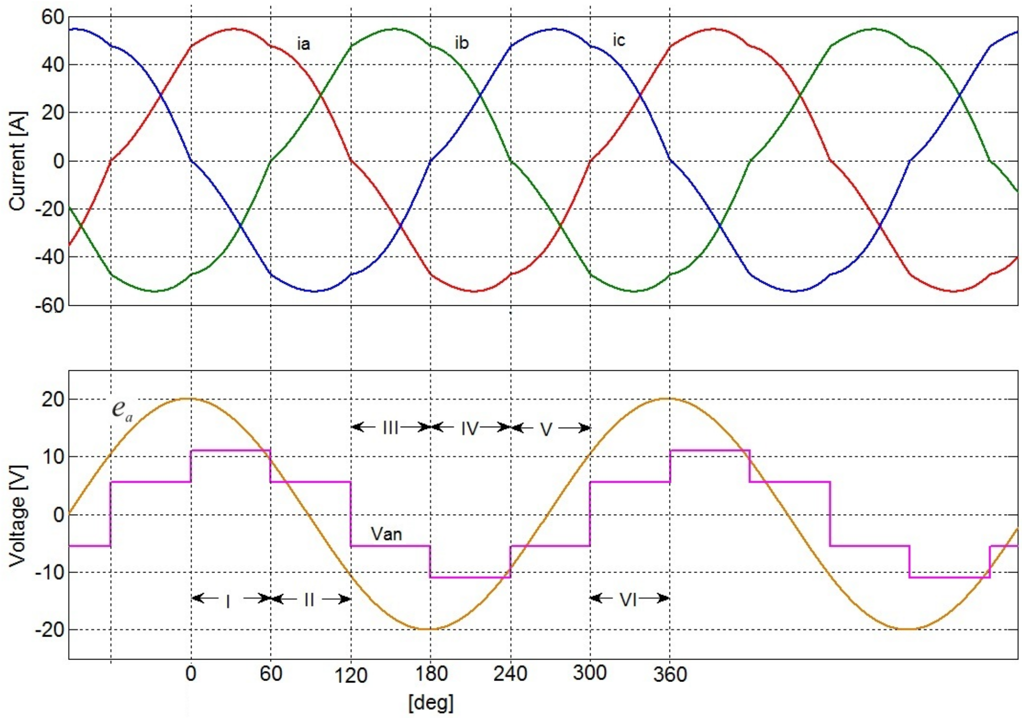


Figure 6.4 (a): Simulated current and voltage waveforms for 3-phase diode bride rectifier in continuous conduction mode at 1800 rpm (E_m = 20V, R_s = 0.08Ω, L_s = 180μH).

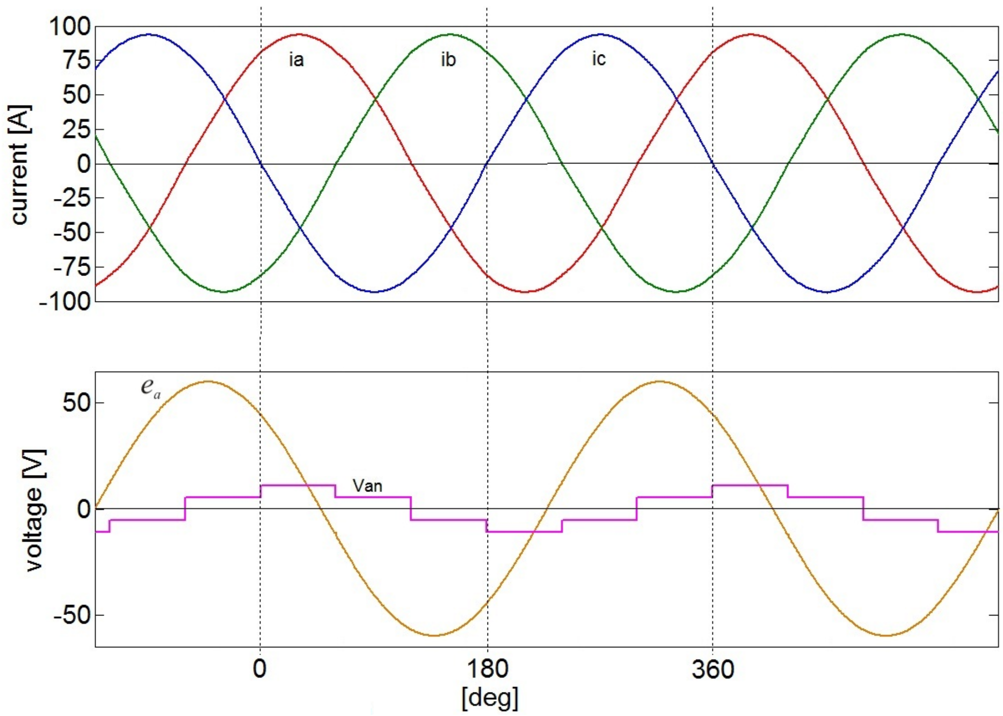


Figure 6.4(b): Simulated current and voltage waveforms for 3-phase diode bride rectifier in continuous conduction mode at 5400 rpm (E_m = 60V, R_s = 0.08Ω, L_s = 180μH).

(a) (b)

Figure 6.5: Measured alternator phase current waveform at 180Hz (1800rpm) for a load of (a) 13 A and (b) 32A.

At low loads (and low speed) the phase currents are no longer continuous as shown in Figure 6.5(a) for a load of 13A at 1800 rpm. Figure 6.5(b) shows that if the load increases to about 32A at the same speed, the measured phase currents are continuous. At low loads the voltage drop across the inductor and the energy stored in the inductor are not sufficient to ensure continuous current conduction. As the load increases, the energy stored in the inductor also increases.

In the analysis that follow, the currents i_a, i_b, and i_c are approximated by their sinusoidal fundamental components i_{a1}, i_{b1}, and i_{c1}. This approximation is justified because the back EMF voltages e_a, e_b, and e_c are sinusoidal. Therefore, power transfer can only be achieved through the fundamental components of the line current. However, the losses are probably higher than predicted due to other harmonic components of the current.

For continuous ac-side conduction of the circuit shown in Figure 6.3, three diodes conduct at any given time. Consider the transition when the line current i_a in Figure 6.3 crosses zero in the positive going direction, i.e. transition from Interval V to Interval VI in Figure 6.4(a). Prior to this transition, diodes 4,5, and 6 were conducting. As i_a reaches zero, diode 4 turns off. For continuous ac-side conduction, source voltage associated with this current e_a must be large enough to immediately turn diode 1 on.

In order to simplify the analysis, first we will neglect the influence of the resistance R_s. Consider the interval I (having a 60^{o} duration) when the line current i_a is positive (that is, diode 1 is conducting), the return path commutates from i_b in diode 6 to i_c in diode 2. During this interval, the output current i_o follows the line current i_a. Neglecting the diode voltage drops, the voltage equations for the loop containing e_a, V_o, e_b and the loop containing e_a, V_o, e_c are respectively given by

$$e_a - e_b = V_o + L_s\left(\frac{di_a}{dt} - \frac{di_b}{dt}\right) \tag{6.4}$$

$$e_a - e_c = V_o + L_s\left(\frac{di_a}{dt} - \frac{di_c}{dt}\right) \tag{6.5}$$

Adding (6.4) and (6.5) yields

$$2e_a - e_b - e_c = 2V_o + L_s\left(2\frac{di_a}{dt} - \frac{di_b}{dt} - \frac{di_c}{dt}\right) \tag{6.6}$$

For a balanced source voltages, the sum of (6.1) to (6.3) is identical to zero at any given time. Furthermore, the sum of the AC line currents must be identical to zero at any given time. The derivative of the sum of the currents is also zero. That is

$$e_a + e_b + e_c \equiv 0 \tag{6.7}$$

$$i_a + i_b + i_c \equiv 0 \tag{6.8}$$

$$\frac{d}{dt}\left(i_a + i_b + i_c\right) = 0 \tag{6.9}$$

Equation (6.9) can be written as

$$\frac{di_a}{dt} + \frac{di_b}{dt} + \frac{di_c}{dt} = 0 \tag{6.10}$$

Equations (6.7) and (6.10) can be written as

$$e_a = -e_b - e_c \tag{6.11}$$

$$\frac{di_a}{dt} = -\frac{di_b}{dt} - \frac{di_c}{dt} \tag{6.12}$$

Substituting Equation (6.11) and (6.12) into Equation (6.6) gives

$$3e_a = 2V_o + 3L_s\frac{di_a}{dt} \tag{6.13}$$

$$e_a = \frac{2}{3}V_o + L_s\frac{di_a}{dt} \tag{6.14}$$

The voltage at point a (Figure 6.3) or the input voltage to the diode bridge with respect to the neutral point n is given by

$$v_{an} = e_a - L_s\frac{di_a}{dt} \tag{6.15}$$

Therefore, equation (6.14) can be written as

$$e_a - L_s \frac{di_a}{dt} = \frac{2}{3} V_o \qquad (6.16)$$

$$\therefore v_{an} = \frac{2}{3} V_o \qquad (6.17)$$

If the diode voltage drop is included, then

$$v_{an} = \frac{2}{3} V_o + \frac{2}{3}\left(2V_d\right) = \frac{4}{3}\left(\frac{V_o}{2} + V_d\right) \qquad (6.17a)$$

A factor of 2 is included because there are two diodes between the input voltage to diode bridge with respect to the neutral point *n*.

Thus, in interval I, the voltage v_{an} is constant as shown in Figure 6.4. The voltages at point *b* and *c* with respect to the neutral *n* are also obtained as

$$v_{bn} = v_{cn} = v_{an} - V_o \qquad (6.18)$$

$$\therefore v_{bn} = v_{cn} = -\frac{1}{3} V_o \qquad (6.19)$$

If the diode voltage drop is included,

$$v_{bn} = v_{cn} = -\frac{2}{3}\left(\frac{V_o}{2} + V_d\right) \qquad (6.19a)$$

The above analysis can be repeated for the six full commutation intervals that make up a full cycle with each cycle having a 60^o duration. Figure 6.6 shows the current paths corresponding to the intervals I to VI. In this figure, the current paths are represented by thick lines while diodes that are not conducting are represented by open switches. Table 6.1 also gives the diodes conducting at a given interval and the values of the diode input voltages v_{an}, v_{bn}, and v_{cn}. The table shows that at any given interval three diodes are conducting.

6.3.2 Modelling of output performance

As shown in Figure 6.4, the input voltage to the diode bridge with respect to the neutral (v_{an} or v_{bn} or v_{cn}) is a stepped waveform. Fourier series analysis shows that this waveform comprises the fundamental and non-triplen odd harmonics (5th, 7th, 11th, 13th,…) [119]. The Fourier series magnitude coefficients of the fundamental and other harmonics of the voltage waveform v_{an} can be represented as

$$v_{an} = \frac{4}{k\pi}\left(\frac{V_o}{2} + V_d\right) \qquad (6.20)$$

for $k = 1,5,7,11,13$; otherwise $v_{an} = 0$.

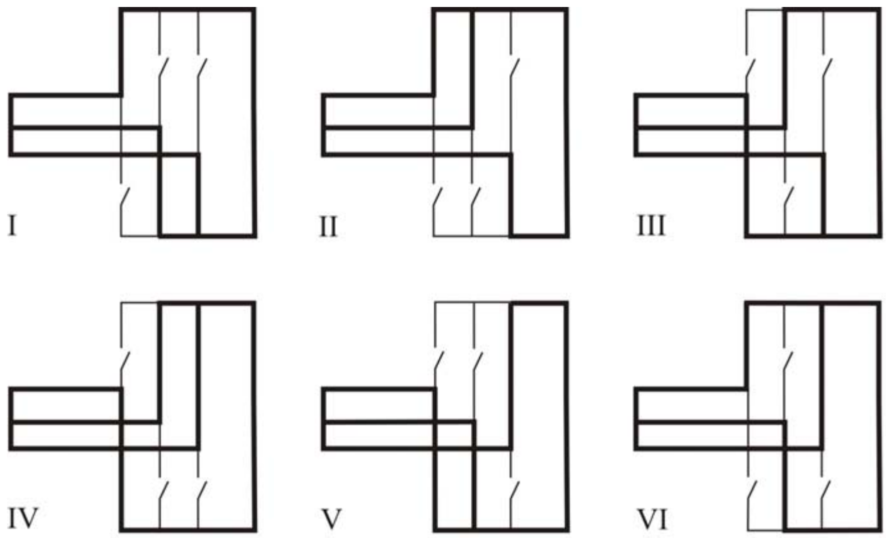


Figure 6.6: Current paths during the six intervals of a complete cycle. The thick lines indicate the path of current flow.

Table 6.1: The intervals of a full cycle, conducting diodes and diode input voltage

Interval	Duration	Conducting diodes		v_{an}	v_{bn}	v_{cn}
I	$0 \le \omega t \le \pi/3$	*D1*	*D6, D2*	$\frac{4}{3}\left(\frac{V_o}{2}+V_d\right)$	$-\frac{2}{3}\left(\frac{V_o}{2}+V_d\right)$	$-\frac{2}{3}\left(\frac{V_o}{2}+V_d\right)$
II	$\pi/3 \le \omega t \le 2\pi/3$	*D1, D3*	*D2*	$\frac{2}{3}\left(\frac{V_o}{2}+V_d\right)$	$\frac{2}{3}\left(\frac{V_o}{2}+V_d\right)$	$-\frac{4}{3}\left(\frac{V_o}{2}+V_d\right)$
III	$2\pi/3 \le \omega t \le \pi$	*D3*	*D4, D2*	$-\frac{2}{3}\left(\frac{V_o}{2}+V_d\right)$	$\frac{4}{3}\left(\frac{V_o}{2}+V_d\right)$	$-\frac{2}{3}\left(\frac{V_o}{2}+V_d\right)$
IV	$\pi \le \omega t \le 4\pi/3$	*D3, D5*	*D4*	$-\frac{4}{3}\left(\frac{V_o}{2}+V_d\right)$	$\frac{2}{3}\left(\frac{V_o}{2}+V_d\right)$	$\frac{2}{3}\left(\frac{V_o}{2}+V_d\right)$
V	$4\pi/3 \le \omega t \le 5\pi/3$	*D5*	*D4, D6*	$-\frac{2}{3}\left(\frac{V_o}{2}+V_d\right)$	$-\frac{2}{3}\left(\frac{V_o}{2}+V_d\right)$	$\frac{4}{3}\left(\frac{V_o}{2}+V_d\right)$
VI	$5\pi/3 \le \omega t \le 2\pi$	*D1, D5*	*D6*	$\frac{2}{3}\left(\frac{V_o}{2}+V_d\right)$	$-\frac{4}{3}\left(\frac{V_o}{2}+V_d\right)$	$\frac{2}{3}\left(\frac{V_o}{2}+V_d\right)$

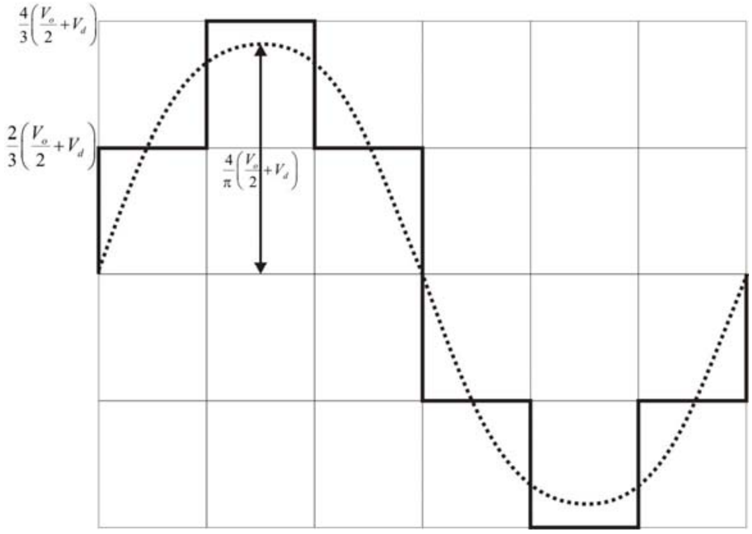


Figure 6.6a: Input voltage to rectifier and its corresponding fundamental component

The fundamental can then be written as

$$v_{an1} = \frac{4}{\pi}\left(\frac{V_o}{2} + V_d\right)\sin\left(\omega t - \phi\right) \tag{6.21}$$

where ϕ is the angle between phase a voltage e_a and its corresponding fundamental of input voltage to diode bridge with respect to the neutral point v_{an1}.

The voltage v_{an} can be approximately represented by its fundamental component since the back EMF voltages of Equations (6.1) to (6.3) are sinusoidal and hence power transfer can only be achieved through the fundamental component of the voltages v_{an}, v_{bn}, and v_{cn}.
Therefore,

$$v_{an} \approx v_{an1} = \frac{4}{\pi}\left(\frac{V_o}{2} + V_d\right)\sin\left(\omega t - \phi\right) \tag{6.22}$$

$$v_{bn} \approx v_{bn1} = \frac{4}{\pi}\left(\frac{V_o}{2} + V_d\right)\sin\left(\omega t - \phi - 2\pi / 3\right) \tag{6.23}$$

$$v_{cn} \approx v_{cn1} = \frac{4}{\pi}\left(\frac{V_o}{2} + V_d\right)\sin\left(\omega t - \phi + 2\pi / 3\right) \tag{6.24}$$

The line currents i_a, i_b, and i_c can also be approximated by their fundamental components i_{a1}, i_{b1}, and i_{c1}. Furthermore, if we assume that the diode bridge rectifier acts as a pure restive load, then the input voltage to diode bridge with respect to the neutral point n is in phase with its respective line currents. Therefore, the line currents i_a, i_b, and i_c will have the form

$$i_a \approx i_{a1} = \sqrt{2} I_{s1} \sin\left(\omega t - \phi\right) \tag{6.25}$$

$$i_b \approx i_{b1} = \sqrt{2} I_{s1} \sin\left(\omega t - \phi - 2\pi / 3\right) \tag{6.26}$$

$$i_a \approx i_{c1} = \sqrt{2} I_{s1} \sin\left(\omega t - \phi + 2\pi / 3\right) \tag{6.27}$$

where $I_{m1} = \sqrt{2} I_{s1}$ and ϕ are respectively the magnitude and phase of the fundamental component of the line currents. Since the currents i_{a1}, i_{b1}, and i_{c1} are in phase with their respective line-to-neutral voltages (input voltage to diode bridge with respect to the neutral) v_{an}, v_{bn}, and v_{cn} the line-neutral voltages can be replaced by an equivalent resistance defined by

$$R_l = \frac{V_{o1}}{I_{m1}} \tag{6.28}$$

where V_{o1} is the magnitude of the fundamental component of line-to-neutral voltages given by

$$V_{o1} = \frac{4}{\pi}\left(\frac{V_o}{2} + V_d\right) \tag{6.29}$$

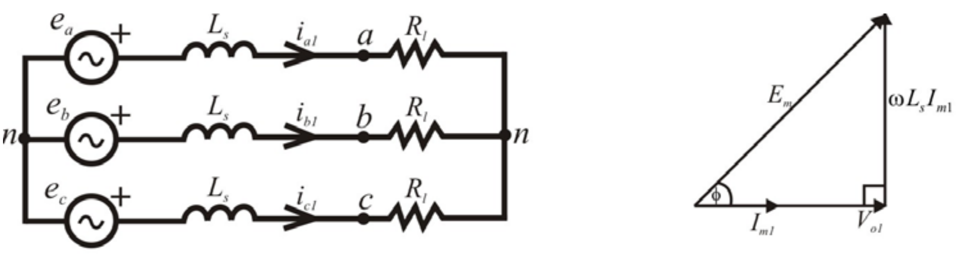
Figure 6.7(a) shows an equivalent circuit for the simplified three-phase rectifier model. The line current in phase a can be defined by the phasor

$$\mathbf{I}_a = \frac{E_m}{\sqrt{R_l^2 + (\omega L_s)^2}} e^{-j\tan^{-1}(\omega L_s/R_l)} \triangleq I_{m1} e^{-j\phi} \tag{6.30}$$

$$\therefore I_{m1} = \frac{E_m}{\sqrt{R_l^2 + (\omega L_s)^2}} \tag{6.31}$$

Substituting the expression for I_{m1} into (6.28), the equivalent resistance can be written as

$$R_l = \frac{V_{o1}}{I_{m1}} = \frac{V_{o1}\sqrt{R_l^2 + (\omega L_s)^2}}{E_m} \tag{6.32}$$



(a) (b)

Figure 6.7: (a) Equivalent circuit for the simplified three phase diode bridge rectifier and (b) phasor diagram of the equivalent circuit.

Simplifying (6.32) in order to solve for R_l we have

$$R_l = \frac{\omega L_s V_{o1}}{\sqrt{E_m^2 - V_{o1}^2}} \tag{6.33}$$

Using the expression in (6.32) and (6.33), the magnitude of the fundamental of the current I_{m1} can be expressed as

$$I_{m1} = \frac{\sqrt{E_m^2 - V_{o1}^2}}{\omega L_s} \tag{6.34}$$

$$I_{m1} = \frac{\sqrt{E_m^2 - \frac{16}{\pi^2}\left(\frac{V_o}{2} + V_d\right)^2}}{\omega L_s} \tag{6.35}$$

Equation (6.34) can be represented by a phasor diagram of Figure 6.7(b) showing the relationship of the phase angle ϕ and the fundamental voltage and current components. Using this phasor diagram, we can define

$$\tan\phi = \frac{\omega L_s I_{m1}}{V_{o1}} \tag{6.36}$$

Substituting for I_{m1} using Equation (6.34) and simplifying we have that

$$\phi = \tan^{-1}\sqrt{\frac{\pi^2 E_m^2}{16\left(\frac{V_o}{2} + V_d\right)^2} - 1} \tag{6.37}$$

The average output current delivered to the constant voltage load V_o can be approximately given by the expression (assuming a lossless rectifier, i.e. AC power equals DC power)

$$I_o \approx \frac{3}{\pi} I_{m1} = \frac{3}{\pi}\frac{\sqrt{E_m^2 - V_{o1}^2}}{\omega L_s} \tag{6.38}$$

$$I_o = \frac{3}{\pi}\frac{\sqrt{E_m^2 - \frac{16}{\pi^2}\left(\frac{V_o}{2} + V_d\right)^2}}{\omega L_s} \tag{6.39}$$

In the derivation of the equivalent resistance given above, the effect of the series resistance R_s associated with the inductance L_s was neglected in order to simplify the analysis. In this subsection, the equations for the fundamental of the line current I_{m1}, the phase angle ϕ, and the average value of the output current delivered to the load are modified to include the series resistance R_s.

The equivalent resistance in this case is obtained by adding R_s to the equivalent resistance obtained without R_s included. That is

$$R_t = R_s + R_l = R_s + \frac{\omega L_s V_{o1}}{\sqrt{E_m^2 - V_{o1}^2}} \tag{6.40}$$

or

$$R_t = \frac{R_s\sqrt{E_m^2 - V_{o1}^2} + \omega L_s V_{o1}}{\sqrt{E_m^2 - V_{o1}^2}} \tag{6.41}$$

Using a similar approach as before, the magnitude of the fundamental of the current I_{m1} can be expressed as

$$I_{m1} = \frac{V_{o1}}{R_t} = \frac{V_{o1}\sqrt{E_m^2 - V_{o1}^2}}{R_s\sqrt{E_m^2 - V_{o1}^2} + \omega L_s V_{o1}} \tag{6.42}$$

The above equation can also be represented by a phasor diagram similar to Figure 6.7(b), the only difference in this case being that the $\boldsymbol{V_{o1}}$ is replaced by ($\boldsymbol{V_{o1} + I_{m1}R_s}$). The phase angle can be obtained from the expression

$$\tan\phi = \frac{\omega L_s I_{m1}}{V_{o1} + I_{m1}R_s} \tag{6.43}$$

The average output current delivered to the constant voltage load and output power can be obtained using a similar approach as in the previous section.

6.4 Experimental validation

To verify the models developed in the previous sections measurements were performed using a 14V, 45A recycled vehicle alternator. The parameters of the alternator are summarized in Table 6.2. Measurement tests conducted on the alternator also made use of the setup described in Chapter 5. The alternator is connected directly to the DC motor, although a speed transmission system will be required for wind application as presented in subsequent section of this Chapter. The alternator battery terminal and the regulator terminal are connected to the positive of a DC power supply in order to supply the required initial field current and to turn on alternator’s control. The battery terminal is the rectified output terminal from the alternator. The DC power supply negative terminal is connected to alternator casing which is connected to ground. Due to high currents that will be measured during the test, the load current is measured indirectly by measuring the voltage drop across a shunt connected in series as shown in the schematics of Figure 6.8.

Table 6.2: Parameters of the automotive alternator

Pole pairs	p	6
Stator resistance	R_s	0.08 Ω
Number of phases	m	3
Stator connection		Y
Output voltage	V_o	14 V
Rated output current	I_o	45 A
Back EMF constant (at I_f = 3.5A)	k	0.017 V-s/A-rad

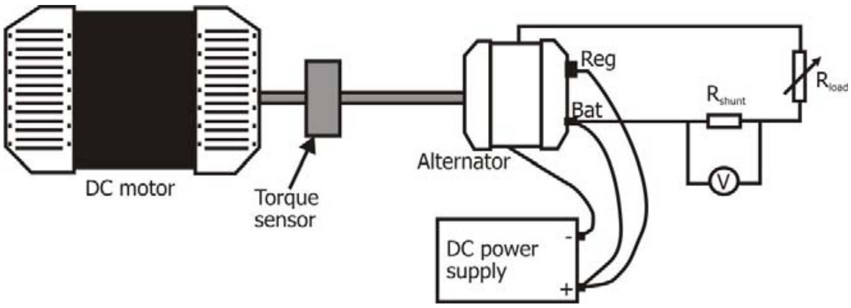


Figure 6.8: Schematics of alternator connection to laboratory measurement setup

6.4.1 Open circuit test

The open circuit test is performed to determine:

- the alternator back-EMF voltages and constant *k*, the magnitude of the back EMF voltage is proportional to the frequency and field current as given in

$$E_m = k\omega_m i_f \tag{6.44}$$

- and, the no load losses (mechanical losses and iron losses).

In this test, the field current is kept constant by supplying an external current of about 3.5A, the alternator is driven over a wide speed range at no load condition while measuring the line voltage, input torque and speed. The measured back EMF constant is given in Table 6.2 while the measured torque and speed gives the no load losses.

6.4.2 Losses and efficiency

The losses that occur in the alternator system are:

- Rotor field losses
- Stator copper losses
- Stator iron losses
- Rotor iron losses in rotor claw poles
- Mechanical losses
- Diode rectifier losses

The copper losses in the stator and rotor can be calculated as

$$P_{Cus} = 3I_s^2 R_s \tag{6.45}$$

$$P_{Cur} = I_r^2 R_r \tag{6.46}$$

The mechanical losses can be expressed as shown below, with one part depending on the bearing and varying proportionally with speed and another part depending on the inbuilt fan and varying with speed to the power of 3 according to [120], [116].

$$P_{Mech} = P_b\left(\frac{n}{n_o}\right) + P_f\left(\frac{n}{n_o}\right)^3 \qquad (6.47)$$

where P_b and P_f are the bearing loss and fan loss at n_o rated speed. The bearing loss and the fan loss are determined using measurement data by solving a set of simultaneous equations based on Equation (6.47). Table 6.3 gives the bearing and fan losses determined from measured mechanical loss data. A plot of the variation of measured alternator mechanical losses with rotational speed is shown in Figure 6.9. The mechanical losses were measured at no-load with no DC excitation supplied to rotor field. The measurement shows that at alternator speed of 2740 rpm, the contributions from the bearing and fan as a percentage of the output power are 6.3% and 2.5% respectively.

Table 6.3: Measured bearing and fan losses at 2740 rpm

Component	**Loss [W]**	**Contribution [% of $^*P_{out}$]**
Bearing loss	38	6.3%
Fan loss	15	2.5%
Total	**53**	**8.8%**

$^*P_{out}$ = 600W

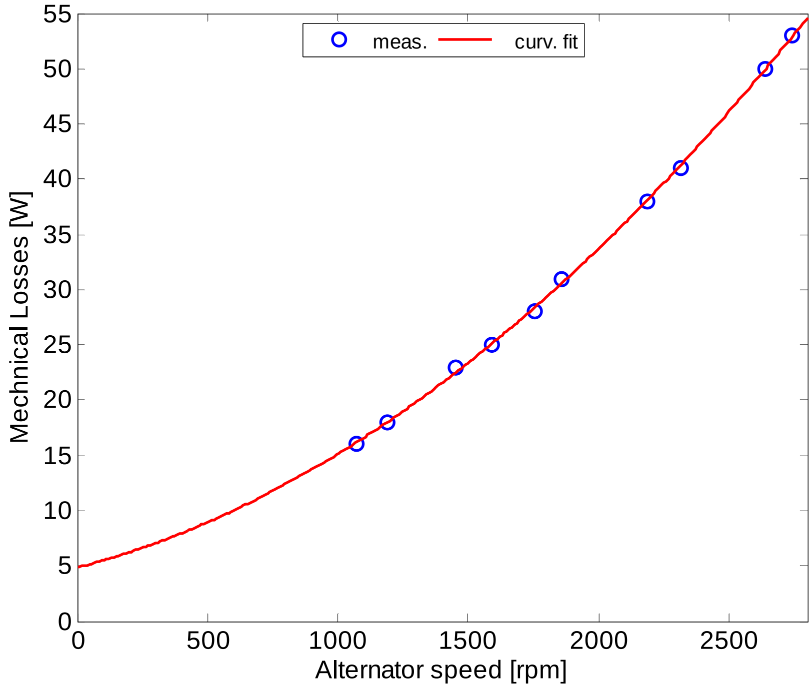


Figure 6.9: Measured alternator mechanical loss variation with rotational speed.

The diode rectifier losses, which are sometimes neglected, may not be insignificant and is calculated as [120], [116].

$$P_{Dio} = 3(\Delta V_{diode} + I_s R_{diode}) I_s \tag{6.48}$$

where ΔV_{diode} is the constant voltage drop (threshold voltage) on a diode, about 0.7V and R_{diode} is the equivalent diode resistance.

The iron losses in the stator and solid claw poles of the rotor are not so easy to model. Slotting harmonics of the air-gap field induce eddy currents into the rotor claws [14]. To calculate iron losses in the stator will also require some information about the laminations used. If this is available, then the iron losses in the stator can be modelled using traditional iron loss models which depends on the flux density and frequency as given in Equations 6.49 to 6.51 [81], [121] – [123].

$$P_{Fes} = P_h + P_e \tag{6.49}$$

$$P_h = k_h f B^{\beta} \tag{6.50}$$

$$P_e = k_e f^2 B^2 \tag{6.51}$$

where

P_h, and P_e are respectively the specific hysteresis loss and specific eddy current loss.

k_h and k_e are respectively hysteresis and eddy current constants, and β is the Steinmetz constant ($1.5< \beta <2.3$), all of which depend on the lamination material.

The total iron losses in the rotor and stator were obtained by recording the difference between the measured no-load input power with and without DC excitation to the rotor field. The iron losses in the stator and rotor P_{Fe} can also be obtained experimentally through separation of losses [116], [124]. That is, by subtracting the output power and sum of other losses from the input power, the total iron losses in stator and rotor is calculated as given in Equation 6.52. To separate the iron losses in stator and rotor, it was found by [120] that the ratio of iron losses (rotor to stator) is about 2:1. With the losses determined, alternator efficiency can be calculated as shown in Equation 6.53.

$$P_{Fe} = P_{in} - P_{out} - P_{Cus} - P_{Cur} - P_{Mech} - P_{Dio} \tag{6.52}$$

$$\eta = \frac{P_{out}}{P_{out} + P_{Cus} + P_{Cur} + P_{Mech} + P_{Dio} + P_{Fe}} \tag{6.53}$$

The measured total iron losses in the stator and rotor obtained through no-load measurement as earlier described are plotted as shown in Figure 6.10. The plot shows that measured iron losses increases steeply at alternator speeds above 2000 rpm. Figure 6.11 shows a plot of the measured loss components variation with alternator speed. Although the field excitation was externally supplied using DC power supply, the rotor losses were included in the plot because the losses still exist in the alternator.

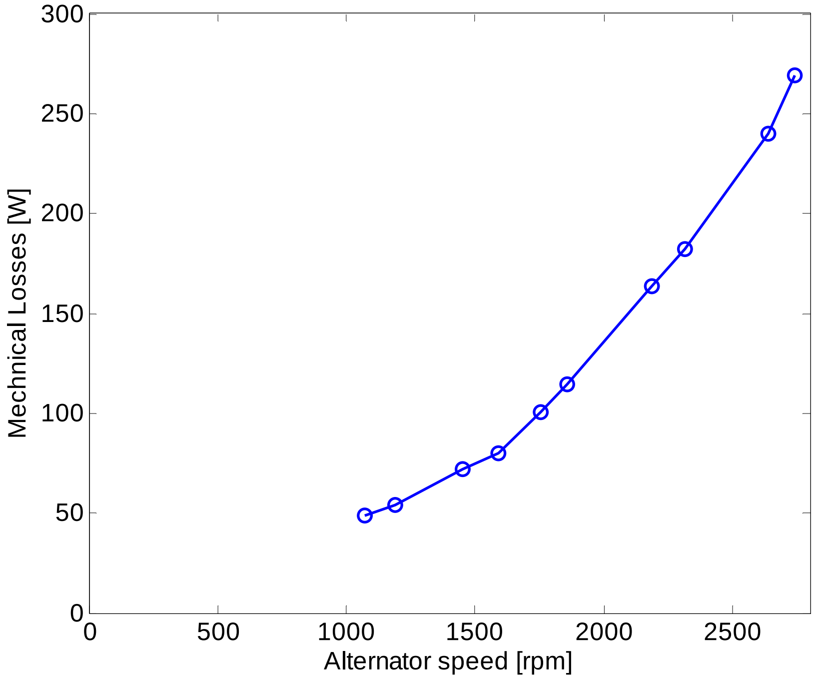


Figure 6.10: Measured alternator total iron losses in the stator and rotor

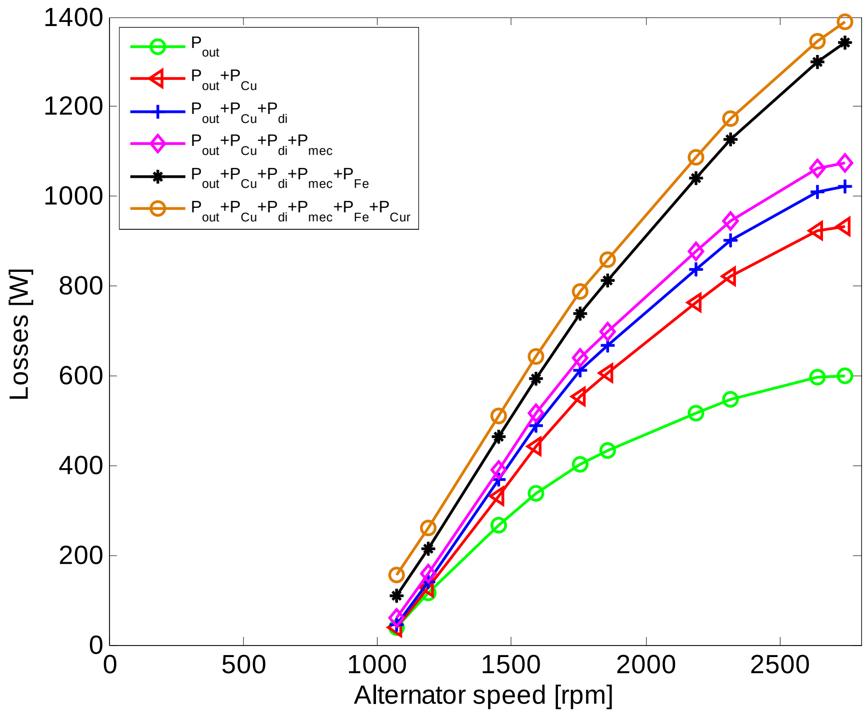


Figure 6.11: Measured variation of alternator loss components with rotational speed.

The major source of losses are the stator copper losses and the iron losses in the stator and rotor claws. These losses increase as the speed and load increases. Table 6.4 gives a breakdown of the losses as a percentage of the output power. The table indicates a similar pattern in terms of contribution of losses compared with what is found in literature [114], [116]. The high contribution of stator copper loss is an indication that when the alternator is used to supply loads greater than 30A (about 400W at 14V DC output) it is accompanied by high losses in the stator copper as shown in Figure 6.11. At high loads the stator winding temperature increases to higher levels, resulting in increased copper losses due to the increasing winding resistance.

Table 6.4: Measured loss components at 2740 rpm (I_f = 3.5A)

Loss component	**Loss [W]**	**Contribution [% of $^*P_{out}$]**
Copper (stator)	332	55.3%
Diode	89	14.8%
Iron (stator & rotor)	269	44.8
Mechanical	53	8.8
Rotor copper	44	7.3
Total	**787**	**131%**

$^*P_{out}$ = 600W

Figure 6.12 shows a plot of the measured alternator efficiency variation with speed (at 14V DC and varying load) for different values of externally supplied field current. The plot shows that the alternator attains its maximum efficiency of about 54% at lower speeds (1300 rpm to 1600 rpm). At higher speeds, the efficiency drops off significantly to less than 45% at 2800 rpm. The alternator is able to attain an efficiency of 54% when supplied with a field current of 3.5A and 3.7A. However, at higher speeds (> 1600 rpm) the alternator is slightly more efficient when supplied with a field current of 3.5A than with 3.7A.

6.4.3 Output power characteristics

Figure 6.13 shows the measured and calculated (using Equation 6.39) output power variation with output voltage. This measurement was performed with the internal regulator of the alternator disabled (the internal regulator keeps the output voltage constant at 14V). A constant field current of 3.5A was supplied to the field windings using a DC power supply. A variable resistor is connected across the alternator terminals for load variation. The speed is kept constant at 1500 rpm while the load is varied. This is repeated for speeds of 2000 rpm and 2500 rpm.

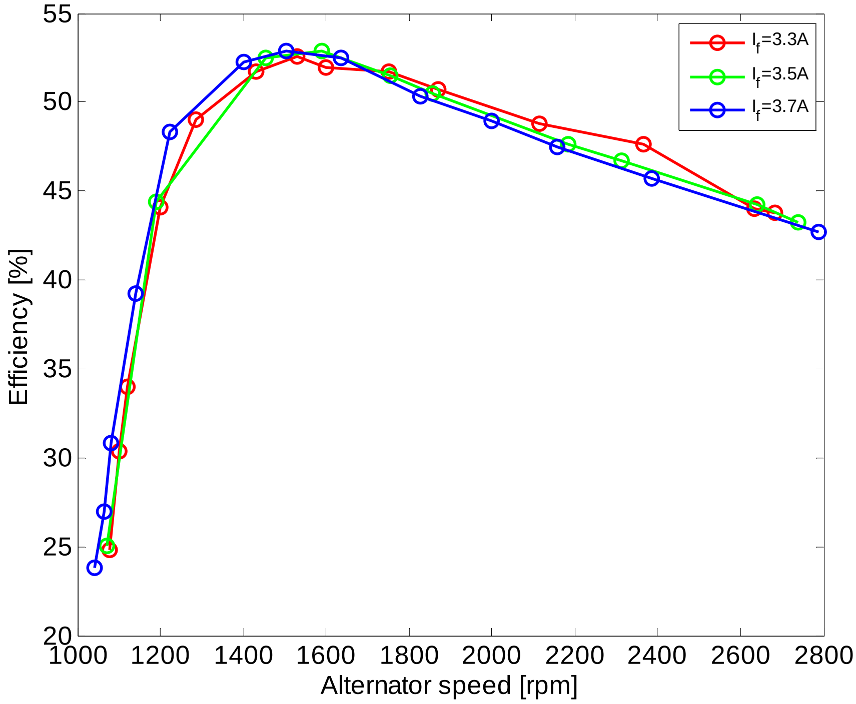


Figure 6.12: Measured efficiency variation with speed for different constant field current values.

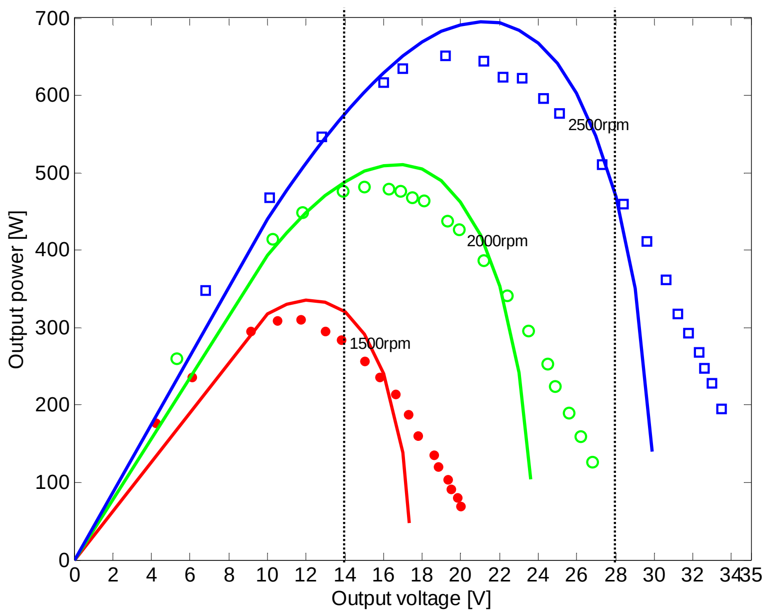


Figure 6.13: Measured and calculated (using Equation 6.39) alternator DC output power variation with output voltage at constant field current of 3.5A.

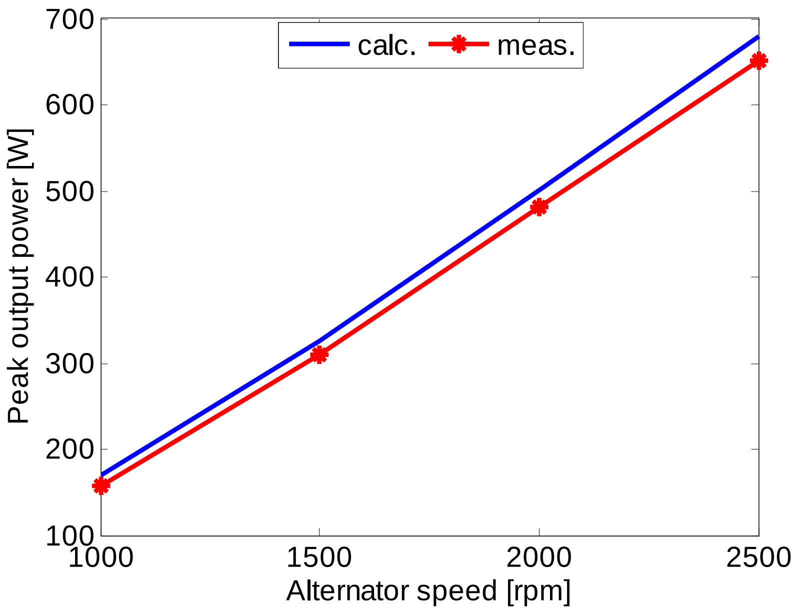


Figure 6.14: Measured and predicted alternator peak output power variation with speed

It can be observed from Figure 6.13 that at high values of output voltage (low load), the output power increases while the output voltage remains nearly constant (right side of each curve) until near maximum power is generated. As the load increases further, the voltage begins to decrease at a faster rate thereby reducing the power until nearly no power is generated at near short circuit.

The plot shows that there is reasonable agreement between the predicted alternator characteristics and measurement near the nominal operating points of the alternator (i.e. close to the peak generated power). However, at near open circuit (right side of each curve) and near short circuit (left side of each curve), the model is not able to accurately predict alternator performance.

At any given speed and output voltage, the output power can be reduced below the value shown in the Figure 6.13 by reducing the field current which in turn decreases the back EMF voltage. The figure also shows vertical (dashed) lines marked 14 V and 28 V intersecting the curves which indicates the DC output voltage system that can be generated at certain speeds. For instance, the dashed line of 28V indicates that this output voltage cannot be generated at 1500 rpm.

For each curve in Figure 6.13, there is a certain output voltage at which maximum output power is achieved. If the maximum power points in the figures are connected by a line it is observed that these point have a linear relationship with the output voltage. A plot of the maximum power variation with speed is shown in Figure 6.14. The plot indicates that the maximum power increases linearly with alternator speed. That is, the minimum speed at which the alternator can generate a given maximum power increases as the output voltages increases.

6.5 Optimization of alternator performance

This section focuses on how the automotive alternator can be optimized for application in small wind turbine. It is shown that the alternator can be optimized for a specific turbine. Therefore, the characteristics of the turbine for which this particular alternator can be used optimally is presented. Measurement tests conducted on the alternator to establish its optimal operating conditions are also presented. In order to improve the energy yield from the alternator integrated to a turbine in battery charging application, the output characteristics of the alternator has to match the turbine output characteristics. The section presents concepts to reduce the poor match over the operating speed range of the turbine and alternator.

6.5.1 Variable and constant field current supply

The field windings of alternators need to be energized by supplying it with an initial field current. In addition to the field excitation that has to be supplied, the alternator's inbuilt controller (regulator) requires a 12V DC voltage to turn on the controls. However, as soon as the alternator attains the speed necessary to generate output voltage, power supply to the field and regulator is not necessary.

The inbuilt controller regulates the output voltage at 14 V by continuously sampling the battery voltage and adjusting the field current accordingly. One option is the variable field operation (the inbuilt regulator is retained) in which the field current supply is varied by the internal regulator depending on the load. When the load increases, the output voltage falls. To keep the output voltage at the required value the regulator varies the field current by increasing the duty cycle of the pulse-width modulated voltage applied to the field winding. And vice versa when the load decreases. If the inbuilt regulator is retained then the same connection is made as in automotive application. That is, the alternator +Bat terminal and the regulator terminal are both connected to a 12 V battery + terminal. In this case a small battery may be included to ensure that DC supply for field excitation is implemented at all times.

An alternative option is the constant field operation (the inbuilt regulator is disabled) where a constant field current is supplied to the field from an external supply. This has the advantage that extra control can be implemented for performance optimization. For instance, a maximum power tracker can be implemented to sample the frequency (and hence the speed) and load the alternator in such a way that it operates at the turbine's maximum power points at any given wind speed. In addition, maximum output power can be generated by supplying full field current.

Measurement tests were conducted to determine alternator performance at three field current values. In this measurement test, the DC output voltage is maintained at a constant value of 14 V by varying the load and the speed. First the field current of 3.3A is supplied to the alternator field winding via a DC power supply. A low load is then connected to the alternator terminals while the speed is gradually increased until the generated DC output voltage reaches 14 V. As the load is then increased, the output voltage falls. The alternator speed is increased until the DC output voltage again reaches 14 V. This is repeated for different loads and speeds while keeping the output voltage at 14 V. Measurements are also taken for field current values of 3.5A and 3.7A.

Figure 6.15 shows a plot of the measured alternator output power variation with speed for three different externally supplied field current values. At a speed of around 1000rpm the alternator begins to generate power. As the speed increases, the output power rises rapidly but begins to level off as the speed increases to about 3000rpm. As the alternator speed increases, power generation is limited by the increase in resistive (I^2R) losses and the increasing impedance of the inductance *(L_s)* as both the current and frequency increase. The speed at which the generated output power remains nearly constant with further increase in speed decreases with supplied field current. When the field is supplied with higher current, more power is generated. However, increasing the field current from 3.5A to 3.7A results in no significant increase in output power.

6.5.2 Choice of turbine

The performance of the alternator in wind turbine application depends on the characteristics of the turbine which is integrated with the alternator. The power output from a turbine depends, among other things, on the power coefficient (C_p) and wind speed of the site as presented in Chapter 3 of this thesis. A realistic maximum C_p value for small wind turbines is about 30% as presented in Chapter 3. This knowledge guided the plot of the c_p-λ curve.

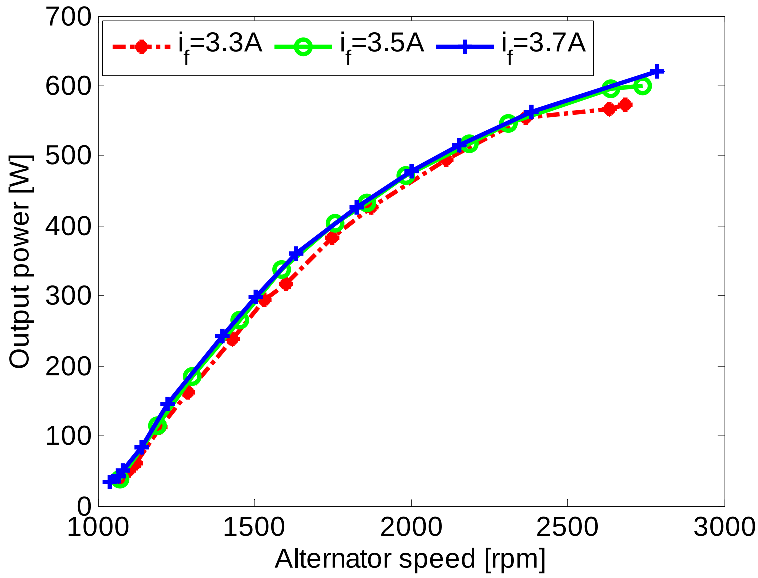


Figure 6.15: Measured output power variation with speed for different field current values.

Figure 6.16 shows a c_p-λ curve (i.e. power coefficient variation with tip speed ratio) for a certain wind turbine. This turbine has an optimum c_p value of 30% at a tip speed ratio of 6. The c_p-λ curve was plotted using numerical approximations similar to those developed in [125] – [127]. The approximation used for this plot is given as

$$c_p = 0.42\left(85\lambda_i - 0.9\theta - 5.3\right)e^{(-16\lambda_i)} + 0.00068\lambda \tag{6.54}$$

with

$$\lambda_i = \frac{1}{\left(\lambda + 0.08\theta\right)} - \frac{0.035}{\theta^3 + 1} \tag{6.55}$$

The tip speed ratio is defined as [52]

$$\lambda = \frac{\omega R}{v_w} \tag{6.56}$$

where ω is the mechanical speed (in rad/s) of the turbine, R is the turbine radius and v_w is the wind speed.

For a given turbine diameter, the predicted c_p-λ characteristics can be used to obtain the turbine's output power for several wind speeds as shown in Figure 6.17. This plot shows the output power of a 3.9 m diameter turbine using the c_p-λ curve of Figure 6.16 for wind speeds of 3.5 m/s up to 8 m/s at a fixed pitch angle θ (fixed pitch turbine). For a given wind speed, the output power increases as the turbine's speed increases to a point where maximum power is delivered. That is, as the tip speed ratio increases the turbine speed increases according to Equation 6.56 while the c_p also increases according to Figure 6.16 and Equation 6.54.

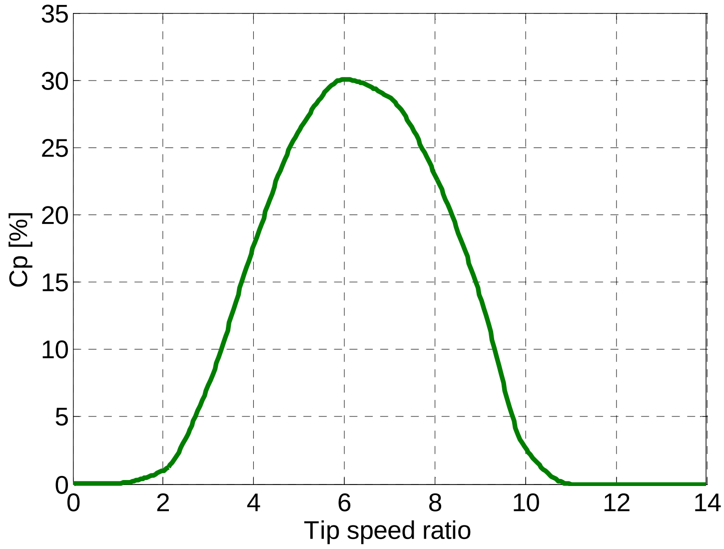


Figure 6.16: Analytical predictions of c_p-λ characteristics for a particular turbine.

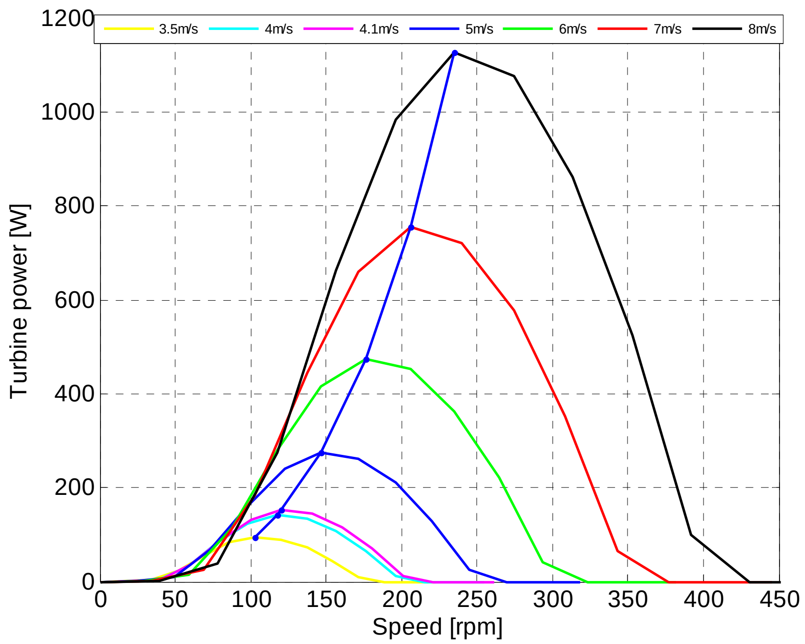


Figure 6.17: Turbine output power variation with speed using predicted c_p-λ characteristics.

Therefore, for each wind speed there is a certain turbine speed at which the turbine produces maximum power, which corresponds to the optimum c_p value of about 30%. The maximum power points of the turbine are indicated by dots on each curve of Figure 6.17. The points can be connected together to form the turbine's maximum power variation with wind speed.

A turbine rotating at low speeds will allow the wind to pass through the blades undisturbed without capturing much of the energy from the wind. At such low speeds very little power is generated because the c_p is also very low. A turbine rotating at very high speeds will appear as a solid barrier to incoming wind, again ensuring that very little energy from the wind is captured by the turbine due to turbine operation away from its optimum c_p value. At speeds greater than that at which maximum power occur, the tip speed ratio is greater than its optimum value.

In battery charging system with uncontrolled diode bridge rectifier, the turbine will accelerate or decelerate as necessary to balance the turbine input power and the alternator input power [128]. If the alternator power curve rises too rapidly, the turbine rotor will stall due to turbine operation at low tip speed ratio. Similarly, if the alternator power curve rises too slowly, the turbine rotor will over speed as it operates at high tip speed ratio [129]. In both cases, the system performance is degraded due to loss of power. Therefore to obtain good performance from the turbine system it is required that the alternator power curve be closely matched to the turbine output power curve.

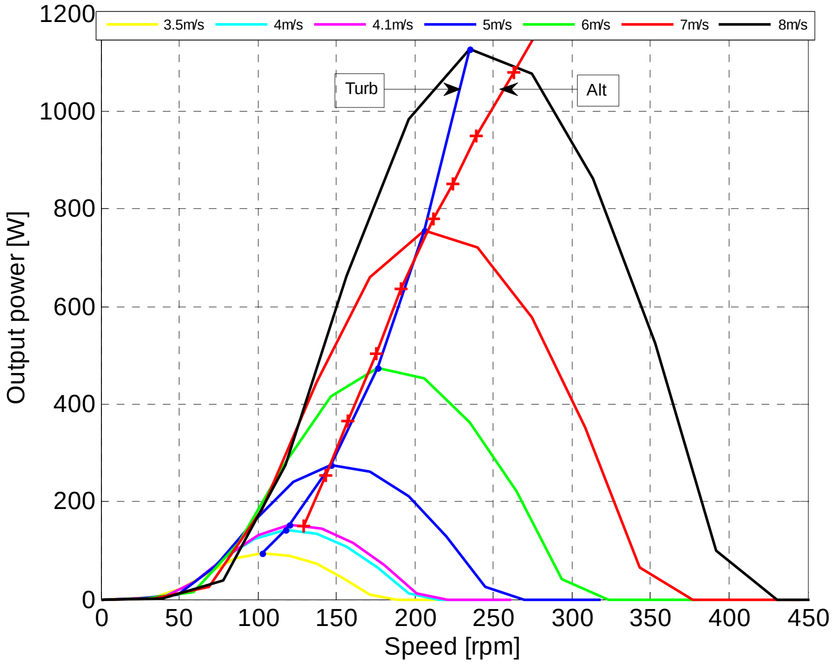


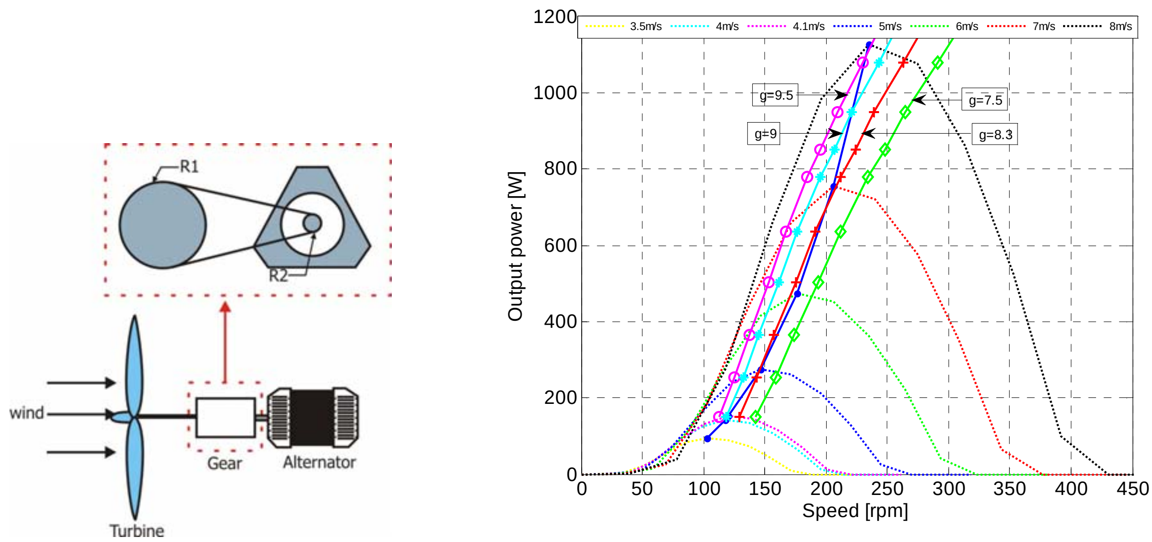
Figure 6.18: Turbine output power and measured alternator input power variation with speed.

The operating power curve of the alternator can be obtained by the intersections between the turbine output characteristics and the alternator input power variation with speed as shown in Figure 6.18. In this figure, *Alt* represents the measured input power supplied to the alternator (at a field current of 3.5A) which resulted in the output power curve of Figure 6.15. A transmission system with gear ratio of 8.3 was used to adapt the alternator speed to the turbine speed. The alternator input power is used because in wind application, the output power from the turbine is the input power to the alternator. If the wind turbine is to operate at the optimal power points, the turbine output power should match the alternator input power such that the output power from the turbine generating system will be equivalent to the plot of Figure 6.15.

In Figure 6.18, the turbine was selected to achieve the best possible match between turbine and alternator. At a wind speed of 4.1m/s using a turbine diameter of 3.9m, the maximum output power of the turbine is 111W at a turbine speed of 120 rpm and optimum c_p and λ values of 30% and 6 respectively. However, at this wind speed, the alternator input power is 110W at a speed of 130 rpm. The turbine will rotate faster to balance this power: the tip speed ratio increases while c_p decreases as the turbine operates away from its optimum c_p-λ values. The new operating point in the c_p-λ curve is calculated to be 29.7% and 6.5 which is still close to the optimum. At the rated wind speed of 8m/s, the alternator input power is 1090W at a speed of 260 rpm while the turbine produces it maximum output power of 1126W at this wind speed while rotating at a speed of 240 rpm and optimum c_p and λ values. Again, the turbine has to accelerate to balance this power by operating at new c_p-λ values of 29.6% and 6.6. At wind speeds of 5 to 7 m/s, alternator input power closely matches the maximum turbine output power curve, ensuring it operates at its optimum c_p-λ values. Therefore, by careful selection of turbine characteristics the alternator performance can be optimised for a given wind turbine.

6.5.3 Choice of gear ratio

Automotive alternators require high speeds before any output can be generated. The alternator used in this research requires a minimum of about 1070 rpm before generating output power at 14 V DC output voltage. It is obvious that for small wind turbine application, a direct-drive topology is not suitable with this alternator. In automotive application a belt system is also used with ratio of 2:1 to 3:1 relative to the engine speed for small vehicles and gear ratio up to 5:1 in large utility vehicles. For wind application, the difference between the pulley diameters at the turbine end and alternator need to be larger to achieve required gear ratio. This type of speed transmission was selected as the existing skills for such a system, as used in vehicles, can be utilized for our application. The selected gear ratio to achieve optimum match between the turbine shaft speed and alternator speed is 8.3 using belt and pulley system. The effect of some gear ratios on the turbine power output versus wind speed is shown in Figure 6.19.



(a) (b)

Figure 6.19: (a) Proposed speed transmission system, and (b) choice of gear ratio

6.6 Comparison of Energy Yield

In this section, the energy yield from the two generator concepts presented in this thesis are compared with that of commercially available systems. First the turbine used for the vehicle alternator system is introduced. Next, the energy yield from this system is compared with values for the axial flux PM generator of Chapter 5, as well as some commercially available systems presented in Chapter 3 for a site with average wind speed of 3.7m/s.

Table 6.5 gives the characteristics of the selected turbine used for the energy yield prediction of the vehicle alternator. The output power from this system is the measured alternator output power as presented in the previous sections. In order to simplify the energy yield prediction, it is assumed that the control of the turbine is such that the output power is kept constant at the rated value above rated wind speed. In reality most small wind turbines are furling controlled using a tail vane for yaw control.

Table 6.5: Wind turbine characteristics for the vehicle alternator system

Rated output power (kW)	1.126
Rotor diameter (m)	3.9
Rated wind speed (m/s)	8
Rated speed (rpm)	240
Optimum tip speed ratio	6
Maximum aerodynamic efficiency (%)	30
Mass density of air (kg/m^3)	1.225

At higher wind speeds, the turbine output power can go above the limit of the alternator or the wind turbine design. To mitigate against this, small wind turbines use mechanical control (furling) to turn the rotor out of the wind resulting in a decrease in the aerodynamic power or a steep drop in the power curve [130]. Typically, the tail vane is hinged, allowing the turbine rotor to furl (turn) in high winds thereby providing both power regulation and over speed protection. Above the rated wind speed, the power curve of a furling controlled turbine is often “peaky”, and not constant as assumed in this analysis since the turbine rotors can furl abruptly at wind speeds slightly less than rated. This results in an energy yield which is lower than the value presented here.

In Chapter 3, we presented the energy yield from a turbine as dependent on the output power versus wind speed characteristics, the wind speed and wind variation of the site. The wind variation in most areas can be described by the Weibull distribution which depends on the measured average wind speed of the site. In Chapter 3, we used an average wind speed of 3.7m/s which is the measured average wind speed in the first year of the field test of some commercially available small wind turbines at Schoondijke, the Netherlands.

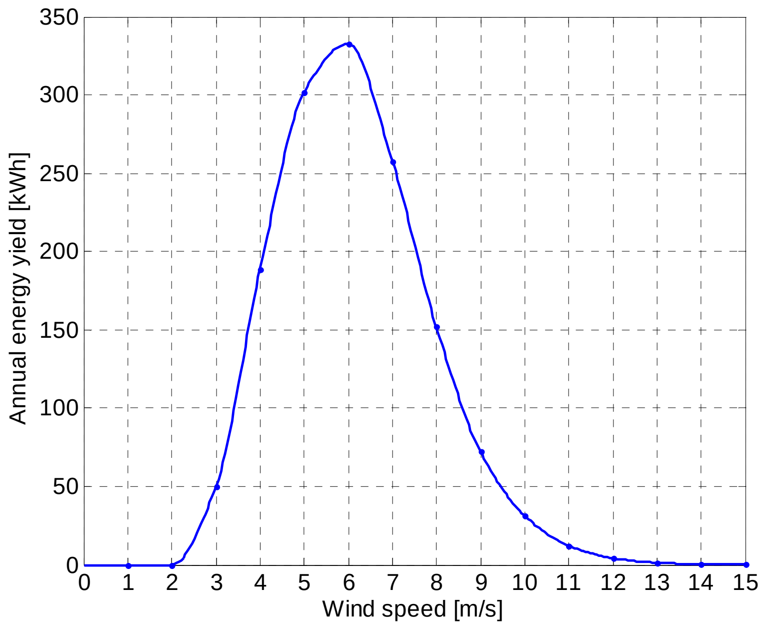


Figure 6.20: Annual energy yield variation with wind speed for the alternator system in a site with average wind speed of 4.0m/s.

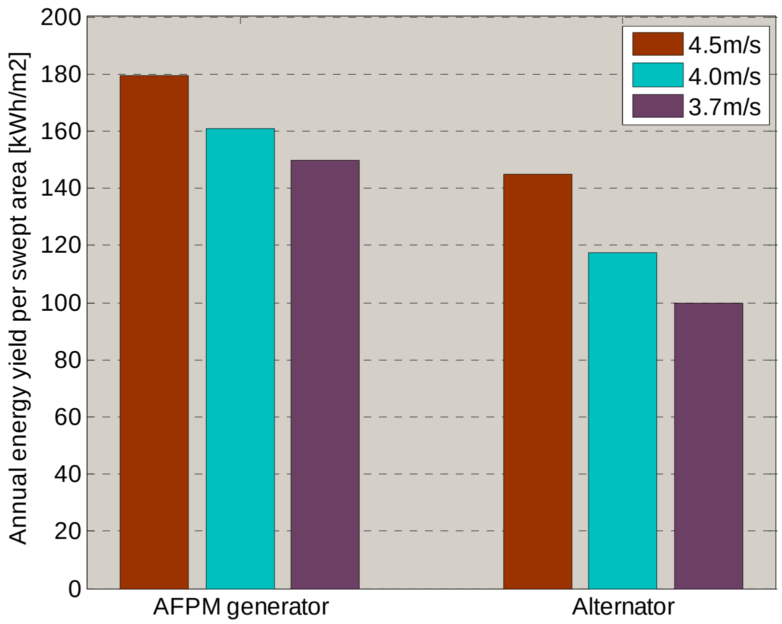


Figure 6.21: Comparison of annual energy yield per swept area of the axial flux PM generator and alternator systems for three sites with different average wind speeds of 4.5, 4.0 and 3.7 m/s. Turbine diameters of 2.5m and 3.9m were used for the axial flux PM generator and alternator systems respectively.

However, it is worth mentioning that if this alternator is sited in such a low wind speed area, the energy yield will be very low as it will experience frequent *start-stop* due to starting problems [10] as explained in Chapter 3. A site with a higher average wind speed is preferred to ensure that higher wind speeds occur for significant percentage of the time. Figure 6.20 shows the turbine's annual energy yield variation with wind speed for the alternator system in a site with average wind speed of 4.0 m/s. This plot was obtained by multiplying the output power at a given wind speed with the Weibull wind distribution for a period of 1 year (T is 8760 hours). Therefore, the annual energy yield at a given wind speed is the generated electricity by the turbine if the turbine operates at that particular wind speed for a year.

To ensure a fair comparison of the energy yield, losses in the transmission system and main bearing are included. The vehicle hub bearing used in Chapter 5 for the manufactured prototype axial flux permanent magnet generator is proposed as the main bearing to connect the automotive alternator to the turbine via the speed transmission system. In Section 5.8 the bearing loss at 300 rpm using our proposed vehicle hub bearing was calculated to be 24 W. The bearing loss is then modelled as being proportional to speed as given in Equation 5.25. Efficiencies of between 90% and 98% are reported for various systems using belts with 95% being a typical value [131. In this analysis, speed transmission efficiency of 95% is assumed.

The sum of the annual energy yield at different wind speeds (area under the curve of Figure 6.20) site is the turbine's total yearly energy production for the given site. In Chapter 3, we introduced the annual energy yield per swept area as a figure of merit for comparison of small wind turbine performance. The annual yield per swept area was obtained by dividing the total annual energy production by the rotor swept area.

Figure 6.21 shows a comparison of the annual energy yield per swept area of axial flux PM generator and alternator systems for three sites with average wind speeds of 4.5, 4.0 and 3.7 m/s. Note that the turbine used for the axial flux PM generator system is a 2.5m diameter turbine which is smaller than the 3.9m diameter turbine introduced for the vehicle alternator system. The rationale for the use of a turbine with smaller diameter is due to the absence of cogging in the axial flux PM generator, and its lower output power and higher efficiency compared with the vehicle alternator.

As expected, the axial flux PM generator performed better in terms of the annual energy yield per swept area. In a site with low average wind speed of 3.7m/s, the annual energy yield per swept area of the axial flux PM generator was 50% higher than the alternator system. This is probably due to the absence of cogging in the axial flux PM generator which enables power generation at low wind speeds. However, as the average wind speed of the site increases, the difference between the annual energy yield per swept area of the two systems reduces. At average wind speeds of 4.0m/s and 4.5m/s, the annual energy yield per swept area of the axial flux PM generator is respectively 36% and 23% higher than the alternator system.

Table 6.6 also gives a comparison of the energy production of the two generator concepts with six commercially systems presented in Chapter 3 for a site having an average wind speed of 3.7m/s. The table shows that the annual energy yield per swept area of the axial flux PM generator is comparable with the best performing commercially available turbine. The performance of the vehicle alternator system is also comparable with many commercially systems. It is worthy to mention that considering the inherent advantages of the vehicle alternator such as availability of components and skills for maintenance, as well as its cost effectiveness, this concept proved to be a viable option for small wind application.

Table 6.6: Comparison of energy yield of generator concepts with commercially available small wind turbines for a site having average wind speed of 3.7m/s.

Turbine	Diameter [m]	Swept area [m^2]	Annual yield [kWh]	Annual yield per swept area [kWh/m^2]
AFPM generator	**2.5**	**4.91**	**735**	**150**
Automotive Alternator	**3.9**	**11.95**	**1191**	**100**
Fortis Montana	5	19.64	2691	137
Fortis Passaat	3.12	7.65	578	76
Zephyr Airdolphin	1.8	2.54	393	155
Ampair	1.7	2.27	245	108
Swift	2.08	3.40	243	71
Turby*	2	5.3	266	50

*Vertical axis turbine. Others are horizontal axis turbines

6.7 Design improvements

The measurement tests conducted revealed that the alternator is characterized by high losses particularly at high loads which degrades the generated output power. This section presents some design improvements to improve alternator efficiency. These improvements are not necessarily for small wind application but for automotive alternators in general. Therefore, the proposed design improvements in this section may not lead to a low cost solution.

1) Increase the DC Bus voltage from 14V to 28 or higher. At a speed of about 2700 rpm, stator copper losses contributed over 55% of total losses. If the DC bus is increased, the efficiency will also increase since the stator current, and hence stator copper losses, will decrease.

2) Increasing the output voltage from 14V to 42V will also decrease the per unit diode rectifier loss because the voltage drop (~1V) across the diodes will not be significant compared with an output voltage of 42V.

3) The present alternator system has a modest slot fill factor, usually less than 30% [116]. The slot geometry reveals that more copper can be added to improve the slot fill factor and increase the generated voltage.

4) The use of thinner laminations. Iron losses in the stator and rotor constituted about 45% of the total losses at 2740 rpm. Eddy current losses in the stator vary with the square of the lamination thickness as given in [132]. The present alternator uses laminations which are about 0.5mm thick. Reducing the lamination thickness will reduce the stator iron losses and increase alternator efficiency.

5) Use of soft magnetic composites for the manufacture of alternator claw poles. In literature, the ratio of rotor and stator iron losses is 2:1 [120]. Reducing the eddy current losses in the rotor claws will significantly reduce total iron losses and improve alternator efficiency. Although, soft magnetic composites generally have higher hysteresis losses compared with conventional silicon-iron laminations or solid steel, they also have lower eddy current losses as stated in Section 4.4.2. Therefore, eddy current losses in the rotor can be reduced significantly by using soft magnetic composite material compared with solid steel, especially at high speeds where eddy current losses could become dominant. However, the use of such material will likely reduce the mechanical ruggedness of the alternator.

6) The use of assisting permanent magnets. Permanent magnets can be added between the rotor claws. The included permanent magnets increase the excitation provided by the rotor field windings. They also act to destroy the interclaw excitation leakage flux of the field coil and, thus, enhance the main flux [116], [132]. However, the mechanical placement of the permanent magnets between claws and its structural integrity are not easy to secure [116].

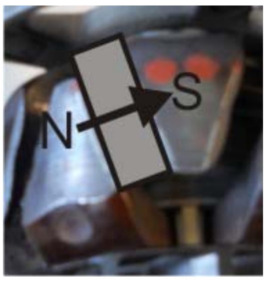


Figure 6.27: Assisting PMs between rotor claws

7) The rotor can also be replaced with permanent magnets which eliminates rotor field losses and reduces rotor eddy current losses as already proposed in [115].

6.8 Conclusions

The concept of adapting an automotive alternator as generator for small wind turbine application was presented. It was shown how such a system can be integrated to a turbine using a speed transmission system with a gear ratio of 1:8.3. The following are the concluding remarks from this chapter:

1. The use of vehicle alternator for small wind turbine application is attractive for a 14 V DC output system.

2. If the alternator is to be used for higher output voltage such as 28 V or 42 V, the alternator's internal regulator have to be bypassed. Furthermore, as the desired output voltage increases, the minimum speed required to generate some output also increases.

3. Direct-drive implementation of alternator for wind turbine application is highly unlikely due to its high speed requirements. A minimum speed of about 1000 rpm is required to generate any output from the alternator at 14 V output voltage.

4. The alternator field winding need to be energized by supplying it with an initial field current. A small 12 V battery of a few ampere-hours can be used for this purpose.

5. Measurement tests to validate predicted output power of a typical vehicle alternator shows that at 2500 rpm, measured alternator output power was about 600 W at 14 V DC.

6. Although the efficiency of the alternator is generally low, its maximum efficiency of about 54% occur at low speeds (about 1500 rpm) which is advantageous for our application where low speeds occur more often. At higher speeds, the efficiency drops off significantly to about 45% at 2500 rpm.

7. It was shown that optimization of alternator performance by the selection of suitable turbine parameters and gear ratio is an effective method of achieving good matching of the turbine characteristics with alternator. The alternator performance was therefore optimised for 3.9 m diameter turbine using a belt and pulley system.

8. Results from a comparison of the energy yield per swept area showed that for low wind speed areas the axial flux PM generator system performed significantly better than the vehicle alternator system. In a site with an average wind speed of 3.7m/s, the annual energy yield per swept area of the axial flux PM generator was 50% higher than the alternator system.

9. However, as the average wind speed of the site increases, the difference between the annual energy yield per swept area of the two systems reduces. For instance, at average wind speeds of 4.0m/s and 4.5m/s, the annual energy yield per swept area of the axial flux PM generator is respectively 36% and 23% higher than the alternator system, showing that the vehicle alternator system is competitive for areas with average wind speeds of 4m/s or higher.

10. The energy yield per swept area of the axial flux PM generator (for a 2.5m diameter turbine) and vehicle alternator (for a 3.9m diameter turbine) were found to be 150kWh/m^2 and 100kWh/m^2 respectively, for a low wind speed site with average wind speed of 3.7m/s. For the axial flux PM generator, this value is comparable with the best performing commercially available system, while the performance of the vehicle alternator system is also comparable with many commercially systems.

11. Design improvements were proposed to improve alternator output performance such as increasing the DC bus, the use of thinner stator laminations, improving the slot fill factor, the use of assisting permanents between rotor claws and replacing the rotor with permanent magnets.

Chapter 7

Conclusions and Recommendations

The research summarized in this thesis aims to develop suitable low cost generators for small wind turbine application. A low cost generator solution is necessary to make small wind turbines an attractive option for remote areas of developing countries which are considered areas with the greatest potentials for such systems.

To fulfil this objective, this thesis addressed three major problems identified as being responsible for the continued low penetration of small wind turbines in developing countries:

1) high cost of current systems;
2) maintainability of systems;
3) energy yield and low wind speed operation.

Chapter 2 of this thesis analysed some renewable energy projects and identified major reasons for the failure of projects implemented in developing countries as high cost of systems and lack of skills for maintenance, thereby highlighting problems 1) and 2).

Chapter 3 analysed the performance of commercially available systems in low wind speed areas in terms of their energy yield and cost, thereby highlighting problem 3. Due to large discrepancies in the energy yield predicted by the manufacturers and measurement, a method to obtain the turbine's coefficient of performance was proposed to achieve good match.

To address the high cost and maintainability of systems, Chapter 4 proposed to manufacture generator systems in a small workshop. A comparison of the manufacturability and manufacturing cost of selected generator configurations was presented. From Chapter 4 onward, the scope of the thesis was limited to the generator used in small wind turbines.

Chapter 5 described the design, manufacture and performance of a prototype generator using the configuration with the best manufacturability and least cost of manufacture as proposed in Chapter 4. Generator manufacturability and low cost capability was demonstrated. Measurement results obtained demonstrated the performance of the prototype generator and the effect of design choices on generator performance.

Chapter 6 proposed the use of automotive claw pole alternator to achieve cost reduction and maintainability. This concept was also proposed to address the problem of availability of materials, which is a major limitation of the manufactured prototype generator. The applicability of this generator in wind was demonstrated. The energy yield from this system was compared with manufactured generator and with existing systems described in Chapter 3.

In this chapter, conclusions are drawn from the work presented in this thesis and recommendations are made for future research.

7.1 Conclusions

The conclusions of this thesis are presented in this section with respect to the identified problems and challenges to the implementation of renewable energy systems and small wind turbines in developing countries, and how each problem was addressed in the thesis. Chapter 2 highlighted the reasons for the failure of renewable energy systems in developing countries while Chapter 3 highlighted the effects of low wind speed operation of small wind turbines. The conclusions drawn from these two chapters are first presented which were the problems addressed in this thesis. Next, the conclusions pertaining to how each identified problem was addressed in the thesis are discussed in subsequent sub sections.

7.1.1 Renewable energy systems and developing countries

The thesis identified several reasons for the poor performance of renewable projects in developing countries. The case studies investigated showed that the present cost of renewable energy systems are mostly beyond the reach of poor rural people, even with a credit scheme that makes funds available at low interest rates. Perhaps, the greatest reason for lack of long term success of renewable energy projects in developing countries is technical challenges. Installing renewable energy system such as small wind turbines in rural areas comes with the added challenge of system maintenance because required skills for performing such maintenance are mostly not available.

From the study of reasons for the failure of renewable energy systems, the following conclusions were made:

- Cost have to be lowered so that rural population can afford renewable energy systems;
- Development of technical skills is imperative to increase knowledge about the technology; in addition, simplification of systems is also necessary for good operation;
- To achieve cost reduction, promote local economy and industry, system components need to be manufactured locally;
- The socio-cultural environment should be taken into account in project design;
- Entrepreneurship and good business model will increase project sustainability;
- Community participation is key to renewable energy project success in developing.

7.1.2 Small wind turbines in low wind speed areas

This thesis investigated the operation of small wind turbines under low wind speed condition and the energy yield of the turbines under these conditions. The study showed that there is the need for small wind turbine manufacturers to pay attention to low wind speed operation of systems since it is sited mostly in low and moderate wind climates. Low wind speed operation has consequences on the energy yield of the turbines due to difficulties in turbine starting, which are exacerbated by the presence of cogging in the generator.

Comparison of the annual energy yield showed that most systems failed to meet the performance stated by the manufacturers. In at least two systems, calculated annual energy yield was higher than measured values from field test by more than a factor of two.

The major conclusions drawn with respect to cost of generated electricity and energy yield of commercially available small wind turbines in a low wind speed area are given below.

- To improve energy yield from the turbine, optimization of small wind turbine operation for low wind speeds is required. The thesis demonstrated that turbines that performed well in terms of annual energy yield per rotor swept area (high kWh per m^2) were mostly those with low cut-in wind speeds.
- A realistic maximum coefficient of performance of small wind turbines is about 30%. The thesis showed that turbines with coefficient of performance values significantly higher than 30% had large differences between measured and predicted energy yield while turbines with coefficient of performance values close to 30% had acceptable differences.
- Accurate prediction of the turbine's annual energy yield for a given operating condition can be achieved by deriving a good estimate of the coefficient of performance using measured annual energy yield. The usefulness of this approach was demonstrated in the thesis.
- The cost of systems is considered so high that it makes the implementation of small wind turbines in developing countries prohibitively expensive without external subsidy. Compared with large wind turbines, the cost of generated electricity (€ per kWh) of the most cost effective small wind turbine is higher by a factor of 7.

In the ensuing subsections, the conclusions pertaining to how the identified problems and challenges were addressed in the thesis are discussed.

7.1.3 Choice of generator

Two generator concepts were proposed in this thesis to address the previously identified challenges and problems. The motivation for the selected generator concepts include: simplicity, cost reduction, manufacturability and maintainability, availability of components and skills for maintenance. The proposed generator concepts are the axial flux permanent magnet generator with air cored stator using the concept made popular by Hugh Piggott, and the automotive alternator with minor modifications. The simplicity of construction of AFPM generator in a small workshop and its low manufacturing cost was demonstrated in this thesis. The applicability of the automotive alternator concept to a small wind turbine was also demonstrated in this thesis.

The following conclusions were made regarding the proposed generators for small wind turbine application in developing countries.

- The penalty paid by the use of the vehicle hub bearing is a bearing loss of 49W (or 90% of no-load losses) at 300rpm. It was shown that the use of a hub bearing with smaller inner diameter will reduce the bearing losses and improve generator efficiency. For instance, it was shown that if a bearing with half the diameter of the previous unit was used, the bearing losses will reduce by half while generator efficiency will increase to 87% at 300 rpm.
- One major difference between coreless and slotted machines is that eddy currents are induced in the stator conductors of a coreless machine since the stator windings are exposed to the magnetic field from the permanent magnets. The loss contribution due to eddy currents in stator conductors was quantified through measurement and calculation. It was shown that the loss contribution from stator eddy currents is not significant: at 300 rpm this loss is just 4W, which is about 7% of the total no-load losses.
- Optimization of the AFPM generator design can lead to a generator which is 36% lighter, €9 cheaper and 12% more efficient than manufactured prototype.
- The use of the present automotive alternators for small wind turbine application is suitable for 14 V DC system as it works well for low alternator speeds. Measured results shown in this thesis demonstrated that as the desired output voltage increases, the minimum speed required to generate some output also increases. For instance, we showed that an output voltage of 28 V DC cannot be generated at speeds less than 1500 rpm.
- The alternator attains maximum efficiency (about 54%) at low speeds which is suitable for small wind turbine application where low and medium wind speeds are predominant and high wind speeds are rare. The thesis demonstrated that at 14 V DC and 1500 rpm, the measured output power from this alternator was about 300W at an efficiency of 54%. At a higher speed of 2500 rpm, measured output power increases to 600W (at 14V DC) while the efficiency drops to 45%.
- Optimization of alternator performance by the selection of suitable turbine parameters and gear ratio was found to be an effective method of achieving good matching of the turbine characteristics with alternator. For a 3.9m diameter turbine, the selected gear ratio to achieve optimum match between the turbine shaft speed and alternator speed is 1:8.3 using a belt and pulley system.

7.1.4 Manufacturability and maintainability

A motivating factor for the choice of selected generator concepts was manufacturability and maintainability of the system. The AFPM generator was selected because of its manufacturability in a small workshop. On the other hand, the automotive alternator was selected because of its maintainability in a small workshop.

The following conclusions were drawn with respect to manufacturability and maintainability of generator concepts.

- The AFPM generator concept has good manufacturability: it can be built in a small workshop using short and uncomplicated process, basic tools and easily available materials, resulting in a low cost solution.
- The manufacture of the AFPM generator components encourages community participation thereby increasing source for family income and acceptability. This is a key advantage in terms of achieving sustainable renewable energy development in developing countries.
- The automotive alternator requires a gear system for coupling to the turbine. In this thesis, we proposed the use of a belt and pulley system which is comparable to the system connecting the alternator to the crankshaft in automotive application.
- The automotive alternator concept has good maintainability due to the availability of skills for maintenance which have been established over the years even in rural areas of developing countries.

7.1.5 Energy yield

The air cored stator of the AFPM generator eliminates stator iron losses and cogging which improves generator efficiency and turbine starting at low wind speeds. Therefore, this generator concept is an excellent choice for small wind turbine in low wind speed areas. Although the automotive alternator has stator slots and hence cogging, it attains its highest efficiency at low rotational speeds which is desirable for small wind turbine application.

From the comparison of the energy yield of the proposed generator systems, as well as commercially available systems, the following conclusions were made.

- As expected, for low wind speed application the AFPM generator performed significantly better than the automotive alternator system. This thesis demonstrated that in a site with annual average wind speed of 3.7m/s, the generated annual energy yield per swept area of the AFPM generator was 50% higher than the alternator system.
- The automotive alternator system becomes increasingly competitive with the AFPM generator for areas with annual average wind speeds of 4m/s or higher. It was shown that at an annual average wind speeds of 4.0m/s and 4.5m/s, the annual energy yield per swept area of the AFPM generator is respectively 36% and 23% higher than the alternator system.
- The energy yield from the AFPM generator is comparable with the best performing commercially available system. It was shown that for a 2.5m diameter turbine, the annual energy yield per swept area of the AFPM generator was 150kWh/m^2 for a low

wind speed site with average wind speed of 3.7m/s, compared with 155kWh/m^2 for the best performing commercially available turbine.

- The energy yield from the automotive alternator system is also comparable with many commercially available systems. The thesis showed that for a 3.9m diameter turbine, the annual energy yield per swept area was 100kWh/m^2 for a site with average wind speed of 3.7m/s, which was higher than at least 50% of the commercially available turbines used in the analysis.
- The AFPM generator and the automotive alternator concepts are suitable low cost generators for small wind turbine application in developing countries. On one hand the performance of the AFPM generator demonstrated its suitability particularly for low wind speed areas. On the other hand, there is a possibility that if the automotive alternator system is sited in low wind speed areas, the energy yield could be worse as the turbine may experience frequent *start-stop* due to starting problems. The thesis proposed that this system should be sited in areas with higher average wind speed to ensure that higher wind speeds occur for significant percentage of the time. However, this is not a requirement since wind is free and the alternator is a low cost system with several inherent advantages.

7.2 Thesis contributions

The main contributions of this thesis can be summarized as follows:

1) This thesis has broadened ideas for sustainable renewable energy implementation in developing countries. We showed that the key to a successful implementation of renewable energy technology in rural communities is *Community Participation*. The thesis proposed the following community-based conceptual framework for renewable energy project implementation:
    - There is a relationship between long term sustainability and the needs being served which can be effectively assessed through community participation.
    - Community participation in evolving appropriate and sustainable technical options can help develop local skills and build competencies and capacities within the community.
    - Community-based ownership structure can lead to high acceptance because the projects are owned by the people themselves.

2) Insight into the influence of low wind speeds on the performance of small wind turbines is provided. In this thesis, we showed that low wind speed operation has consequences on the energy yield of small wind turbines due to starting problems. Turbines that performed well in terms of annual energy yield per rotor swept area were

those with low cut-in wind speeds. Furthermore, realistic coefficient of performance of small wind turbines in low wind speed areas is a value less than 30%.

3) The thesis proposed the use of an axial flux permanent magnet generator with air cored stator to address the limitations of existing systems such as manufacturability, and high cost, and to achieve sustainable small wind turbine development in developing countries through community participation. To demonstrate its attractiveness for developing countries in terms of manufacturability and cost reduction, the proposed generator was manufactured in a small workshop using easily available materials.

4) Bearing losses and stator eddy current losses were quantified thereby illuminating the effects of design choices on the performance of an axial flux PM generator with air cored stator. In this thesis, measurement of no-load losses were conducted and separated into various components as presented in Section 5.6.4 in order to study the effect of such losses and how generator performance can be improved.

5) The thesis also proposed the use of automotive alternators as generators for small wind turbines to address the problem of permanent magnet availability. Concepts to achieve applicability in wind and good matching of the turbine characteristics with alternator was demonstrated, such as, constant field excitation, choice of turbine parameters, and gear ratio.

7.3 Recommendations

After presenting the results contained in thesis, some recommendations and ideas for further research are given in this section.

There is a need to improve the performance of the manufactured prototype axial flux PM generator. An obvious option is the use of a more efficient bearing. In this thesis the effect of bearing parameters on bearing losses were qualitatively compared based on certain assumptions. It is recommended to validate the calculated results by measuring bearing losses from different hub bearings.

In addition, this machine used epoxy resin for winding support. At high loads, the windings become heated indicating poor heat removal from the windings. If the winding temperature becomes too high isolation integrity could be compromised. It is recommended to investigate the use of alternative materials for the stator winding support.

Other generator configurations such as the use of soft magnetic composite materials should be investigated and compared with the manufactured prototype. Core sections (core back and tooth) of slotted geometries can be manufactured separately, allowing preformed coils to be placed around the tooth. This approach can reduce end winding length and improve slot fill factor and generator efficiency compared with machines with punched laminations. The stator core can also be a toroid (slotless stator) with windings round the toroidal ring (TORUS machine). Compared with machines with punched laminations, soft magnetic composite-based machines could offer a simplified manufacturing process and cost reduction, however, iron losses are generally higher in such machines. The feasibility of constructing these stator structures in small workshops should be evaluated. Comparison between the existing axial flux PM generator and the *new* generator with respect to cost of manufacture and performance will give insight and experience about the use of such materials for low cost generator manufacture.

It is recommended to realize the proposed design improvements for the vehicle alternator and validate the feasibility and cost competiveness of such schemes.

This study did not address the use of automotive alternators for output voltages higher than 14V DC. The use of power electronics converters such as switched mode rectifiers to boost output voltage from the alternator is recommended for further investigation.

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Summary

Low Cost Small Wind Turbine Generators for Developing Countries

PhD Thesis

by Samuel Ofordile Ani

Wind energy accounts for an increasing percentage of the energy supplied to the electricity network. Electricity generation from wind is now cheaper than other renewables and almost cost competitive with other conventional sources of electricity generation. However, this impressive growth is largely due to advances in large wind turbines, particularly off-shore wind turbines. Small wind turbines on the other hand have not been developing at such an impressive rate. In the past few years, an annual growth rate of about 30% has been recorded in the installed large wind power capacity while the average growth of small wind turbines was 9%. This is despite its huge potentials in providing electricity to more than 1 billion people living mostly in developing countries without electricity.

The objective of this thesis is to develop suitable low cost generators for small wind turbine application. A low cost generator solution is necessary to make small wind turbines an attractive option for remote areas of developing countries which are considered areas with the greatest potentials for such systems. To fulfil this objective, this thesis addresses three major problems identified as being responsible for the continued low penetration of small wind turbines in developing countries: 1) high cost of current systems; 2) maintainability of systems; and 3) energy yield and low wind speed operation. In addressing these challenges, this thesis focuses on the generator which is a major component of small wind turbines.

Analysis of small wind turbines in low wind speed areas

The analysis is based on the energy yield per swept area and cost of generated electricity in a low wind climate. Small wind turbines operate mostly in low and moderate wind regimes, being sited where the energy is needed and not necessarily where wind is best. Low wind speed operation has consequences on the energy yield of small wind turbines due to

difficulties in turbine starting, which are exacerbated by the presence of cogging in the generator. Comparison of the annual energy yield of commercially available systems showed that most systems failed to meet the performance stated by the manufacturers. In at least two systems, calculated annual energy yield is higher than measured values from field test by more than a factor of two.

Turbines that performed well in terms of annual energy yield per rotor swept area were mostly those with low cut-in wind speeds. Furthermore, the cost of generated electricity of the most cost effective (and the least cost effective) small wind turbine is 0.34 €/kWh (and 4 €/kWh), compared with 0.05 €/kWh for large wind turbines. Turbines with predicted coefficient of performance values significantly higher than 30% had large differences between measured and predicted energy yield. Accurate prediction of the turbine's annual energy yield for a given operating condition can be achieved by deriving a good estimate of the coefficient of performance using measured annual energy yield.

Choice of generator

Two generator concepts were proposed in this thesis to address the previously identified challenges and problems. The motivation for the selected generator concepts include: simplicity, cost reduction, manufacturability and maintainability, availability of components and skills for maintenance. The proposed generator concepts are the axial flux permanent magnet generator with air cored stator and the automotive alternator with minor modifications.

Compared to a conventional slotted stator, an air cored (coreless) stator is easier to manufacture as it permits the use of preformed coils and eliminates the need for complex equipment required for making a laminated stator core. In addition, an air cored stator is preferred because it eliminates cogging which makes it easier for the turbine to start at low wind speeds. The outer rotor configuration of the selected axial flux PM generator also makes integration of generator to turbine simpler as generator can be bolted easily to turbine rotor.

The choice of the automotive alternator was motivated by the need to provide an alternative low cost solution, since the availability of PMs cannot be guaranteed at all times. Automotive alternators on the hand are inexpensive, easily available and with well-established skills albeit for vehicle application.

The manufacturability of the axial flux PM generator with air cored stator was demonstrated using easily available materials such as vehicle hub bearing. Measurement tests show that this component, although low cost and easily available, introduced a high bearing loss (about 90% of no-load losses) in the generator system. This bearing loss can be reduced by the use of a vehicle hub bearing with smaller diameter.

One major difference between coreless and slotted machines is that eddy currents are induced in the stator conductors of a coreless machine since the stator windings are exposed to the magnetic field from the permanent magnets. The loss contribution due to eddy currents in stator conductors was quantified through measurement and calculation. It was shown that the loss contribution from stator eddy currents is not significant (7% of no-load losses).

This thesis showed that the use of the present automotive alternators for small wind turbine application is suitable for 14 V DC system. For a higher DC output voltage, a higher gear ratio is required because the minimum speed required to generate some output also increases. The alternator attains maximum efficiency (about 54%) at low speeds (about 1500 rpm) which is suitable for small wind turbine application where low and medium wind speeds are predominant and high wind speeds are rare. At higher speeds measured output power increases but the efficiency drops significantly. It was shown that optimization of alternator performance by the selection of suitable turbine parameters and gear ratio is an effective method of achieving good matching of the turbine characteristics with alternator.

Comparison of energy yield

This thesis showed that the energy yield of the proposed generator systems is comparable with that of commercially available systems. The annual energy yield per swept area of the system with axial flux PM generator is 150kWh/m^2 for a low wind speed site with average wind speed of 3.7m/s, compared with 155kWh/m^2 for the best performing commercially available turbine. The annual energy yield per swept area of the system with automotive alternator is 100kWh/m^2 for the same site, which is higher than at least 50% of the commercially available turbines used in the analysis.

For low wind speed application, the AFPM generator performed significantly better than the automotive alternator system. However, the automotive alternator system becomes increasingly competitive with the AFPM generator for areas with annual average wind speeds of 4m/s or higher. It was shown that at an annual average wind speeds of 4.0m/s and 4.5m/s, the annual energy yield per swept area of the AFPM generator is respectively 36% and 23% higher than the alternator system. To reduce frequent *start-stop* due to starting problems and improve energy yield, the automotive alternator system should be sited in areas with average wind speed of at least 4.0m/s so that higher wind speeds occur for a significant percentage of the time.

Samenvatting

Goedkope Kleine Windturbine-Generatoren voor Ontwikkelingslanden

Proefschrift

door Samuel Ofordile Ani

Windenergie draagt in toenemende mate bij aan de elektriciteitsproductie. Elektriciteit opgewekt uit wind is nu goedkoper dan uit andere duurzame energiebronnen en bijna kostenconcurrerend met conventionele bronnen voor elektriciteitsproductie. Deze indrukwekkende groei komt grotendeels door ontwikkelingen op het gebied van grote windturbines en in het bijzonder off-shore windturbines. Kleine windturbines hebben zich echter veel trager ontwikkeld. In recente jaren is de geïnstalleerde capaciteit voor grote windturbines met 30% toegenomen, terwijl deze toename voor kleine windturbines slechts 9% bedroeg. Dit ondanks de enorme mogelijkheden voor het leveren van elektriciteit aan meer dan één miljard mensen die vooralsnog zonder elektriciteit leven, voornamelijk in ontwikkelingslanden.

Het doel van dit proefschrift is het ontwikkelen van goedkope generatoren voor toepassing in kleine windturbines. Een goedkope generator is nodig om kleine windturbines aantrekkelijk te maken voor gebruik in afgelegen gebieden van ontwikkelingslanden. Deze gebieden worden gezien als grootste markt voor zulke generatoren. Voor het bereiken van dit doel beschouwt dit proefschrift drie problemen die de grootschalige toepassing van kleine windturbines in ontwikkelingslanden in de weg staan: de hoge kosten van bestaande systemen, het onderhoud van systemen, en de energieopbrengst en bedrijf bij lage windsnelheden. Bij het behandelen van deze problemen ligt de nadruk van dit proefschrift op de generator, omdat deze een belangrijk onderdeel is van kleine windturbines.

Analyse van kleine windturbines in windarme gebieden

De analyse is gebaseerd op de energieopbrengst per rotoroppervlak en de kosten van de opgewekte elektriciteit in windarme klimaten. Kleine windturbines worden voornamelijk dicht bij de energiegebruikers geplaatst en staan daardoor vaak in gebieden met lage tot matige gemiddelde windsterktes. Een lage windsnelheid heeft gevolgen voor de energieopbrengst van kleine windturbines doordat de turbine moeilijk opstart. Kleefkoppel in de generator vergroot dit probleem verder. Een vergelijking van de jaarlijkse energieopbrengst van commercieel beschikbare systemen toonde aan dat de meeste systemen de opgaaf van de fabrikant niet halen. Bij minstens twee systemen is de gemeten opbrengst meer dan twee keer lager dan de berekende opbrengst.

Verder bleek dat de windturbines met een hoge jaarlijkse energieopbrengst per rotoroppervlak voornamelijk turbines zijn die reeds bij lage windsnelheden opstarten. Bovendien zijn de kosten van de elektriciteit uit de rendabelste en onrendabelste kleine windturbines 0.34 €/kWh en 4 €/kWh. Voor grote windturbines bedragen de kosten 0.05 €/kWh. Turbines met prestatiecoëfficiënten veel hoger dan 30% lieten grote verschillen zien tussen de gemeten en voorspelde energieopbrengsten. Een goede schatting voor de jaarlijkse opbrengst onder gegeven omstandigheden kan verkregen worden door een goede prestatiecoëfficiënt te bepalen aan de hand van gemeten opbrengsten.

Keuze van het generatortype

Twee generatorconcepten zijn voorgesteld in dit proefschrift als oplossing voor de voorgenoemde problemen. De concepten zijn gekozen op grond van eenvoud van het ontwerp, kostenverlaging, maakbaarheid en onderhoudbaarheid, beschikbaarheid van de onderdelen en de vaardigheid van het onderhoudspersoneel. De voorgestelde concepten zijn de axiale flux permaneet-magneetgenerator met luchtstator en een licht aangepaste auto-alternator.

Vergeleken met een conventionele gegroefde stator is een luchtstator eenvoudiger te fabriceren doordat vormspoelen gebruikt kunnen worden en doordat de complexe apparatuur voor het produceren van het blikpakket niet nodig is. Een bijkomend voordeel is dat een machine met een luchtstator geen kleefkoppel vertoont, waardoor de windturbine eenvoudiger kan starten bij lage windsnelheden. Er is gekozen voor een buitenrotor-ontwerp omdat dit de integratie van de windturbine en generator eenvoudiger maakt doordat de generator gemakkelijk aan de turbine-rotor bevestigd kan worden.

De auto-alternator is geselecteerd als goedkoper alternatief, omdat de beschikbaarheid van permanente magneten niet altijd gegarandeerd kan worden. Auto-alternators zijn goedkoop, ruimschoots beschikbaar en veel personen zijn bekend met het onderhoud en gebruik ervan. De toepassing in windturbines is echter niet ideaal, doordat ze in de eerste plaats ontworpen zijn voor gebruik in auto's.

De maakbaarheid van de axiale flux PM-machine met luchtstator is gedemonstreerd met eenvoudig beschikbare onderdelen zoals een wiellager uit een auto. Metingen laten zien dat dit onderdeel, alhoewel goedkoop en goed beschikbaar, tot hoge lagerverliezen leidt (ongeveer 90% van de nullastverliezen). Deze verliezen kunnen verlaagd worden door een lager met een kleinere diameter te gebruiken.

Een groot verschil tussen conventionele machines en machines met luchtstator is dat in de geleiders van machines met luchtkernstator, wervelstromen worden opgewekt doordat de wikkelingen zijn blootgesteld aan het veld van de magneten. De verliesbijdrage door wervelstromen in de stator-geleiders is gekwantificeerd met metingen en berekeningen. Er is aangetoond dat de verliezen door wervelstromen niet significant zijn (7% van de nullastverliezen).

Dit proefschrift toont aan dat kleine windturbines met auto-alternators geschikt zijn voor een 14 V_{DC}-system. Voor een hogere werkspanning is en hogere overbrengingsverhouding nodig doordat de minimumsnelheid voor het leveren van energie toeneemt. Een auto-alternator bereikt zijn hoogste rendement (circa 54%) bij lage toerentallen (ongeveer 1500 toeren/minuut) en is daarmee geschikt voor toepassing in een kleine windturbine in een gebied met voornamelijk lage windsnelheden. Bij hogere toerentallen neemt het geleverde vermogen toe maar daalt het rendement sterk. Het wordt aangetoond dat het optimaliseren van het alternator-rendement door het kiezen van geschikte turbine-eigenschappen en overbrengingsverhouding een effectieve methode is voor het verkrijgen van een goede aanpassing tussen de turbine en alternator.

Vergelijking van de energieopbrengst

Dit proefschrift laat zien dat de energieopbrengst van de voorgestelde systemen vergelijkbaar is met die van commercieel beschikbare systemen. De jaarlijkse opbrengst per rotoroppervlak voor het systeem met de axiale flux PM-machine bedraagt 150 kWh/m² in een gebied met een gemiddelde windsnelheid van 3.7 m/s, vergeleken met 155 kWh/m² voor de best presterende commercieel beschikbare turbine. In de zelfde omstandigheden brengt het systeem met de auto-alternator 100 kWh/m² op, wat nog steeds meer is dan de helft van de beschouwde commercieel beschikbare systemen.

Bij lage windsnelheden presteert de AFPM-generator aanzienlijk beter dan het auto-alternator-systeem. Het alternator-systeem wordt echter aantrekkelijker bij gemiddelde windsnelheden boven de 4 m/s. Bij gemiddelde windsnelheden van 4.0 m/s en 4.5 m/s is de jaarlijkse opbrengst van de AFPM-generator respectievelijk 36% en 23% hoger dan het alternator-systeem. Om veelvuldig starten en stoppen te voorkomen en de opbrengst te verhogen, verdient het de voorkeur om het auto-alternator-systeem te installeren in gebieden met een gemiddelde windsnelheid van tenminste 4 m/s.

List of Publications

Journals

1. **S.O. Ani**, H. Polinder and J.A. Ferreira, "Comparison of energy yield of small wind turbines in low wind speed areas". *IEEE Transaction on Sustainable Energy*, June 2012.

2. **S.O. Ani**, H. Polinder and J.A. Ferreira, "Small wind power generation using automotive alternators", *submitted to Renewable Energy Journal.*

Conference papers

3. **S.O. Ani**, H. Polinder and J.A. Ferreira, "Low Cost Axial Flux Permanent Magnet Generator for Small Wind Turbines", *IEEE Energy Conversion Congress & Exposition (ECCE)*, Raleigh, North Carolina, USA, Sept. 15-20, 2012.

4. **S.O. Ani**, H. Polinder and J.A. Ferreira, "Performance of axial flux permanent magnet generator for human power application, *IET Conference on Power Electronics and Drives* (PEMD), Bristol, UK, 27-29 March, 2012.

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6. **S.O. Ani**, H. Polinder and J.A. Ferreira, "Energy Yield of Two Generator Systems for Small Wind Turbine Application", *IEEE International Electric Machines & Drives Conference,* Niagara, 15-18 May, 2011, pp. 745-750.

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