FUNDAMENTAL STUDY AND OPTIMIZATION OF OUTER-ROTOR HYBRID EXCITATION FLUX SWITCHING GENERATOR FOR GRID CONNECTED WIND TURBINE APPLICATIONS

ABDIFATAH MOHAMUD ARAB

UNIVERSITI TUN HUSSEIN ONN MALAYSIA
UNIVERSITI TUN HUSSEIN ONN MALAYSIA

STATUS CONFIRMATION FOR MASTER’S THESIS

FUNDAMENTAL STUDY AND OPTIMIZATION OF OUTER-ROTOR HYBRID EXCITATION FLUX SWITCHING GENERATOR FOR GRID CONNECTED WIND TURBINE APPLICATIONS

ACADEMIC SESSION : 2015/2016

I, ABDIFATAH MOHAMUD ARAB agree to allow this Master’s Thesis to be kept at the Library under the following terms:

1. This Master’s Thesis is the property of Universiti Tun Hussein Onn Malaysia.
2. The library has the right to make copies for educational purposes only.
3. The library is allowed to make copies of this report for educational exchange between higher educational institutions.
4. ** Please Mark (√)

☐ CONFIDENTIAL (Contains information of high security or of great importance to Malaysia as STIPULATED under the OFFICIAL SECRET ACT 1972)

☐ RESTRICTED (Contains restricted information as determined by the Organization/institution where research was conducted)

☐ FREE ACCESS

Approved by,

(WRITER’S SIGNATURE) (SUPERVISOR’S SIGNATURE)

Permanent Address :
H.NO; 08, Goljano Street
Codominium, Hargesia, Somaliland

Date: 26 JANUARY, 2016

Supervisor’s name
DR. ERWAN BIN SULAIMAN

Date : 26 JANUARY, 2016

NOTE:

** If this Master’s Thesis is classified as CONFIDENTIAL or RESTRICTED, Please attach the letter from the relevant authority/organization stating reasons and duration for such classifications.
FUNDAMENTAL STUDY AND OPTIMIZATION OF HYBRID EXCITATION FLUX SWITCHING GENERATOR FOR GRID CONNECTED WIND TURBINE APPLICATIONS

ABDIFATAH MOHAMUD ARAB

A thesis submitted in
Fulfillment of the requirement for the award of the
Degree of Master of Electrical Engineering

Faculty of Electrical & Electronic Engineering
Universiti Tun Hussein Onn Malaysia

JANUARY, 2016
I hereby declare that the work in this thesis is my own except for quotations and summaries which have been duly acknowledged.

Student : .................................................................

ABDIFATAH MOHAMUD ARAB

Date : 26 JANUARY, 2016

Supervisor : .................................................................

DR. ERWAN BIN SULAIMAN
DEDICATION

To my mother and father
ACKNOWLEDGEMENT

Thoughtful gratitude is given to the Almighty ALLAH, the creator of the universe in whom we breathe and have our being for diligently guiding us through this practical training and our academic life up to this point of completion of my master degree studies.

I also wish to express my gratitude to my supervisor, Dr. Erwan Bin Sulaiman for his excellent guidance, ideas, advice and patience during this project. Without his constructive and critical comments, continues encouragement and good humor while facing difficulties, I could not have completed this research work. I am also very grateful to him for guiding me to think independently.

Without support from technical staff and my lab fellows of FSM research group, this research would not have been undertaken. My sincerely thanks to all my FSM group friends who helped me every time with their technical knowledge.

It is always very pleasant and enjoyable to work in UTHM with a group of highly dedicated people, who have always been willing to provide help, support and encouragement whenever needed. I would like to thank all my lecturers and friends during my journey of study in UTHM. Life would have never been that existing and joyful without you.

Finally, I would like to give sincere words to my parents for their endless love, support, motivation and a continuous prayers which makes me try whatever I consider is worth doing.
ABSTRACT

Effective generation of energy enables commercial and industrial facilities to minimize production costs, increase profits, and stay competitive. Most of electrical energy consumed in industrial facilities is received from electrical generators. Therefore it is necessary to perform research in order to develop advanced electric generators with less cost and high efficiency. There has been a recent interest in flux switching generators (FSG) in which all the flux sources are positioned in the stator that make the rotor simple, robust and brushless. Hence, this project presents an operating principle of a new proposed outer-rotor hybrid excitation flux switching generator. In this Generator a combination of a permanent magnet (PM) and field excitation coil (FEC) are used as the main flux sources. Additional FEC can be used to control the flux so that constant voltage can be produced at various wind conditions. Moreover, twelve coil tests, Three Phase coil test flux excited by PM only, Back-EMF at various speed and stack-length conditions, magnetic flux strengthening at various current densities and flux distribution are investigated by using JMAG software. The result shows that the generated voltage is directly proportional with the change of speed and stack-length and the size of the improved stack-length design has incremented 7.4 times of the initial design. Moreover, another technique of improving induced B-EMF was proposed which is deterministic optimization method (DOM). The parameters of the design are optimized one at a time starting from the rotor dimensions followed by the stator parts such as PM, FEC and AC and the improved design indicated a higher output voltage.
ABSTRAK

Penjanaan tenaga yang berkesan membolehkan kemudahan perdagangan dan perindustrian untuk mengurangkan kos pengeluaran, meningkatkan keuntungan, dan kekal berdaya saing. Kebanyakkan tenaga elektrik yang digunakan dalam industri diterima daripada penjana tenaga elektrik. Justeru itu, penyelidikan terhadap penjana tenaga elektrik yang lebih mendalam pada masa hadapan haruslah dilaksanakan untuk menjimatkan kos dan meningkatkan kecekapan. Terdapat beberapa kajian dalam penjana pensuisan fluks (FSG) di mana semua sumber fluks diletakkan dalam pemegun yang membuat pemutar ringkas, mantap dan tanpa berus. Oleh itu, projek ini memberi satu prinsip operasi yang mencadangkan luar pemutar penguajaan hibrid penjana tenaga pensuisan fluks. Penjana tenaga ini menggabungkan magnet kekal (PM) dan penguajaan medan gegelung yang digunakan sebagai sumber fluks utama. FEC tambahan boleh digunakan mengawal fluks supaya voltan yang berterusan boleh dihasilkan dalam pelbagai keadaan angin. Selain itu, dua belas ujian gegelung, tiga fasa ujian gegelung fluks teruja dengan PM sahaja, Back-EMF di pelbagai kelajuan dan panjang, pengukuhan fluks magnet di pelbagai ketumpatan arus dan pengedaran fluks dikaji dengan menggunakan perisian JMAG. Hasil kajian menunjukkan bahawa voltan yang dihasilkan adalah berkadar terus dengan perubahan kelajuan dan panjang. Saiz reka bentuk yang lebih baik telah dihasilkan dan 7.4 kali ganda daripada reka bentuk asal. Selain itu, salah satu lagi teknik untuk meningkatkan back-EMF telah dicadangkan iaitu kaedah pengoptimuman berketentuan (DOM), di mana parameter reka bentuk dioptimumkan satu demi satu bermula dari dimensi pemutar diikuti oleh bahagian-bahagian stator seperti PM, FEC dan AC dan reka bentuk yang lebih baik menunjukkan voltan yang telah dihasilkan adalah lebih tinggi.
TABLE OF CONTENTS

DECLARATION ii
DEDICATION iii
ACKNOWLEDGEMENT iv
ABSTRACT v
ABSTRAK vi
TABLE OF CONTENTS vii
LIST OF TABLES x
LIST OF FIGURES xi
LIST OF PUBLICATIONS xiv
LIST OF AWARDS xiv

CHAPTER 1 INTRODUCTION 1
1.1 Research Background 1
1.2 Problem Statement 3
1.3 Objectives of the Study 3
1.4 Scope 3
1.5 Thesis outline 4

CHAPTER 2 LITERATURE REVIEW 5
2.1 Introduction 5
2.2 Introduction to Electrical Generators 5
2.3 Squirrel Cage Induction Generators 6
2.4 Double Fed (wound rotor) Induction Generator 8
### CHAPTER 2  DESIGN OF HIGH PERFORMANCE PERMANENT-MAGNET SYNCHRONOUS WIND GENERATOR

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>Design of high performance permanent-Magnet synchronous wind Generator</td>
</tr>
<tr>
<td>2.6</td>
<td>Design Dimension of the Rotor</td>
</tr>
<tr>
<td>2.7</td>
<td>Optimal sizing of Rotor Magnet</td>
</tr>
<tr>
<td>2.8</td>
<td>AC Generator Construction</td>
</tr>
<tr>
<td>2.9</td>
<td>Principles of AC Construction</td>
</tr>
<tr>
<td>2.10</td>
<td>AC Generator Function</td>
</tr>
<tr>
<td>2.11</td>
<td>Principles of Operation of synchronous Machines</td>
</tr>
<tr>
<td>2.12</td>
<td>Electricity</td>
</tr>
<tr>
<td>2.13</td>
<td>PM Synchronous Machine</td>
</tr>
<tr>
<td>2.14</td>
<td>Radial Flux or Axial Flux</td>
</tr>
<tr>
<td>2.15</td>
<td>Axial Flux Machines</td>
</tr>
<tr>
<td>2.16</td>
<td>Longitudinal or Transversal Flux Machines</td>
</tr>
<tr>
<td>2.17</td>
<td>Inner Rotor or Outer Rotor</td>
</tr>
<tr>
<td>2.18</td>
<td>No Load Analysis of ORHEFSM</td>
</tr>
<tr>
<td>2.19</td>
<td>Design Study of 12Slot-10Poles Outer Rotor HEFSM</td>
</tr>
<tr>
<td>2.20</td>
<td>Design Improvement of a new ORHEFSM</td>
</tr>
<tr>
<td>2.21</td>
<td>Experimental Test of a 72Slot-78Pole high Performance PMSG</td>
</tr>
</tbody>
</table>

### CHAPTER 3  METHODOLOGY

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Introduction</td>
</tr>
<tr>
<td>3.2</td>
<td>Design and Investigation of HEFSG</td>
</tr>
<tr>
<td>3.3</td>
<td>Introduction to JMAG-Designer Software</td>
</tr>
<tr>
<td>3.4</td>
<td>Project Design</td>
</tr>
<tr>
<td>3.5</td>
<td>Project Analysis</td>
</tr>
<tr>
<td>3.6</td>
<td>Project Design Improvement</td>
</tr>
</tbody>
</table>

### CHAPTER 4  RESULTS AND ANALYSIS

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>Introduction</td>
</tr>
<tr>
<td>4.2</td>
<td>Twelve Coil Arrangement Test</td>
</tr>
<tr>
<td>4.3</td>
<td>Three Coil Test (clockwise direction)</td>
</tr>
</tbody>
</table>
4.4 U, V, W 44
4.5 Final Coil Test (clockwise direction) 45
4.6 Cogging Torque Test 45
4.7 Calculation of DC FEC current 46
4.8 Back-Emf versus Rotor position 47
4.9 Flux Strengthening 48
4.10 Magnetic Flux-Linkage and Back-EMF versus FEC Current Densities 48
4.11 Flux Distribution 49
4.12 Speed Impact on B-EMF 51
4.13 Stack-length Impact on B-EMF 51
4.14 Comparison of speed and Stack-length Impact on B-EMF 52
4.15 Design improvement 53
4.16 Deterministic Optimization Method 55

CHAPTER 5  CONCLUSION AND FUTURE WORKS 59

5.1 Introduction 59
5.2 Conclusion 59
5.3 Future Works 60

REFERENCES 61
## LIST OF TABLES

1.1 Material selection for stator, rotor, armature coil And d FEC  
   
1.2 Initial design parameters  

2.1 Value of Ie when Jₑ equals to 5, 10, 15, 20,25 and 30A/mm²  

3.1 Comparison of HEFSG design parameters
# LIST OF FIGURES

2.1 Proposed structure of outer-rotor HESFG .......................... 4
2.2 Classification of main types of generators .......................... 6
2.3 Basic schematic of SCIG ............................................ 7
2.4 Magnetic pole system generated by currents in the stator and rotor windings ............................................. 8
2.5 Per-phase equivalent circuit of an induction machine .......... 9
2.6 Doubly-fed induction generation system power flows .......... 10
2.7 Wind power generation using double fed induction .......... 10
2.8 Schema graph of PMSG and magnet dimension: 78pole, 72-slot PMSG; (b) magnet dimension 11
2.9 Schematic diagram of permanent-magnet synchronous (PMSG): Magnetic flux path 12
2.10 A magnetic circuit model for the proposed structure: (a) Complete magnetic circuit Model; b) simplified model 12
2.11 Relationship between normalized airgap flux density And permeance coefficient 14
2.12 Relationship between αp-p and air gap flux density: (a) αp-p = 1; (b) αp-p = 0.5 .................................................. 15
2.13 Induced voltages of PMSG with different αp-p by Maxwell 2D: a) phase voltages b) line voltage 16
2.14 AC Generator Function .............................................. 17
2.15 Synchronous Machine construction salient-pole rotor .......... 18
2.16 Schematic cross section of a synchronous machine with A cylindrical round-rotor (turbo generator) 19
2.17 AC Generator Function .............................................. 20
2.18 Lines of force of opposite polarity magnets ..................... 21
2.19 lines of force of same polarity magnets 21
2.20 Magnet Fields created by current flow in a conductor
2.21 Magnetic field produced by the flow of electric current in a coil—shaped conductor
2.22 Ionic Clouds of positive and Negative currents
2.23 the flow of electrons inside a conductor material
2.24 Cross sectional view in radial direction and in axial direction, respectively of a typical radial PMSG [24]
2.25 Cross sectional in radial direction and in axial direction Respectively of a typical axial flux PMSG [24]
2.26 Fraction of a typical transversal flux PMSG
2.27 Inner rotor PMSG (left) and an outer rotor PMSG (right)
2.28 Armature coil phase setting
2.29 Three-phase flux linkage generated by PM
2.30 Back-Emf at 3000rpm
2.31 Flux path of PM only
2.32 Design parameters defined as D1- D10
2.33 Fundametal back-Emf at 3000rpm
2.34 Experimental apparatus: (a) schematic diagram
(b) platform photo
2.35 Experimental wiring photo
2.36 Measured and simulated no-load induced voltages
(a) double three-phase winding (b) six phase winding
3.37 General work flow of the project implementation
3.38 project design flowchart
3.39 JMAG Designer
3.40 JMAG editor
3.41 Design parameters shown as D1- D10
3.42 Initial HEFSG design
4.43 HEFSG twelve coil arrangement test
4.44 Combination of four armature coils that have similar pattern
4.45 UVW Circuit
4.46 UVW Flux clockwise field test
4.47 Cogging torque graphh against rotor position
4.48 Back-Emf at various FEC 47
4.49 Flux strengthening versus Electric cycles 48
4.50 Flux linkage and induced voltage versus various Current densities 49
4.51 Comparison of flux paths 50
4.52 Speed effect on B-EMF 51
4.53 Stack-length effect on B-EMF 52
4.54 Back-EMF versus rotor speed and stack-length 53
4.55 Design parameters as shown as D1- D10 54
4.56 Rotor Radius optimization 55
4.57 Rotor width optimization 55
4.58 Rotor depth optimization 56
4.59 PM width optimization 56
4.60 FEC width optimization 56
4.61 AC Width optimization 57
4.62 AC length optimization 57
4.63 Comparison of initial and improved HEFSG 57
4.64 Comparison of initial and improved HEFSG 58
LIST OF PUBLICATION

proceeding Paper:


LIST OF AWARDS

(i) Certificate of participation at IEEE Student Conference on Research and Development (Scored 2015), Berjaya Time Square, Kuala Lumpur
CHAPTER I

INTRODUCTION

1.1. Background of Study

With the rapid development of wind power technologies and significant growth of wind power capacity installed worldwide, various types of wind generator systems have been developed. Among the well-known wind generator systems are:

(i) Permanent magnetic synchronous generator with direct-generators with three-stage gearbox and single-stage gearbox.

(ii) Electricity excited synchronous generator with direct-driven.

(iii) Variable speed constant frequency squirrel cage induction generator with three-stage and three-single stage gearbox [1] [2].

Cost effective and reliable large wind generator systems are becoming increasingly attractive in order to make wind energy to have better competition with other more traditional sources of electricity like coal, Gas and nuclear generation. Various wind turbine concepts and wind generators have been developed during last two decades. Based on the structure of the drive trains, these wind turbine concepts may be classified into geared drive and direct drive concepts. Moreover, various types of generators have been applied, such as permanent magnet
synchronous generator (PMSG), doubly fed induction generator (DFIG), electricity excited synchronous generator (EESG), and squirrel cage induction generator (SCIG) [3].

Squirrel Cage Induction Generators are widely used in windmills due to the several advantages, such as robustness, mechanical simplicity and low price. The rotor speed of a SCIG varies with the amount of power generated. The generator will always draw the reactive power from the grid. The speed varies over a very small range above synchronous speed as it is coupled with the grid, hence, it is commonly known as a fixed-speed generator[4].

Moreover, double fed induction generators (DFIG) are also used for wind turbine. They are an induction machines with a wound rotor where the rotor and stator are both connected to electrical sources. They offer several advantages including; they operate at variable rotor speed while the amplitude and frequency of the generated voltages remain constant. Generation of electrical power at lower wind speed, virtual elimination of sudden variations in the rotor torque and control of the power factor in order to maintain the power factor at unity. However, DFIG requires complex power conversion circuitry, the slip rings on the wound rotor induction machine used to implement the doubly-fed induction generator requires periodic maintenance [5].

Furthermore, permanent magnet synchronous generators are also used for wind turbine. They have various advantages over other generators such as lower cost and lower maintenance, due to the removal of brushes, slip rings and rotor windings. However, it is not concerned in variable speed applications since the generator is connected to the grid through a converter that will adapt the frequency of the induced voltage to the grid frequency. Also the field provided by magnet is not controllable. Hence it is not possible to regulate voltage [6] [7]. Therefore, in this paper 12slot-10 pole outer-rotor hybrid excitation flux switching generator is proposed to overcome the highlighted drawbacks mentioned above. The generator design is simple, it consists of single piece of rotor and all the magnetic flux sources such as PM and DC field excitation coils (FEC) are located on the stator body.
1.2. Problem Statement

The increasing demand of a cheaper, low background noise, low loss, less regular maintenance, variable speed and controllable magnetic field wind turbine generators have extremely risen nowadays.

To overcome the drawbacks of constant speed and uncontrollable magnetic field of the permanent magnet synchronous generator, a new outer-rotor hybrid excitation flux switching generator (HEFSG) was proposed in which the combination of permanent magnet (PM) and field excitation coil (FEC) are the main flux sources with direct-driven topology. Additional current densities can be applied to the FEC to control the output voltage.

1.3. Objectives of the study

The objectives of this project are:-

(i) To investigate the operating principle of outer-rotor hybrid excitation flux switching generator and to confirm the coil phase and the number of turn of each armature coil of the proposed generator for wind turbine generator applications

(ii) To analyse the performances of the proposed generator on the impact of wind speed and stack-length until the target output voltage of 415V is achieved.

(iii) To optimize the parameters of the proposed design and the number of turns.

1.4. Scopes

The scopes of this project will involve simulation using JMAG designer and JMAG editor software. The proposed design will focus on the following areas:-

- The new design has a combination of permanent magnet and field excitation coil as the main flux sources
- Additional FEC was used to control the flux so that constant voltage can be produced at various wind conditions
- Analysis result has involved coil test, flux strengthening and weakening, EMF.
- Target induced output voltage is 415V
- Deterministic Optimization Method was used to optimize the design
Table 1.1: Material selection for stator, rotor, armature coil and FEC [37]

<table>
<thead>
<tr>
<th>Parts</th>
<th>Material used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator</td>
<td>35H210</td>
</tr>
<tr>
<td>Rotor</td>
<td>35H210</td>
</tr>
<tr>
<td>Armature coil</td>
<td>Copper</td>
</tr>
<tr>
<td>FEC</td>
<td>Copper</td>
</tr>
<tr>
<td>PM</td>
<td>NEOMAX35AH</td>
</tr>
</tbody>
</table>

1.5. Thesis outline

A new structure of 3-phase concentrated winding flux switching generator, in which the PM is placed in the stator, was proposed and the structure of the machine is shown in figure 1. Due to the elimination of PM in rotor part, the mechanical strength of the machine is improved and becomes more suitable for low speed high torque wind generator. In addition, the concentrated windings of armature coil reduce the coil end strength, thus reducing the machine weight and copper loss. In order to control the PM flux, DC (FEC) was introduced in such a way that the air-gap field provided by PM can be controlled with variable flux capabilities especially to provide high torque by controlling the direction and magnitude of the FEC current. Since two flux sources namely PM and DC FEC are employed in this machine, the machine is named as hybrid excitation flux switching generator (HEFSG) with outer-rotor configuration.

The proposed wind generator design has the ability to provide output voltage similar to conventional 415V power supply.
LITERATURE REVIEW

2.1. Introduction

One way of generating electricity from renewable sources is to use wind turbines that convert the energy contained in flowing air into electricity. The main advantages of electricity generation from renewable sources are the absence of harmful emissions and the infinite availability of the prime mover that is converted into electricity. This chapter contains the introduction and the classification of electrical generators. Initially each type of electrical generator is explained. It also explains working principles of each generator.

2.2. Introduction to electrical Generator

An electric generator is a device that converts mechanical energy to electrical energy. A generator in a wind turbine is used to convert the aerodynamic mechanical power of the blades to electrical power. Electrical power can be produced in two forms alternating (alternating current AC) or direct current (DC). Generators have two main subcategories as shown in figure 2.1, AC and DC. For each subcategory, there are several options, and AC generators have subcategories
of synchronous and Asynchronous, and DC generators just have the subcategory brushed. Brushed DC generators have a lot of maintenance need with the brushes and were quickly eliminated as an option for the wind turbine. Asynchronous and synchronous AC generators have several options, however permanent magnet was chosen because they are often produced with a high number of poles, which allows for a low RPM (revolutions per minute) range, and turbine production without a gearbox, the figure below shows the available options for generators.

Figure 2.1: Classification of main types of generators

2.3. Squirrel Cage Induction Generators

Asynchronous Induction generators are widely used in wind mills due to the several advantages, such as robustness, mechanical simplicity and low price. Induction machines operate in the generating and motoring modes fundamentally in the same manner except for the reversal power flow. Therefore, the equivalent circuit and the associated performance are valid for different slip. If the rotor is driven by a prime mover above the synchronous speed, the mechanical power of the prime mover is converted into electrical power to the utility grid via
stator winding. SCIG feed only through the stator and generally operate at low negative slip, approximately 1 to 2 per cent. Hence the rotor speed of a SCIG varies with the amount of power generated. The generator will always draw the reactive power from the grid. Reactive power consumption is partly or fully compensated by capacitors in order to achieve a power factor close to unity and make the induction machine to self-excite. The speed varies over a very small range above synchronous speed as it is coupled with the grid, hence Commonly known as a fixed-speed generator [9].

The SCIG is a self-excited induction generator where a three-phase capacitor bank is connected across the stator terminals to supply the reactive power requirement of a load as shown in figure 2.2 and generator was discovered by Basset and Potter in the 1930s. When such an induction machine is driven by an external mechanical power source, the residual magnetism in the rotor produces an Electromotive Force (EMF) in the stator windings[4] [10]. This EMF is applied to the capacitor bank causing current flow in the stator winding and establishing a magnetizing flux in the machine. An induction generator connected and excited in this manner is capable of acting as a stand-alone generator supplying real and reactive power to a load.

Figure 2.2: basic schematic of SCIG [4]
2.4. Double Fed (wound rotor) Induction Generator

The DFIG is an induction machine with a wound rotor where the rotor and stator are both connected to electrical sources, hence the term ‘doubly-fed’. The rotor has three phase windings which are energized with three-phase currents. These rotor currents establish the rotor magnetic field. The rotor magnetic field interacts with the stator magnetic field to develop torque. The magnitude of the torque depends on the strength of the two fields (the stator field and the rotor field) and the angular displacement between the two fields. Mathematically, the torque is the vector product of the stator and rotor fields. Conceptually, the torque is developed by magnetic attraction between magnet poles of opposite polarity where, in this case, each of the rotor and stator magnetic fields establishes a pair of magnet poles, figure 2.3. Clearly, optimum torque is developed when the two vectors are normal to each other. If the stator winding is fed from a 3-phase balanced source the stator flux will have a constant magnitude and will rotate at the synchronous speed [5]. We will use the per-phase equivalent circuit of the induction machine to lay the foundations for the discussion of the torque control in the DFIG. The equivalent circuit of the induction machine is shown in figure 2.4. The stator side has two ‘parasitic’ components, $R_s$ and $L_s$, which represent the resistance of the stator phase winding and the leakage inductance of the phase winding respectively. The leakage inductance models all the flux generated by current in the stator windings that does not cross the air-gap of the machine, it is therefore not useful for the production of torque. The stator resistance is a natural consequence of the windings being fabricated from materials that are good conductors but nonetheless have finite conductance (hence resistance). The magnetizing branch, $L_m$, models the generation of useful flux in the machine – flux that crosses the air-gap is either from stator to rotor or vice-versa [11].
Figure 2.3: Magnetic pole system generated by currents in the stator and rotor windings. The stator and the rotor field generate a torque that tends to try and align poles of opposite polarity.

In this case, of rotor experiences a clockwise torque [6]

![Figure 2.4: Per-phase equivalent circuit of an induction machine](image)

Like the stator circuit, the rotor circuit also has two parasitic elements. The rotor leakage reactance $L_r$ and the rotor resistance $R_r$. In addition, the rotor circuit models the generated mechanical power by including an addition rotor resistance component $R_r (1-s)/s$. Note that the rotor and stator circuits are linked via a transformer whose turn ratio depends on the actual turns ratio between the stator and rotor (1:k), and also the slips of the machine in an induction machine the slip is defined as :-

$$S = \frac{N_s - N_r}{N_s} \tag{2.1}$$

$$N_s = \frac{60f_e}{p} \text{ rpm} \tag{2.2}$$

Where $p$ is the number of pole pairs and $f_e$ is the electrical frequency of the applied stator voltage, we will first consider the operation of the machine as a standard induction motor. If the rotor circuit is left open circuit and the rotor locked (standstill), when stator excitation is applied, a voltage will be generated at the output terminals of the rotor circuit, $V_r$. The frequency of this output will be at the applied stator frequency as slip in this case is 1. If the rotor is turned progressively faster and faster in the sub-synchronous mode, the frequency at the output terminals of the rotor will decrease as the rotor accelerates towards the synchronous speed. At
synchronous speed the rotor frequency will be zero. As the rotor accelerates beyond synchronous speed (the super-synchronous mode) the frequency of the rotor voltage begins to increase again, but has the opposite phase sequence to the sub synchronous mode. Hence, the frequency of the rotor voltage is

\[ F_r = S \times F_e \] (2.3)

No rotor currents can flow with the rotor open circuit; hence there is no torque production as there is no rotor field \( \psi_r \), figure 2.5. If the rotor was short circuited externally, rotor currents can flow, and they will flow at the frequency given by equation (2.3). The rotor currents produce a rotor magnetic field, \( \psi_r \), which rotates at the same mechanical speed as the stator field, \( \psi_s \). The two fields interact to produce torque, figure 2.6. It is important to recognize that the rotor magnetic field and the stator magnetic field both rotate at the synchronous speed. The rotor may be turning asynchronously, but the rotor field rotates at the same speed as the stator field [5]. The mechanical torque generated by the machine is found by calculating the power absorbed (or generated) by the rotor resistance component \( R_r (1-s)/s \). This is shown to be

\[ P_{mech} = 3|I_r|^2 \left( \frac{1-s}{s} \right) R_r \] (2.4)

Figure 2.5: Doubly-fed induction generation system power flows [5].

Figure 2.6: Wind power generation using double fed induction [5].
2.5. Design of High Performance Permanent-Magnet Synchronous Wind Generator

The permanent-magnet synchronous generator (PMSG), which is less noisy, high efficiency and has a long life span, has becomes one of the most important types of equipment in wind turbine systems. In 2008, Bumby designed and fabricated a 5 kW, 150 rpm axial vertical permanent-magnet (PM) generator driven directly by wind and a water turbine, where the generator uses trapezoidal shaped magnets to enhance the magnetism over conventional circular magnets. The average efficiency is 94% under no core losses and only limited eddy current loss [13]. In 2011, Maia used finite element method (FEM) software to analyses the operation characteristics of an axial PM wind turbine with rated output power of 10 kW while running at the speed of 250 rpm [14]. He [15] indicated that the electromagnetic properties of the permanent-magnet machine are highly dependent on the number of slots per pole, phase, magnet shape, the stator slots and the slot opening.

Axial flux PMSGs are widely used for vertical-axis wind turbines [18–22], however, since the axial structure magnet is placed on the inner surface of the rotor without slot and facing the stator as shown in figure 2.7, it will lengthen the distance between upper and lower magnets, which in turn requires much more magnet material and cost to improve the operational efficiency.

Figure 2.7: Schema graph of PMSG and magnet dimension: (a) structure of a 78-pole, 72-slot PMSG; (b) magnet dimension [23]
2.6. Design Dimension of the Rotor

Figure 2.8 below shows a simple and generally used surface mount with the basic geometric structure. It has a complete magnetic flux circuit, half N-pole and half S-pole, the magnetic flux travels from the rotor surface through the air gap, the magnetic silicon steel in the stator, the air gap, and then back to the rotor to form a complete closed-loop [23].

![Schematic diagram of permanent-magnet synchronous generator (PMSG): Magnetic flux path](image)

Figure 2.8: Schematic diagram of permanent-magnet synchronous generator (PMSG): Magnetic flux path [23]

The equivalent magnetic circuit can be modeled as shown in Figure 2.9. The stator yoke width should be selected properly for reducing flux leakage and preventing magnetic saturation due to too small width of the yoke, or over weight and dimension coming from thicker yoke [24].

![Magnetic circuit model for the proposed structure](image)

Figure 2.9: A magnetic circuit model for the proposed structure: (a) complete magnetic circuit Model; (b) simplified magnetic circuit model [19]
The air gap flux can be written as \( \phi_g = K_1 \cdot \phi \), where the leakage factor \( K_1 \) is typically less than unity. For rapid analysis of the magnetic circuit, leakage magnetic reluctance \( R_1 \) is ignored as shown in figure 2b. In addition, since the steel reluctance \( (R_r + R_s) \) is small relative to the air-gap reluctance \( R_g \), the steel reluctance can be eliminated by introducing a reluctance factor \( K_r \) having its value chosen to be a constant slightly greater than unity to multiply the \( R_g \) to account for the neglected \( (R_r + R_s) \). For the machine with surface magnets under consideration, the leakage and reluctance factors are typically in the ranges of 0.9–1.0 and 1.0–1.2, respectively, while the flux concentration factor is ideally 1.0.

The magnetic flux can be derived as [24]

\[
\phi = \frac{\phi_r 2R_m}{2R_m + 2R_g + R_s + R_r} = \frac{\phi_r 2R_m}{2R_m + 2K_r R_s} = \frac{\phi_r}{1 + K_r \frac{R_g}{R_m}}
\]  

(2.5)

Since the relationship between permeance coefficient \( (P_c) \) and air gap flux density is nonlinear, doubling \( P_c \) does not double \( B_g \). Doubling \( P_c \), however, means doubling the magnet length, which doubles its volume and associated cost accordingly. Using the relation

\[
P_c = \frac{l_m A_g}{l_g A_m}
\]  

(2.6)

And

\[
R_m = \frac{l_m}{\mu_r \mu_0 A_m}, R_g = \frac{l_g}{\mu_0 \mu_g}, B_g = \frac{\phi_g}{A_s}, B_r = \frac{\phi_r}{A_m}
\]  

(2.7)

Equation (2.4) becomes:

\[
A_g = \frac{B_r A_m}{1 + K_r \frac{\mu_r}{\mu_c}}
\]  

(2.8)

Assuming that all the magnetic fluxes leaving the magnet through an air gap go into the stator core, then:

\[
A_g = A_m
\]  

(2.9)
Since, as indicated above, $K_r$ is slightly greater than unity, it is further assumed that $K_r=1$. Thus substituting equation (2.9) into equation (2.8) results in:

$$\frac{B_g}{B_r} = \frac{1}{1 + \mu_r \frac{l_g}{l_m}}$$

(2.10)

Determination of the air gap length $l_g$ depends on the gap magnetic flux density and the processing of machine structure. If the air gap length is too short, it will cause serious eccentric force at high speed. Wider air gap length, however, will reduce the gap magnetic flux density and lower efficiency. The optimal ratio between magnet thickness and the air gap is usually selected in the range of 4–6 as shown in Figure 2.10. [19]. Usually generator designer determines magnetic thickness in accordance with this search range. Meanwhile, production and installation tolerances must be considered to decide the eventual air gap length in order to avoid motor assembly complexity and operating problems. Equation (2.10) will be used to decide the initial air gap length.

![Figure 2.10: Relationship between normalized air gap flux density and permeance coefficient.](image)

Ignoring the magnetic effects caused by the stator teeth,

The distribution of air gap flux density can be illustrated by Figure 2.11. The ratio $\alpha_{p-p}$ [20] between the width of the magnet and the pole-pitch of rotor core, written as the ratio of pole-arc $\alpha_{arc}$ to pole-pitch $\alpha_{pitch}$, is defined in Equation (11), where $\alpha_{arc}$ and $\alpha_{pitch}$ are the angular span of any single magnet and that between the center lines of any two adjacent magnetic poles, respectively. It is related to flux density. Specifically, the greater ratio, the longer magnet arc
length, will result in higher flux density. If the gap magnetic flux density waveform is closer to sinusoidal, then the induced voltage harmonics content will be smaller:

$$\alpha_{p-p} = \frac{\alpha_{arc}}{\alpha_{pitch}}$$  \hspace{1cm} (2.11)

When \(\alpha_{p-p}\) is unity, the N and S poles of the magnet are consecutive, i.e., without a gap in between, the gap flux density is a square wave. In general, for \(0 \leq \alpha_{p-p} \leq 1\), Fourier series expansion of the flux density at any electrical degree \(\theta_e\) in the air gap can be derived as

$$B_g = \frac{2B_{g,\text{peak}}}{\pi} (x + a)^n = \sum_{k=0}^{\infty} \frac{1 - (-1)^{kh}}{kh} \cos \left[ kh \left( \frac{1 - \alpha_{p-p}}{2} \right)x180^0 \right] \sin kh \theta_e$$  \hspace{1cm} (2.12)

Where \(B_{g,\text{peak}}\) is the maximum flux density of air gap and \(K_h\) is the K-the harmonic.

![Figure 2.11: Relationship between \(\alpha_{p-p}\) and air gap flux density: (a) \(\alpha_{p-p} = 1\); (b) \(\alpha_{p-p} = 0.5\)](image)

Equation (2.13) yields the k-th harmonic flux ratio

$$B_{kh} = \frac{1 - (-1)^{kh}}{kh} \cos \left[ kh \left( \frac{1 - \alpha_{p-p}}{2} \right)x180^0 \right]$$  \hspace{1cm} (2.13)

It is seen from Equation (2.11) that the air gap flux density ratio of harmonic is determined by different \(\alpha_{p-p}\). For balanced three-phase, the third harmonic can be eliminated by using Y-
connected wiring. The harmonic distortion is not proportional to the phase and line voltages, but depends on the third harmonic of the phase voltage. Even if the third harmonic of the phase voltage will not appear in the line voltage, it will cause losses within each phase winding.

### 2.7. Optimal Sizing of Rotor Magnet

Aiming at high induced voltage and low harmonic distortion, sizing of rotor magnet will be conducted by the best pole-arc to pole-pitch ratio $\alpha_{p-p}$ fixing the internal and external diameters of stator and rotor. Assuming open stator slot, finite element analyses using Maxwell 2-D software for five different $\alpha_{p-p}$, i.e., $\alpha_{p-p} = 0.667, 0.800, 0.857, 0.909, \text{and } 1.000$ are given. Figure 2.12 shows the various phase voltage $V_p$ and line voltage $V_l$ values obtained by Maxwell 2-D with different $\alpha_{p-p}$. When $\alpha_{p-p} = 0.800$, the values for $V_p$ and $V_l$ are 243.3 V and 458.4 V, respectively [7].

![Figure 2.12: Induced voltages of PMSG with different $\alpha_{p-p}$ by Maxwell 2-D: (a) Phase voltage; (b) Line voltage](image-url)
2.8. AC Generator Construction

A main part of the alternator, obviously, consists of stator and rotor. But, unlike other machines, in most of the alternators, field exciters are rotating and the armature coil is stationary. The electrical machine, which generates AC, is known as Ac generator or alternator. The alternator may be constructed with either the armature or the field structure as revolving member as shown in figure 2.13. Small Ac generators and of low voltage ratings are commonly made with rotating armature. In such generators, the required magnetic field is produced by DC electro-magnets placed on the stationary member called the stator and the current generated is collected by means of brushes and slip-rings on the revolving member called the rotor [26].

Practically all the large rating generators are made with revolving fields. In such generators revolving field structure or rotor has slip-rings and brushes for supply of excitation current from an outside Dc source and the stationary armature, (also called the stator), which is made up of thin silicon steel laminations securely clamped and held in place in the steel frame, accommodates coils or windings in the slots.

Figure 2.13: AC Generation Construction
2.9. Principles of Construction

Synchronous machines come in all sizes and shapes, from the miniature permanent magnet synchronous motor in wall-clocks, to the largest steam-turbine driven generators of up to about 1500 MVA. Synchronous machines are one of two types: the stationary field or the rotating dc magnetic field. The rotating magnetic field (also known as revolving-field) synchronous machine has the field-winding wound on the rotating member (the rotor), and the armature wound on the stationary member (the stator). A dc current, creating a magnetic field that must be rotated at synchronous speed, energizes the rotating field-winding. The rotating field winding can be energized through a set of slip rings and brushes (external excitation), or from a diode-bridge mounted on the rotor (self-excited). Modern large machines typically are wound with double-layer lap windings. The rotor field is either of salient-pole as shown in figure 2.14 or non-salient-pole construction, also known as round rotor or cylindrical rotor as shown in figure 2.15. The cross section of a salient-pole synchronous machine, the rotor is magnetized by a coil wrapped around it. The figure shows a two-pole rotor. Salient-pole rotors normally have many more than two poles. When designed as a generator, large salient-pole machines are driven by water turbines. The second part of the figure shows the three-phase voltages obtained at the terminals of the generator, and the equation relates the speed of the machine, its number of poles, and the frequency of the resulting voltage.

Schematic cross section of a synchronous machine with a cylindrical round-rotor (turbo generator) which is the typical designs for all large turbo generators. Here both the stator and rotor windings are installed in slots, distributed around the periphery of the machine. The second part shows the resulting waveforms of a pair of conductors, and that of a distributed winding. The formula giving the magneto-motive force (mmf) created by the windings.

Figure 2.14: Synchronous machine construction salient-Pole rotor.
2.10. AC Generator Function

According to the Faraday's law of electromagnetic induction, whenever a conductor moves in a magnetic field EMF gets induced across the conductor. If the close path is provided to the conductor, induced EMF causes current to flow in the circuit. The conductor coil ABCD is placed in a magnetic field. The direction of magnetic flux will be from N pole to S pole. The coil is connected to slip rings, and the load is connected through brushes resting on the slip rings. Consider the case 1 from above figure. The coil is rotating clockwise, in this case the direction of induced current can be given by Fleming's right hand rule, and it will be along A-B-C-D. As the coil is rotating clockwise, after half of the time period, the position of the coil will be as in second case of figure 2.16. In this case, the direction of the induced current according to Fleming's right hand rule will be along D-C-B-A. It shows that, the direction of the current changes after half of the time period, which means we get an alternating current [27].

i. Faraday’s law says: - the induced voltage in a coil is proportional to the product of the number of loops and rate at which the magnetic field changes with the loop.

\[
V = N \frac{d\phi}{dt}
\]  

(2.14)
ii. If a coil of area $A$ rotates with respect to a field $B$, and if at a particular time it is an angle $\Theta$ to the field, then the flux linking the coil is $BA\cos\Theta$, and the rate of change of flux is given by

$$\frac{d\Phi}{dt} = BA \frac{d}{dt}(\sin \Theta) = \frac{d\Theta}{dt} \cos \Theta = w \cos \Theta$$

(2.14)

![Figure 2.16: AC Generator Function](image)

### 2.11. Principles of Operation of Synchronous Machines

The synchronous electrical generator (also called alternator) belongs to the family of electric rotating machines. Other members of the family are the direct current (dc) motor or generator, the induction motor or generator, and a number of derivatives of all these three. What is common to all the members of this family is that the basic physical process involved in their operation is the conversion of electromagnetic energy to mechanical energy, and vice versa. Therefore, to comprehend the physical principles governing the operation of electric rotating machines, one has to understand some rudiments of electrical and mechanical engineering [28].

Magnets always have two poles: one called north; the other called south. Two north poles always repel each other as shown in figure 2.18, as do two south poles. However, north and south poles always attract each other as shown in figure 2.17. A magnetic field is defined as a physical field...
established between two poles. Its intensity and direction determine the forces of attraction or repulsion existing between the two magnets.

![Figure 2.17: lines of force of opposite polarity magnets](image1)

![Figure 2.18: lines of force of same polarity magnets](image2)

The direction of the lines of force is given by the “law of the screwdriver”: mentally follow the movement of a screw as it is screwed in the same direction as that of the current; the lines of force will then follow the circular direction of the head of the screw as shown in figure 2.19. The magnetic lines of force are perpendicular to the direction of current.

![Figure 2.19: Magnetic Fields created by current Flow in a conductor](image3)
Electricity is the flow of positive or negative charges. Electricity can flow in electrically conducting elements (called conductors), or it can flow as clouds of ions in space or within gases. A very useful phenomenon is that, forming the conductor into the shape of a coil can augment the intensity of the magnetic field created by the flow of current through the conductor. In this manner as shown in figure 2.23, as more turns are added to the coil, the same current produces larger and larger magnetic fields. For practical reasons all magnetic fields created by current in a machine are generated in coils. See Figure 2.20. The positive clouds are normally atoms that lost one or more electrons; the negative clouds are normally free electrons as shown in figure 2.21. The electrons flow in a conductor for example copper as shown in figure 2.20.

Figure 2.20: Magnetic field produced by the flow of electric current in a coil-shaped conductor.

Figure 2.21: Ionic Clouds of Positive and Negative currents
2.13. PM Synchronous Machine

A direct drive wind energy systems cannot employ a conventional high speed (and low torque) electrical machines. Hartkopf et al. in [26] has shown that the weight and size of electrical machines increases when the torque rating increases for the same active power. Therefore, it is essential task of the machine designer to consider an electrical machine with high torque density, in order to minimize the weight and the size. In [27] [28], it has been shown that PM synchronous machines have higher torque density compared with induction and switched reluctance machines. Thus a PMSG is chosen for further studies in this work. However, since the cost effectiveness of PMSG is an important issue, low manufacturing cost has to be considered as a design criterion in further steps. There are a number of different PMSG topologies; some of them are very attractive from the technical point of view. However, some of the state of the art topologies suffer from complication in manufacturing process which results in high production costs. PM excitation offers many different solutions. The shape, the size, the position, and the orientation of the magnetization direction can be arranged in many different ways. Here, presented topologies include those of which are investigated for low speed applications or variable speed applications. This list encompasses radial or axial flux machines, longitudinal or transversal flux machines, inner rotor or outer rotor machines and interior magnet or exterior magnet machines. Slot less machines are not presented here.
2.14. Radial Flux or Axial Flux

Air-gap orientation can be identified in two different ways. Here a hypothetical normal vector to the air-gap is adopted along the flux direction as shown in figure 2.24. The axis of the machines is assumed to be along the length of the machine in the cylindrical coordinate system. Relation of the normal vector with the axis of the machine decides the radial or axial topology. If the normal vector is perpendicular to axis, machine is called radial. If the normal vector is parallel with the axis, the machine is called axial.

![Diagram showing radial and axial flux orientations](image)

Figure 2.24: Cross sectional view in radial direction and in axial direction, respectively, of a typical radial flux PMSG [29]

2.15. Axial Flux Machines

Various axial flux topologies have been proposed in recent years and their pros and cons are categorized. Generally, in axial flux machines length of the machine is much smaller compared with radial flux machines. Their main advantage is high torque density, so they are recommended for applications with size constraints especially in axial direction. They have found application in gearless elevator systems, and they are rarely used in traction, servo application, and micro generation and propulsion systems [30]. Figure 2.25 shows cross sectional view in radial direction and in axial direction, respectively, of a typical axial flux PMSG. One of the disadvantages with the axial flux machines is that they are not balanced in single rotor single