



MSc Graduation Project

**Design of Fault Tolerant Energy conversion System for
Increasing Wind Turbine Reliability**

Lu Nie

**Supervisors:
Dr. ir. H. Polinder
Ghanshyam Shrestha**



Delft University of Technology

ACKNOWLEDGMENTS

During this MSc graduation project, I would like to thank everyone who provided help. I am extremely grateful to my supervisor, Henk Polinder, associate Professor of TU Delft. He introduced me to the wonderful world of generators, his remarks during this work have always been to the point and valuable.

I would like to thank Ghanshyam Shrestha, PhD student of TU Delft, who has been my daily supervisor throughout this work. I really appreciate his patience. I've learned a lot from him during the time, not only academic knowledge, but also the academic way of thinking.

I would also like to thank Erika Echavarria, PhD student of TU Delft, who gave me a lot of help at the beginning of this work. Everyone I met here, I would like to thank them all for being so kind and friendly to me.

Most important, I want to thank my parents and my friends, who always care for me, and encourage me throughout my time at TU Delft.

ABSTRACT

Wind energy promises to become an important source of energy in the near future. Penetrating large-scale wind power into power systems presents a lot of challenges to power system operators, generation companies and wind turbine manufactures. In order to design less expensive and more efficient wind turbines, manufacturers have tried a lot of possibilities. However reliability is also an important issue. For this reason much attention needs to be paid to the reliability improvement.

In the beginning, this thesis introduces and discusses modern wind turbines, gives failure rates to express the reliability, analyzes problems and the most critical subassemblies of wind turbines, and gives the possible methods to make wind turbines more reliable.

For electrical part of wind turbine, generator is a crucial component. In this thesis a fault tolerant energy conversion system was designed to meet the specification. With certain faults the system can continue operating and output power. Therefore the reliability of wind turbines is increased.

Finally the design procedure, and comparisons of this fault tolerant generator system and conventional generator system are given.

TABLE OF CONTENTS

ACKNOWLEDGMENTS	3
ABSTRACT	5
TABLE OF CONTENTS	7
Chapter 1 Background	9
1.1 Wind energy	9
1.2 Importance of reliability	9
1.3 Fault tolerance	10
1.4 Thesis objectives	10
Chapter 2 Literature review	11
2.1 Definition of reliability	11
2.2 Wind turbine constructions	12
2.3 Wind turbine subassembly	13
2.4 Wind turbine size	16
2.5 Downtime	17
2.6 Conclusions	18
Chapter 3 Data analysis	21
3.1 Data sources	21
3.2 Failure rates	23
3.3 Conclusions	25
Chapter 4 Fault tolerant energy conversion system	27
4.1 Introduction of fault tolerance	27
4.2 Methods to achieve fault tolerance	27
4.3 Fault tolerance of PM generator and converter system	28
Chapter 5 Generator design	31
5.1 Reference generator design	31
5.1.1 Specific requirements	31
5.1.2 Assumption	31
5.1.3 Materials	32
5.1.4 Design method	33

5.1.5 Inductances Calculation.....	34
5.1.6 Design parameters	42
5.1.7 Resulting performance	43
5.2 Fault tolerant generator design	44
5.2.1 Designed inductance	44
5.2.2 Add slot opening.....	45
5.2.3 Finite element results.....	45
5.2.4 Analytical calculation.....	47
5.2.5 Passive rectifier to Active rectifier.....	49
5.2.6 Spacer tooth	52
Chapter 6 Comparisons	57
6.1 Normal energy conversion system.....	57
6.2 Fault tolerant energy conversion system	57
6.3 Cost and performance.....	60
6.4 Reliability and energy yield	61
6.4.1 Converter fault	61
6.4.2 Winding open circuit fault.....	63
6.4.3 Winding short circuit fault.....	64
Chapter 7 Conclusions and future work.....	67
7.1 Conclusions	67
7.2 Future work.....	68
References.....	69
Appendix A Design equations	71

Chapter 1 Background

This chapter gives some introduction about wind energy and the reliability of wind turbines to the reader. Then fault tolerance is introduced to give a solution for the reliability problem of wind turbine. The objectives of this thesis are explained in the last section of this chapter.

1.1 Wind energy

Wind is called a renewable energy source because the wind will blow as long as the sun shines. Onshore wind energy has been utilized for power generation for more than two thousand years. In modern times, wind energy is mainly used in electricity generation, mainly through the use of wind turbines. Offshore wind which is flowing at higher speeds than onshore wind makes the wind turbines to produce more electricity. So there is an increased interest on offshore wind turbines recently.

Since the prevention of climatic change is considered as one of the most important international goals in energy policy, wind turbine technology has been undergoing a dramatic development. Now it is the fastest growing renewable energy source in the world.

Globally, many wind-farms, both onshore and offshore, are being planned and built in recent years. Also, the sizes of wind turbines are becoming larger. The penetration of wind power into the power system is also becoming more and more significant. Therefore wind turbine is an important part of modern energy system.

1.2 Importance of reliability

Generally the wind turbine designs have reached a discrete reliability level and some problems like the noise produced by the blades or the power control have been overcome. However in order to produce more electricity, wind turbines can be sited offshore, where the wind blows harder and larger turbines can be installed.

So many offshore wind farms are being proposed and developed today. It is known that the costs and difficult access to these sites and its consequent impact on maintenance and repair cost constitutes the most important barrier to the achievement of this objective. It can be estimated that the cost for offshore operation is far higher than the cost of the same operation for on-shore wind turbines [1, 2]. This makes the reliability analysis of the future wind turbines play a crucial role for a further development of wind energy.

Reliability, as a critical factor in the success of wind energy projects, directly affects both the project's revenue and the availability to generate power. In order to find out a way to improve the reliability of wind turbines, probabilities and reasons of the failures that exist in wind turbine system need to be analyzed.

1.3 Fault tolerance

Even the reliability of wind turbines has been improved with time and has achieved availability of 98% [16], wind turbines fail at least once a year or even more often for larger turbines [5]. Especially for offshore wind turbines, it will cause low availability due to the difficult access.

In this thesis, only electric system has been discussed. In the event of the failure of one or some of its components, a higher availability can be achieved if the system can continue operating. So apart from reducing failure rates of these components of wind turbines, making the electrical system fault tolerant can also improve the availability of wind turbine.

In order to make electric system fault tolerance in a suitable way, it is necessary to gain insight into the probability of different failures [13].

1.4 Thesis objectives

The main objective of this thesis is to design a fault tolerant energy conversion system and suggest how it can improve the reliability of wind turbines. In order to reach this main target, the following topics need to be covered as well:

- (1) Review wind turbine technologies and focus on the electric components of wind turbines.
- (2) Evaluate the reliability of these subcomponents by analyzing databases containing failures of wind turbines.
- (3) Design the fault tolerant energy conversion system, and compare it with the conventional system.
- (4) Compare the generator system based on efficiency and cost.

At the end of the thesis there is a discussion on the results obtained in the previous parts. The last chapter contains conclusion and some suggestions for further research on topics of fault tolerant generator system for wind turbine application.

Chapter 2 Literature review

2.1 Definition of reliability

Reliability is defined as the probability that a system will perform its intended function during a specified period of time under stated conditions. The modeling of wind turbine reliability in [4] has shown that the Power Law Process (PLP) and Homogeneous Poisson Process (HPP) can be used to analyze the reliability of complex repairable equipment like a wind turbine.

The Power Law Process (PLP) is also called the Weibull Process, whose intensity function is flexible enough to represent the three different phases, particularly suitable to model the reliability of repairable systems. Its intensity function describes the failure rate, of a piece of machinery such as a wind turbine, and has the form with time t is:

$$\lambda(t) = \frac{\beta}{\theta} \left(\frac{t}{\theta}\right)^{\beta-1} \quad (2-1)$$

The parameter β determines the trend of the curve and is called shape parameter. θ is the scale parameter that has dimensions of time and $\theta > 0$; $t \geq 0$. Figure 1 shows the life curve described by (2-1). This curve is referred as the bathtub curve, and it has 3 regions:

1. Early Failures, $\beta < 1$
2. Constant Failure, $\beta = 1$
3. Deterioration, $\beta > 1$

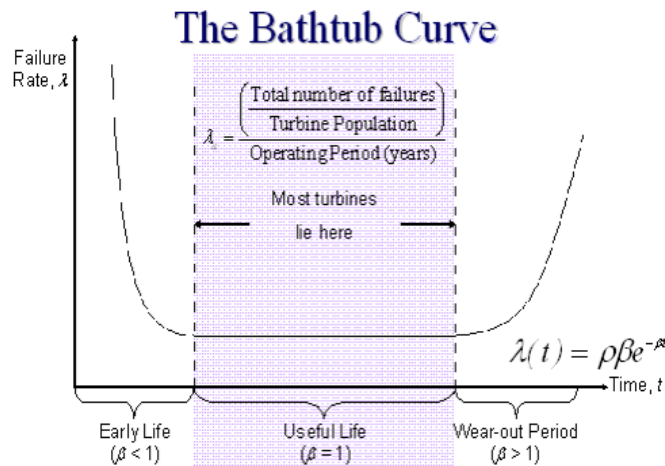


Figure 2-1 The "Bathtub Curve" for the intensity function showing how the reliability varies throughout the life of repairable machinery

If $\beta = 1$ the Equation 1 becomes the Homogeneous Poisson Process (HPP) and θ becomes the Mean Time between Failure (MTBF) of the machine where for a survey series of I intervals of length T_i with n_i failures in each interval:

$$\theta = \frac{1}{\lambda} = \frac{\sum_{i=1}^I T_i}{\sum_{i=1}^I n_i} \quad (2-2)$$

A deterioration phase, where $\beta > 1$, has not yet been encountered in wind turbines, because the turbines are maintained and failing subassemblies will have been replaced. If the reliability of a wind turbine reduces dramatically, it will be taken out of service before the deterioration phase can be detected.

There are not many sources of information to study reliability of wind turbine technology. Only few databases exist with failure information such as the WMEP [6] and LWK [7] in Germany, one in Denmark published by WindStats Newsletter [8], and according to Ref. [9], one in Finland published by the VTT, and one in Sweden published by Elforsk. These data have been used often to study reliability of wind turbines. Few publications attempted to compare the data provided in all these databases. However, they all face the same challenge of comparing different topologies, placed in different sites, and with information collected in different ways [5].

Using the terminology adopted by the bathtub curve model, Windstats Germany (WSD) wind turbines are in the early failure phase, Windstats Denmark (WSDK) wind turbines are in the constant failure phase and LWK wind turbines are approaching the wear out phase [10].

2.2 Wind turbine constructions

As the technology of modern wind turbines matures the construction has become relatively standardized around the three-bladed, upwind, variable speed concept. But within this basic concept there are different architectures, the most commonly used concepts are:

1. Geared wind turbines, a more standardized, high-speed asynchronous generator and partly rated converter, Figure 2-2.
2. Direct drive wind turbines with no gearbox, but a specialized direct drive, low-speed synchronous generator and fully rated converter, Figure 2-3.

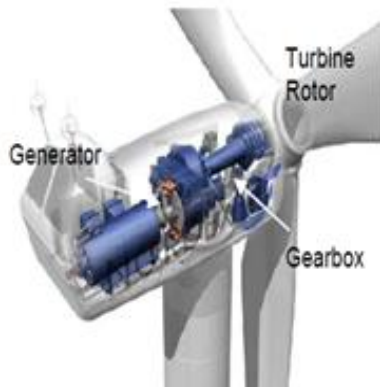


Fig. 2-2 Geared drive concept [3]

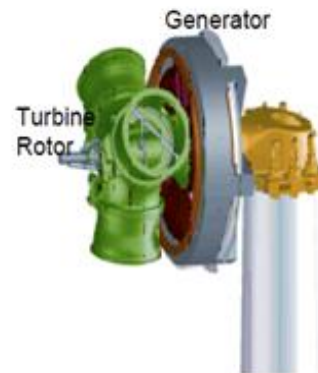


Fig. 2-3 Direct drive concept [3]

For the geared concept, it uses a more standardized, high-speed generator and a partially rated converter, thereby saving cost.

For the direct drive concept, it eliminates the gearbox, which is achieved by coupling the rotor directly with a generator that operates at low rotational speeds. Most commonly a shaft connects the rotor directly with the generator, but some manufacturer use no shaft but only a single bearing, where on one side the hub is mounted and the generator rotor is on the other side. The advantage of this concept is the reduction of rotating parts and nacelle's weight. The full rated converter and the generator size make the cost of this concept high.

2.3 Wind turbine subassembly

In order to understand WT reliability we need to break the WT down into more detail, and this is done using the following nomenclature [3]:

1. System, the whole WT;
2. Subsystem of the WT, such as:
 - a) Rotor, consisting of rotor blades, pitch mechanism and rotor hub;
 - b) Drive train, consisting of main shaft, main bearing, gearbox, brake, generator and couplings;
3. Subassemblies of subsystems, such as the gearbox;
4. Components of subassemblies, such as a bearing in a gearbox.

A wind turbine is made up of a number of key subassemblies. Table 1 summarizes the main functions of subassemblies. Note that these subassemblies can be further broken down into their structural parts, for example the generator consists of a rotor, a stator, slip rings etc.

Table.1 Functions of subassemblies

Subassemblies	Functions
Blades	To rotate due to lift force by wind
Hub	For blades attachment
Pitch system	To adjust blade pitch angle to control power output and limit loads, to brake the wind turbine
Yaw system	To orientate the rotor based on wind direction
(Low & high speed) Shafts	To transmit torque
Gearbox	To increase rotational speed
Electrical generator	To convert mechanical torque to electromagnetic torque
Power Electronics Converter	To match generated electricity to grid specifications
Main transformer	To step up voltage level
Sensors	To measure various operational parameters
Control system & PLC	Monitoring, controlling, automation
Braking system	To brake wind turbine
Electrical systems	To connect WT to the grid, to supply power, etc
Tower	Nacelle mounted on top

Previous work on Reliability analysis for wind turbines [4] concentrated on understanding the behavior of wind turbines and their subassemblies by analyzing the average failure frequency, it offers an important insight into the current reliability of wind turbines, with clear indication about the most problematic subassemblies and the ones for which reliability improvement should more likely be expected.

The conclusions of reference [4] were that the gearbox was not necessarily the most failure prone subassembly and that converter and electrical system components of the wind turbine are less reliable. Similar data, collected from the LWK survey, show a similar result. Failure data are typically collected from operation engineers, who are asked to fill in forms, taken from the German survey WMEP. In fact this comparison suggests that the two German populations, WSD and LWK, have more in common with one another than with the WSDK data. Danish data comes from a population of smaller, older turbines that include relatively few variable speed drive machines, whereas the two German populations include larger turbines with variable speed. Furthermore this consistency proves the validity of the two German surveys.

From the analysis of the overall average failure rate of the three surveys WSD, WSDK and LWK, subassemblies with the highest failure frequency are in descending order as:

- a. Electrical system
- b. Rotor (ie Blades & Hub)
- c. Converter (ie Electrical Control, Electronics, Inverter)
- d. Generator
- e. Hydraulics
- f. Gearbox

Data on failure rates of some subassemblies from these three surveys are compared in ref. [10] which is shown in Table 2 and Figure 2-4.

Table.2 The average failure frequency for each subassembly for all three populations [10]

	WSD (1291-4285 WTs)	WSDK (851-2345 WTs)	LWK (158-643 WTs)
Electrical system	0.2940	0.0468	0.3200
Rotor or blades	0.1910	0.0486	0.1900
Electrical control	0.1820	0.1500	0.2390
Yaw system	0.1080	0.0645	0.1160
Generator	0.1050	0.0497	0.1390
Hydraulic system	0.0958	0.0451	0.1310
Gearbox	0.0929	0.0425	0.1340
Pitch control	0.0893	0.0141	0.0834
Air brakes	0.0411	0.0164	0.0397
Mechanical brake	0.0330	0.0289	0.0554
Main shaft	0.0212	0.0145	0.0311
Other	0.1880	0.2090	0.3670

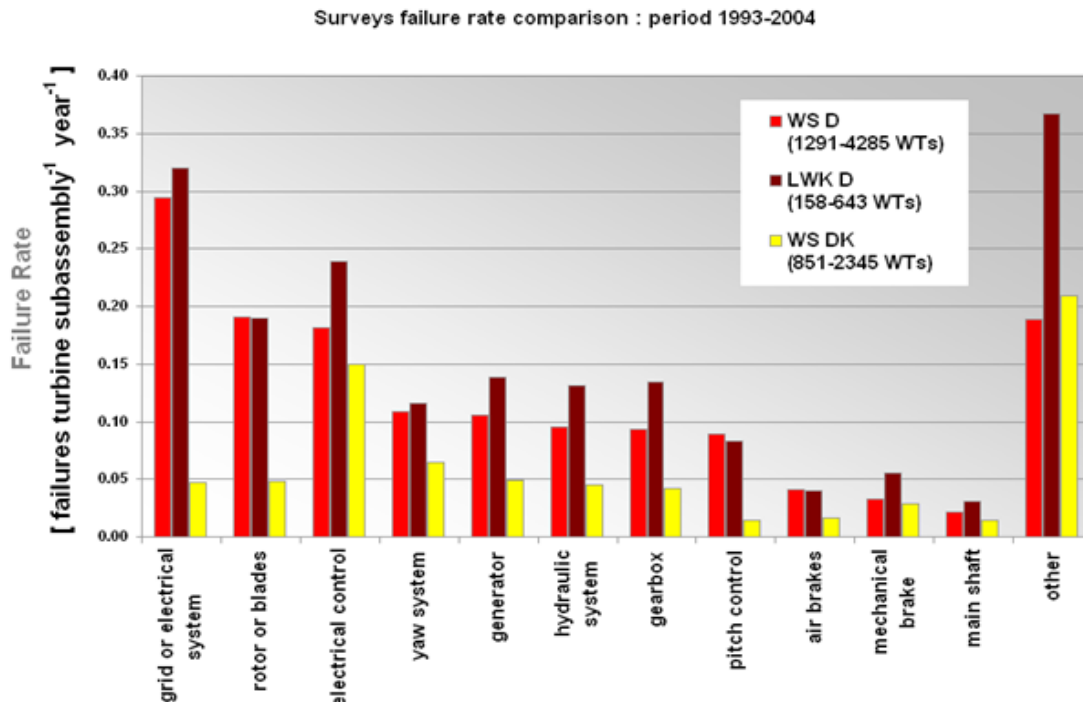


Figure 2-4 Failure rates of subassemblies of wind turbines for 3 different databases [3]

It shows that electrical system and electrical control are the most problematic subassemblies. To improve the reliability of wind turbines will have to focus on the two

electrical related subassemblies. The ways to improve the electrical system of a WT can be revealed with the analysis of the failure modes.

2.4 Wind turbine size

In [3] it is carried out that the wind turbine size is correlated to the failure frequency. Reliability of larger wind turbines is generally lower than small wind turbines. The positive correlation between failure rate and turbine rating is shown in figure 2-5.

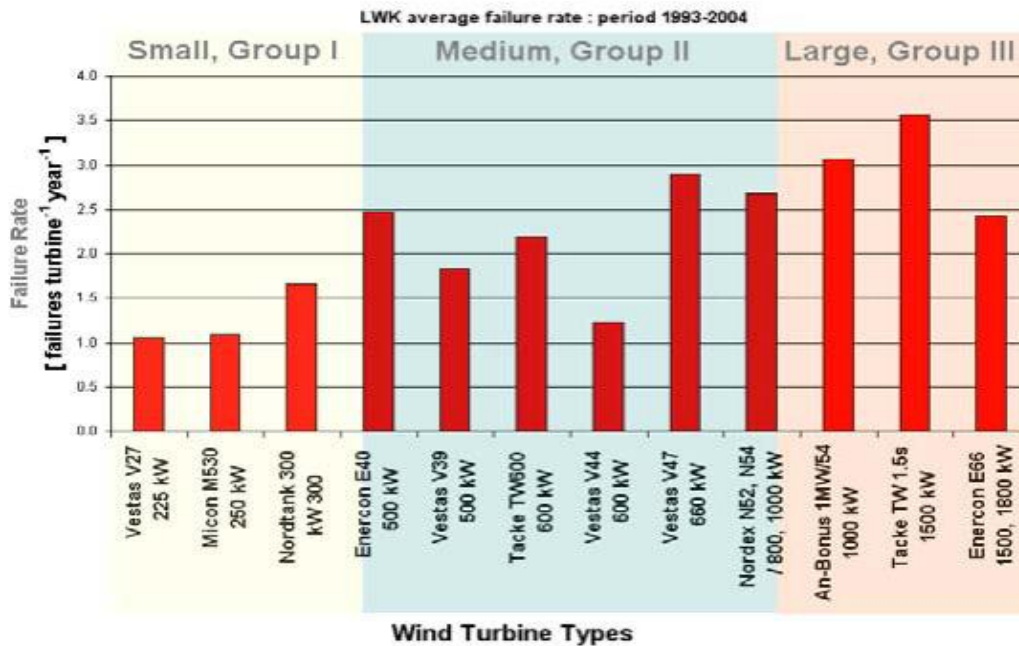


Figure 2-5 the average failure frequency of the three turbines groups [3]

This figure shows the overall average failure frequency. The origin of the increased unreliability of larger turbines can be due to three factors:

1. The newer technology
2. The higher complexity of the technology
3. The effect of the scaling factor due to turbine size that is a higher stress-strength ratio

In order to improve the reliability of the large wind turbines, a different response would be needed for each of the causes, as listed below:

1. Technology development
2. Simplification of the architecture
3. Redefinition of the design standard

From Figure 2-5 we can see that direct drive wind turbines do not necessarily have better reliability than indirect drive wind turbines. It shows that the direct drive E40 has a higher failure frequency than its indirect drive partners of the same size, whereas the direct drive E66 has a lower failure frequency than its partners [3].

2.5 Downtime

There are still many different aspects to consider other than failure rates, for instance, downtime caused by failures, and other effects on reliability.

The reliability issues are affected by the severity of the occurrences rather than the mere frequency. The severity of a failure event can be quantified according to a subjective scale, with a process commonly used by people implementing a failure modes and effects analysis (FMECA). The downtime, resulting from a failure, is subjected to a number of factors of either random or planned nature, as:

- a) Availability of spare parts
- b) Availability of personnel
- c) Accessibility to the WT site
- d) Weather conditions
- e) Corrective maintenance policy

In [12] a thorough reliability analysis focused on comparison of the most prominent architectures is also using failure data from the two German databases, LWK-SH and WMEP. Four wind turbine models, each one representing a specific topology, were selected based on the amount of available data in terms of number of monitored units and years of operation: Micon M1500, Enercon E-40, Tacke TW600, Vestas V39. From the analysis of more than 10 operational years of failure data for these onshore wind turbines located in Germany, it was found that mid power class machines experienced 2 to 5 failures per wind turbine per year. As expected, failure rates are lower for wind turbines close to the coastline where lower turbulence levels are observed.

By taking advantage of the LWK-SH downtimes information, critical subassemblies in terms of resulting downtime per wind turbine prove to be the gearbox, generator, shafts and bearings, blades, and electrical system. For each subassembly, the downtime due to one failure occurrence is given in figure 2-6.

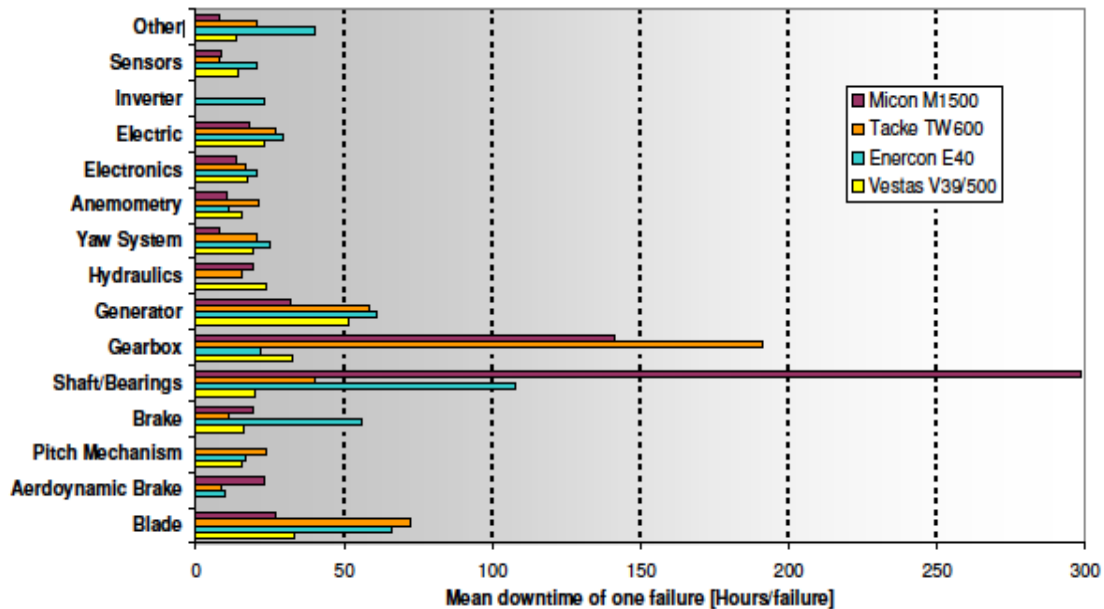


Figure 2-6 Mean downtimes due to a failure [12]

It should be mentioned that some wind turbines do not incorporate certain subassemblies. For example, Micon M1500 is a pure passive stall wind turbine with fixed blades that cannot pitch. Despite the absence of a pitch mechanism, some failures were reported for this subassembly in WMEP. These are included in the graphs just to illustrate that sometimes operators did not report the correct subassembly that failed when filling in the WMEP form. This might be due to different interpretation of categories by the various wind farm operators. Failure rates for Enercon and Vestas aerodynamic tip brakes, as well as Enercon's gearbox and mechanical brakes are presented in the graphs for the same reason.

However, it has been shown that the downtime of gearboxes and generator is much higher than the downtime of electrical-related subassemblies. This suggests that an all-electric, direct drive WT may ultimately have an intrinsically higher availability than an indirect drive WT [10].

2.6 Conclusions

As a critical factor in the success of wind energy projects is the wind turbine system, reliability directly affects both the project's revenue and the availability to generate power. In order to find out a way to improve the reliability of wind turbines, probabilities and reasons of the failures existing in wind turbine system need to be analyzed.

According to the failure rates of some subassemblies from three surveys, Electrical system, Rotor (ie Blades & Hub), Converter (ie Electrical Control, Electronics, and Inverter), Generator, Hydraulics, and Gearbox require reliability attention.

The reliability of larger wind turbines is generally lower than small wind turbines. Direct drive wind turbines do not necessarily have better reliability than indirect drive wind turbines.

Downtime of gearboxes and generator is much higher than the downtime of electrical-related subassemblies. This suggests that an all-electric, direct drive wind turbine may ultimately have an intrinsically higher availability than an indirect drive wind turbine.

Selection of the most reliable implementation and adding redundancy may also help to improve the availability of future offshore wind turbines.

Chapter 3 Data analysis

After getting an overview of wind energy and wind turbine reliability, more specific cognizance is needed to find out an appropriate and effective way to increase the reliability of wind turbine. So we start from analyzing the failure data of electrical components of wind turbine.

3.1 Data sources

Scientific Measurement and Evaluation Programme (WMEP) is a part of the “250MW wind” funding programme, an incentive of the German Federal Government to fund electricity produced by wind turbines across Germany. It first began as a 100 MW programme in 1989, was expanded to 250 MW in 1991, and reached 350MW by 2006. All funded plants had to deliver operational information to the parallel running WMEP monitoring programme for at least 10 years. Even after that period, some operators kept providing data on a voluntary basis for up to 5 more years.

Institut für Solare Energieversorgungstechnik (ISET) in Kassel handles and processes the WMEP database. Every year standardized evaluations are made public in the form of a yearly report (“Wind Energy Report Germany” [14]) and since early 1997 some results are available on the internet [15] as well.

The WMEP database consists of up to 15 years operational data (1989-2006) from approximately 1500 wind turbines of various sizes and technologies. The report that participants in the WMEP programme were requested to fill in the WMEP report, which is shown in Figure 3-1. WMEP database is clearly defined which systems are included since they are further split into subcategories.

From this WMEP database, there is a file with the number of failures of components and their sub-components, such as windings, brushes and bearings are sub-components of generator. For each of these failures the cause and the consequence are registered in the maintenance reports.

<h1 style="margin: 0;">Maintenance and Repair Report</h1> <h2 style="margin: 0;">WMEP 250 MW-Wind</h2>		<div style="display: flex; justify-content: space-between;"> <div> work carried out <div style="display: flex; align-items: center;"> <div style="border: 1px solid black; width: 20px; height: 20px; margin-right: 5px;"></div> <div style="border: 1px solid black; width: 20px; height: 20px; margin-right: 5px;"></div> <div style="border: 1px solid black; width: 20px; height: 20px; margin-right: 5px;"></div> <div style="border: 1px solid black; width: 20px; height: 20px;"></div> </div> <div style="margin-left: 5px;"> day month year </div> </div> <div> reporting <div style="border: 1px solid black; width: 50px; height: 20px;"></div> </div> </div>													
<div style="display: flex; justify-content: space-between; margin-bottom: 5px;"> <div style="border: 1px solid black; width: 150px; height: 20px;"></div> <div style="border: 1px solid black; width: 150px; height: 20px;"></div> </div> <div style="display: flex; justify-content: space-between; font-size: 0.8em;"> post code plant identification number </div> <div style="border: 1px solid black; width: 100%; height: 20px; margin-bottom: 5px;"></div> <div style="border: 1px solid black; width: 100%; height: 20px; margin-bottom: 5px;"></div> <div style="border: 1px solid black; width: 100%; height: 20px;"></div>	<h3 style="margin: 0;">cause of malfunction</h3> <div style="display: flex; justify-content: space-between;"> <div style="width: 45%;"> <input type="checkbox"/> high wind <input type="checkbox"/> grid failure <input type="checkbox"/> lightning <input type="checkbox"/> icing </div> <div style="width: 45%;"> <input type="checkbox"/> malfunction of control system <input type="checkbox"/> component wear or failure <input type="checkbox"/> loosening of parts <input type="checkbox"/> other causes <input type="checkbox"/> cause unknown </div> </div>														
<h3 style="margin: 0;">reason for repair</h3> <div style="margin-top: 5px;"> <input type="checkbox"/> scheduled maintenance <input type="checkbox"/> scheduled maintenance with replacement of worn parts or repair of defects <input type="checkbox"/> unscheduled repair after malfunction </div>	<h3 style="margin: 0;">effect of malfunction</h3> <div style="display: flex; justify-content: space-between; margin-top: 5px;"> <div style="width: 45%;"> <input type="checkbox"/> overspeed <input type="checkbox"/> overload <input type="checkbox"/> noise <input type="checkbox"/> vibration </div> <div style="width: 45%;"> <input type="checkbox"/> reduced power <input type="checkbox"/> causing follow-up damage <input type="checkbox"/> plant stoppage <input type="checkbox"/> other consequences </div> </div>														
<h3 style="margin: 0;">down time</h3> <div style="margin-top: 5px;"> <input type="checkbox"/> not stopped <input type="checkbox"/> stopped </div> <div style="margin-top: 5px;"> <div style="display: flex; align-items: center;"> <div style="margin-right: 10px;">from</div> <div style="border: 1px solid black; width: 60px; height: 20px;"></div> </div> <div style="display: flex; align-items: center;"> <div style="margin-right: 10px;">to</div> <div style="border: 1px solid black; width: 60px; height: 20px;"></div> </div> <div style="display: flex; justify-content: space-around; font-size: 0.8em; margin-top: 5px;"> <div style="border: 1px solid black; width: 20px; height: 20px;"></div> <div style="border: 1px solid black; width: 20px; height: 20px;"></div> <div style="border: 1px solid black; width: 20px; height: 20px;"></div> </div> <div style="display: flex; justify-content: space-between; font-size: 0.8em; margin-top: 5px;"> day month time </div> </div> <div style="margin-top: 5px;"> <div style="border: 1px solid black; width: 150px; height: 20px;"></div> <div style="font-size: 0.8em;">reading of hour counter</div> </div>	<h3 style="margin: 0;">removal of malfunction</h3> <div style="margin-top: 5px;"> <input type="checkbox"/> perfect functioning of plant after <div style="display: flex; justify-content: space-between; font-size: 0.8em;"> <input type="checkbox"/> control reset <input type="checkbox"/> changing of control parameters </div> </div> <div style="margin-top: 5px;"> <h4 style="margin: 0;">repaired or replaced components</h4> <div style="display: flex; justify-content: space-between;"> <div style="width: 45%;"> <input type="checkbox"/> hub <input type="checkbox"/> hub body <input type="checkbox"/> pitch mechanism <input type="checkbox"/> pitch bearings <input type="checkbox"/> rotor blades <input type="checkbox"/> blade bolts <input type="checkbox"/> blade shell <input type="checkbox"/> aerodynamic brakes <input type="checkbox"/> generator <input type="checkbox"/> generator windings <input type="checkbox"/> generator brushes <input type="checkbox"/> bearings <input type="checkbox"/> electric <input type="checkbox"/> converter <input type="checkbox"/> fuses <input type="checkbox"/> switches <input type="checkbox"/> cables/connections <input type="checkbox"/> sensors <input type="checkbox"/> anemometer/wind vane <input type="checkbox"/> vibration switch <input type="checkbox"/> temperature <input type="checkbox"/> oil pressure switch <input type="checkbox"/> power sensor <input type="checkbox"/> revolution counter <input type="checkbox"/> control system <input type="checkbox"/> electronic control unit <input type="checkbox"/> relay <input type="checkbox"/> measurement cables and connections </div> <div style="width: 45%;"> <input type="checkbox"/> gear box <input type="checkbox"/> bearings <input type="checkbox"/> wheels <input type="checkbox"/> gear shaft <input type="checkbox"/> sealings <input type="checkbox"/> mechanical brake <input type="checkbox"/> brake disc <input type="checkbox"/> brake pads <input type="checkbox"/> brake shoe <input type="checkbox"/> drive train <input type="checkbox"/> rotor bearings <input type="checkbox"/> drive shafts <input type="checkbox"/> couplings <input type="checkbox"/> hydraulic system <input type="checkbox"/> hydraulic pump <input type="checkbox"/> pump motor <input type="checkbox"/> valves <input type="checkbox"/> hydraulic pipes/hoses <input type="checkbox"/> yaw system <input type="checkbox"/> yaw bearings <input type="checkbox"/> yaw motor <input type="checkbox"/> wheels and pinions <input type="checkbox"/> structural parts/housing <input type="checkbox"/> foundation <input type="checkbox"/> tower/tower bolts <input type="checkbox"/> nacelle frame <input type="checkbox"/> nacelle cover <input type="checkbox"/> ladder </div> </div> </div>														
<h3 style="margin: 0;">costs stated on bill</h3> <div style="margin-top: 5px;"> <table style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 60%; text-align: right;">material</td> <td style="border: 1px solid black; width: 150px; height: 20px;"></td> <td style="width: 25%; text-align: right;">DM</td> </tr> <tr> <td style="text-align: right;">labour</td> <td style="border: 1px solid black; width: 150px; height: 20px;"></td> <td style="text-align: right;">DM</td> </tr> <tr> <td style="text-align: right;">journey</td> <td style="border: 1px solid black; width: 150px; height: 20px;"></td> <td style="text-align: right;">DM</td> </tr> <tr> <td style="text-align: right;">total cost incl. VAT</td> <td style="border: 1px solid black; width: 150px; height: 20px;"></td> <td style="text-align: right;">DM</td> </tr> </table> </div>	material		DM	labour		DM	journey		DM	total cost incl. VAT		DM	<h3 style="margin: 0;">comments</h3> <div style="margin-top: 5px;"> <div style="border: 1px solid black; height: 20px; margin-bottom: 5px;"></div> <div style="border: 1px solid black; height: 20px; margin-bottom: 5px;"></div> <div style="border: 1px solid black; height: 20px; margin-bottom: 5px;"></div> <div style="border: 1px solid black; height: 20px; margin-bottom: 5px;"></div> <div style="border: 1px solid black; height: 20px; margin-bottom: 5px;"></div> <div style="border: 1px solid black; height: 20px; margin-bottom: 5px;"></div> </div>		
material		DM													
labour		DM													
journey		DM													
total cost incl. VAT		DM													
<h3 style="margin: 0;">operator</h3> <div style="margin-top: 5px;"> <div style="border: 1px solid black; width: 150px; height: 20px; margin-bottom: 5px;"></div> <div style="font-size: 0.8em;">place/date</div> <div style="border: 1px solid black; width: 150px; height: 20px; margin-bottom: 5px;"></div> <div style="font-size: 0.8em;">signature</div> </div>	<h3 style="margin: 0;">replaced main components</h3> <div style="display: flex; justify-content: space-between; margin-top: 5px;"> <div style="width: 45%;"> <input type="checkbox"/> nacelle <input type="checkbox"/> rotor/blade-blades <input type="checkbox"/> hub <input type="checkbox"/> gear box <input type="checkbox"/> generator </div> <div style="width: 45%;"> <input type="checkbox"/> yaw system <input type="checkbox"/> tower <input type="checkbox"/> control system cabinet <input type="checkbox"/> transformer </div> </div>														

Figure 3-1 Maintenance and repair report of WMEP [14]

3.2 Failure rates

In the thesis, we focus on electrical components: generator, electric system and control system. The average failure frequency or rate will be used to assess reliability of different topologies and subassemblies. This is defined as the ratio of the number of failures occurring during a time interval over the number of monitored wind turbines times this interval.

Although any time scale can be used, failure rate is commonly expressed in number of failures per wind turbine per calendar year; in that case it is called annual failure rate and can be calculated using the following equation:

$$f = \frac{\sum_{i=1}^I N_i}{\sum_{i=1}^I X_i T_i} \quad (3-1)$$

Where,

f Annual failure rate

N_i Number of failures occurred during the time interval T_i

X_i Number of wind turbines reported for the time interval T_i

T_i Time intervals (I in total of 1 year each one)

Using the data from the file with the number of failures of components and their sub-components, failure rates of each components and sub-components can be calculated. The results are shown in table 3 and figure 3-2.

Table.3 Calculation results failure rates

Type of failure	Failure rate
Generator-other failures	0.362
Generator-windings	0.088
Generator-brushes	0.082
Generator-bearings	0.112
Electric-other failures	0.585
Electric-converter	0.315
Electric-fuses	0.487
Electric-switches	0.68
Electric-cable connection	0.417
Control system-other failures	0.45
Control system-electronic control unit	0.745
Control system-relay	0.3033
Control system-measurement cables& connections	0.2383

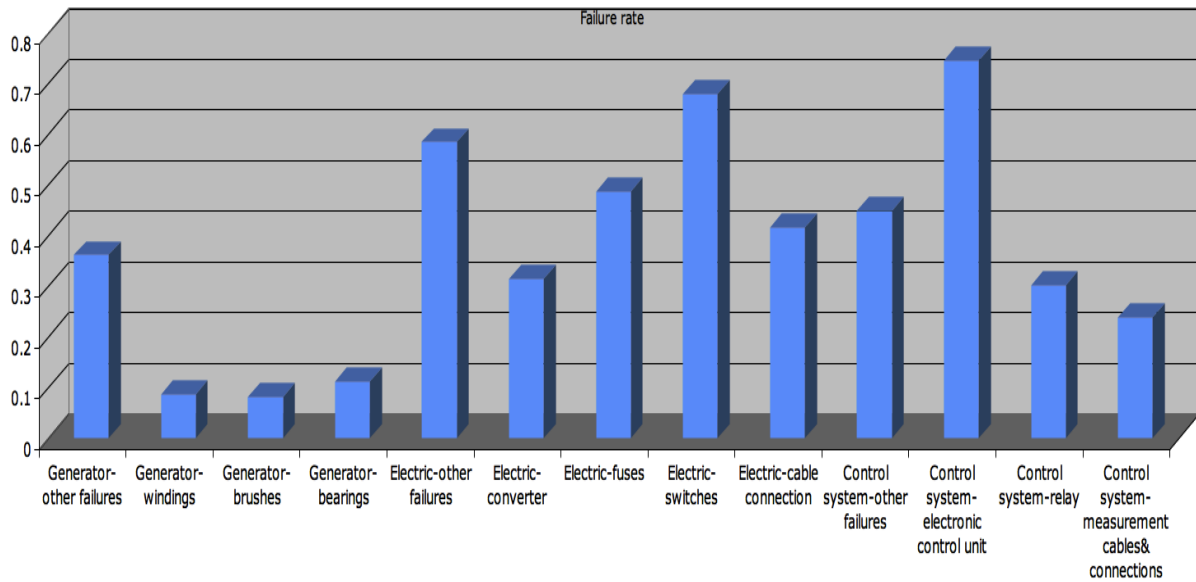


Figure 3-2 Failure rates of three electrical components and their sub-components

From this table, we can see that a large percentage of failures are the other unknown failures. This is a limitation for our work and we cannot figure out how to solve these unknown failures.

We also have a look at the downtime of each component, which is shown in figure 3-3.

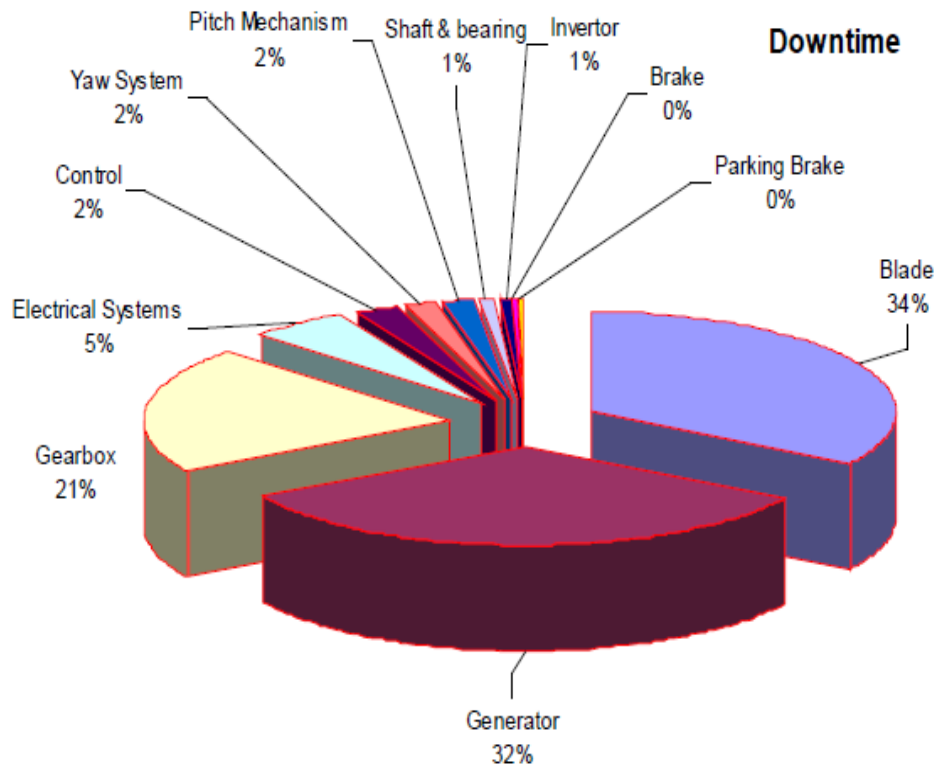


Figure 3-3 Downtime of each component

From this figures, it can be concluded that:

- The generator failure as well as gearbox failure although low on number of failures, the impact on downtime and losses is major
- The control system has the high failure frequency, but a low percentage in the losses. This is due to the fact that most of the failures were auto-restarted (When some failures could not be reset automatically or remotely, the control system also has a significant percentage in the losses, and local repair was necessary.)

3.3 Conclusions

Analyzing the failure rates of three electrical components, we can find that even the generators do not fail frequently as some components like electric system and control system, its large downtime and difficult maintenance are the important factors for the reliability of wind turbines.

So in order to increase the reliability of wind turbines, one thing which should be effective is to design a fault tolerant generator system to enable the wind turbine still works when there is a fault on generator.

Chapter 4 Fault tolerant energy conversion system

This chapter introduces the fault tolerance concept, and lists possible ways to make an energy conversion system fault tolerant. Then it discusses all these method and gives the best solution for an energy conversion system in wind turbine application.

4.1 Introduction of fault tolerance

Fault tolerance is the ability of a system to respond gracefully to an unexpected failure. It can enable a system to continue operating properly in the event of one or more failures of its components. So fault-tolerance can make the system with a high-availability.

Since the failure rate of generators in wind turbines application is higher than the average failure rate of generators in other applications, and the resulting downtime is significant, maybe it is attractive to apply the fault tolerant generator system in wind turbine. When one of the components in the generator system fails, the generator can continue operation to give power. It reduces the risk of unscheduled downtime and also increases the availability.

4.2 Methods to achieve fault tolerance

Five different ways to achieve fault tolerance identified in literature [13] are discussed together with their applicability for wind turbines:

- 1) Converters with redundant semiconductors for three-phase AC machines.

In this series-connection of power semiconductors, if one power semiconductor fails, it can be short-circuited while the others continue operation. However, this method of fault tolerance does not solve faults in the generator. So it will not be used in this thesis.

- 2) Fault tolerant converter topologies for three-phase AC machines.

Topologies such as the switch-redundant topology, the double-switch redundant topology, the phase redundant topology, and cascaded inverter topology can be used. However this method adds a lot of complexity to the system, so it is not necessary that the availability increases a lot.

- 3) Fault tolerance by increasing the number of phases of machine and converter.

The method is the most interesting because it can be done without adding a lot of components, so without adding a lot of cost. The modular electrical arrangement of a multi phase conversion system is shown in figure 4-1.

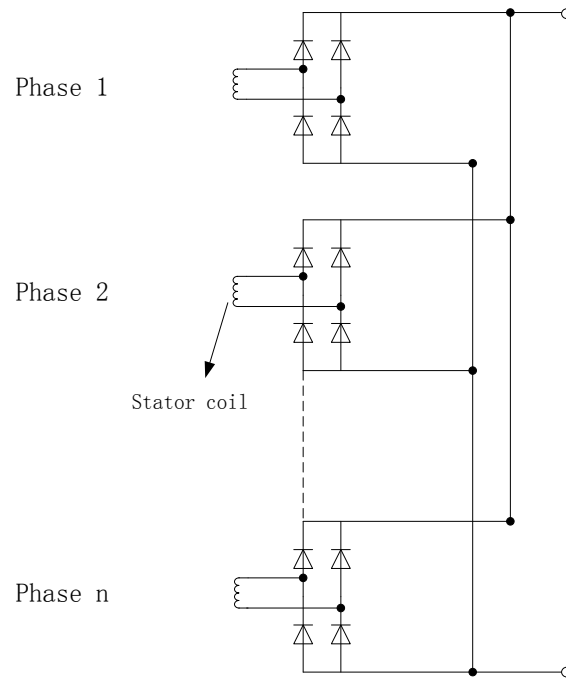


Figure 4-1 Modular electrical arrangement

This approach can deal with faults in the power electronics and with open circuit faults in the machine. But for short circuits faults, it will result in an unacceptably high current.

4) Fault tolerance of switched reluctance machines.

Switched reluctance machines have inherent fault tolerance, but this method is not worked out because switched reluctance machines have lower force densities and are not applied in wind energy.

5) Design for fault tolerance of PM machines and converters.

This system is capable of tolerating the widest variety of failures, including short circuits in the machine. This is achieved by designing a PM generator with a 1 per unit phase inductance and a full bridge converter for each phase. The mutual inductance between the phases should be very small, so that a short circuit in one phase hardly influences the other phases. The 1 per unit inductance can ensure the machine continue operation with a short circuit in the machine, and the short-circuit current is also 1 per unit. Maybe the fault tolerant system is cheaper than the redundant system, but we still need to consider the increase of the generator cost.

4.3 Fault tolerance of PM generator and converter system

From the discussion in section 4.2, we choose to design a fault tolerance of PM generator and converter system in this thesis. And this fault tolerant system will be compared with the normal system at the end.

In order to design this fault tolerant generator to tolerate machine faults such as winding short circuit faults, the most important thing is to gain the one per unit phase inductance which can keep the generator continue operation at rated current with a short circuit in the generator.

Furthermore, we do not want a high mutual inductance between the phases. When there is a fault in one phase, the small mutual inductance gives small influences to other phases.

So, in order to get the one per unit self inductance and ideally low mutual inductance, the calculation of inductances becomes important for this fault tolerant design.

Chapter 5 Generator design

In this chapter, we first design a reference generator. Design requirements, assumptions are listed. Then design parameters and performance of the generator are calculated. However, the phase self inductance of the reference generator is not high enough to give a 1 per unit self inductance. After that, possible ways to make the generator fault tolerant are given and discussed.

5.1 Reference generator design

In our thesis project, a radial flux machine with concentrated winding (8 tooth-9 poles combination) is used because a high winding factor and a low cogging torque can be expected [16]. For concentrated winding, this 8-9 pole-slot combination gives relatively low losses in the back iron and permanent magnets [17]. The configuration of this reference generator is given in figure 5-1.

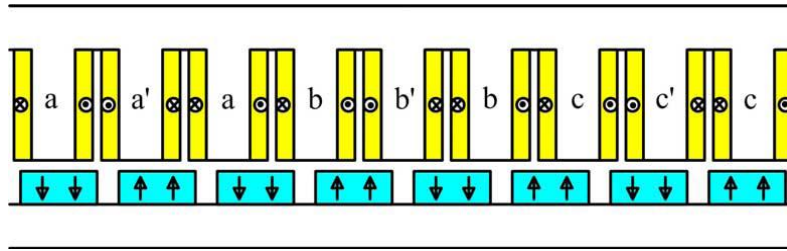


Figure 5-1 A radial flux machine with concentrated winding (8 poles-9 tooth)

5.1.1 Specific requirements

The constraints for this reference generator used in wind turbine application are given as:

1. Power at the grid: 100kW
2. Generator power rating: 110kW (due to the losses in the converter and generator)
3. Rotational speed: 80rpm
4. Blade diameter: 20m
5. Tip speed: 8.4
6. Power coefficient: 0.5
7. Average wind speed: 7.1 m/s

5.1.2 Assumption

Based on the conditions and experience, we make some assumptions to quantify certain parameters:

- a) The permanent magnets temperature is constant, remanant flux density changes due to temperature is not taken into account.
- b) The generator copper temperature is 120°C.

- c) The generator is loaded with a passive rectifier, so the current phasor is very close to the terminal voltage. Even though in reality current will lagging the terminal voltage slightly, for simplicity it is assumed that terminal voltage is in phase with the current, see figure 5-2.

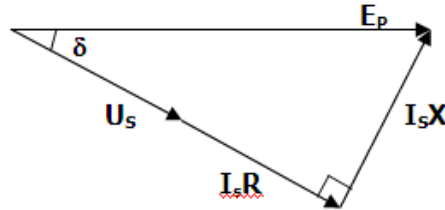


Figure 5-2 A phasor diagram of the generator with passive rectifier

- d) The iron losses are proportional to the frequency to the power of 1.5 and the square of the magnetic flux density.
- e) The higher time harmonics of the stator currents and the higher space harmonics of the air gap flux density are negligible.
- f) The fill factor of the stator slots is 0.6.
- g) The number of stator phases is 3.
- h) This machine without skewing. The winding factor for such design is relatively high and a lower cogging torque can be expected in such designs [18]. Skewing adds complexity to manufactory and adds axial forces to the machine.
- i) The slots are open type (it may goes to other type later based on the design requirment).

5.1.3 Materials

Common materials used in industry are chosen for this design. They may change according to the specific requirements. The prices are roughly estimated which include some labor.

- Stator laminations
Material: M330-50A
Specific losses: $P_{Fe,spec} = 3.3 \text{ W/kg}$ at 50 Hz and 1.5 T,
Mass density: $\rho_{m,Fes} = 7650 \text{ kg/m}^3$,
Flux densities: 1.49 T at 2.5 kA/m, 1.60 T at 5 kA/m, 1.70 T at 10 kA/m,
Cost: $C_{Fes} = 3 \text{ €/kg}$.
- Rotor yoke iron:
Flux density: 1.5 T at 2 kA/m
Mass density: $\rho_{m,Fes} = 7650 \text{ kg/m}^3$,
Cost: $C_{Fe} = 3 \text{ €/kg}$.

- Stator conductors:
Resistivity: $\rho_{Cu} = 0.0238 \mu\Omega\text{m}$ at 120°C ,
Mass density: $\rho_{m,Cu} = 8900 \text{ kg/m}^3$,
Cost: $C_{Cu} = 15 \text{ €/kg}$.
- Magnets:
Material: BM38H
Typical remanent flux density: $B_r = 1.15 \text{ T}$ at 90°C ,
Relative recoil permeability: $\mu_{rm} = 1.09$,
Mass density: $\rho_{m,m} = 7350 \text{ kg/m}^3$,
Cost: $C_m = 70 \text{ €/kg}$.

5.1.4 Design method

Design procedure for this generator is shown in figure 5-3 as a flow chart.

Equations for this generator design are listed in appendix A, and calculation details of self inductance and mutual inductance are given in section 5.1.5.

A optimization Matlab program is used to calculate the annual energy yield from the turbine, based on a wind function characterized by the Weibull parameter $k=2$ (shape parameter) and $A=8 \text{ m/s}$ (scale parameter belonging to an average wind speed of 7.1 m/s). It can gain the maximum annual energy yield by varying the basic dimensions of the generator.

When we come to fault tolerant design for this reference generator, those free parameters in figure 5-3 can be elaborated to gain the 1 per unit phase inductance. Another possibility is to make the stator tooth with a small slot opening. These efforts for fault tolerant design will be discussed in section 5.2.

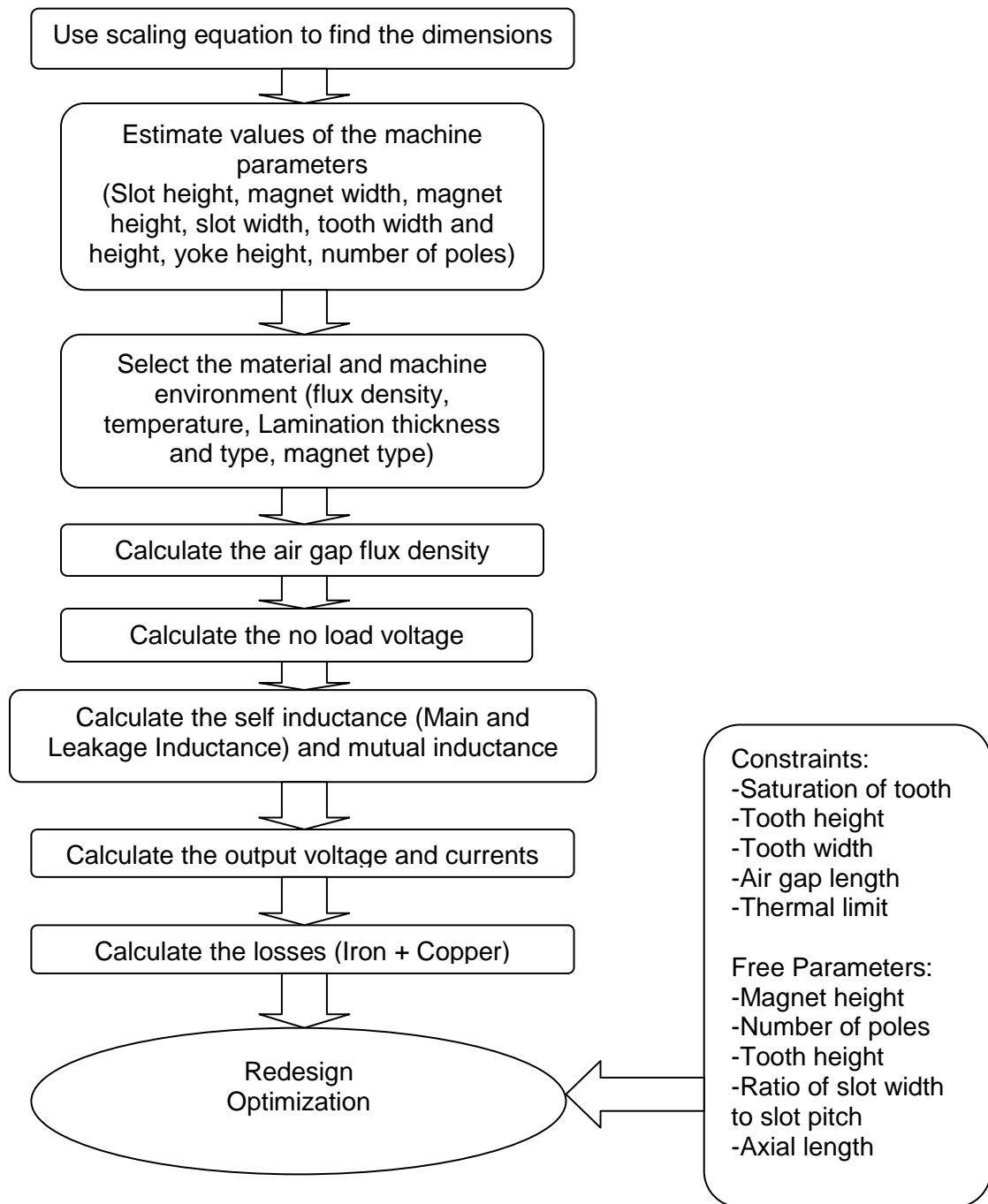


Figure 5-3 Design procedure for generator

5.1.5 Inductances Calculation

Both self inductance and mutual inductance of the reference generator are calculated in this section. These analytical results will be checked by finite element method (FEM).

5.1.5.1 Reluctances

(1) Air gap reluctance

The configuration of the radial flux machine with concentrated winding (8 poles – 9 teeth) and some dimension parameters are shown in figure 5-4. The air-gap reluctance is the reluctance between a tooth and the back iron.

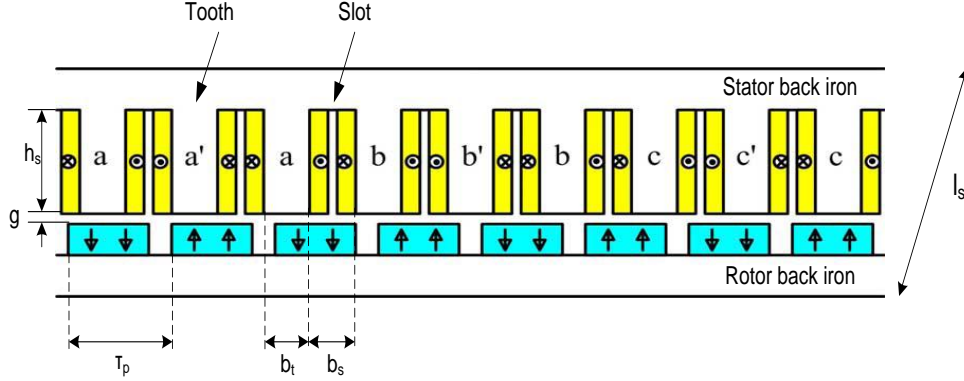


Figure 5-4 Section of a radial flux machine with concentrated winding (8-9 combination) and some dimensions

Using the general expression for the value of reluctance, the air-gap reluctance is expressed by using the effective air gap g_{eff} . The width of flux path is chosen as tooth width plus slot width, because the flux crosses the air gap not only below the tooth, but much wider than the tooth width due to the fringing effect. So the air gap reluctance is calculated by using effective air gap.

$$R_g = \frac{g_{eff}}{\mu_0 l_s (b_t + b_s)} \quad (5-1)$$

This makes the air gap slightly bigger than the physical gap. Effective air gap can be described as:

$$g_{eff} = g_1 k_{carter} \quad (5-2)$$

$$g_1 = g + \frac{l_m}{\mu_{rm}} \quad (5-3)$$

$$k_{carter} = \frac{\tau_s}{\tau_s - \gamma g_1} \quad (5-4)$$

$$\gamma = \frac{4}{\pi} \left(\frac{b_s}{2g_1} \arctan \frac{b_s}{2g_1} - \log \sqrt{1 + \left(\frac{b_s}{2g_1} \right)^2} \right) \quad (5-5)$$

Where

- k_{carter} is the Carter factor [17];
- g is air-gap length;
- l_m is magnet length in the magnetization direction;
- μ_{rm} is relative magnetic permeability of the magnets;
- μ_0 is magnetic permeability in vacuum;
- τ_s is slot pitch;
- b_s is slot width;
- b_t is tooth width;
- l_s is stack length, the length in the direction perpendicular to the plane of the drawing in Figure 5-4.

(2) Leakage reluctance

Some magnet flux jumps from one tooth to the next tooth in the air gap without passing into the magnet, which is illustrated by the path in the air gap in Figure 5-5. The flux follows this path is called leakage flux. Leakage flux from one tooth to the next tooth flows through the leakage reluctance R_σ which is calculated as follows.

First of all, using Ampère's Law:

$$\oint \vec{H} \cdot \vec{\tau} dl = \iint \vec{J} \cdot \vec{n} dA \quad (5-6)$$

$$Hb_s = \frac{N_{\text{slot}} i x}{h_s} \quad (5-7)$$

Where

- N_{slot} is the number of turns of a coil around one tooth;
- h_s is the slot height;
- x is a variable used in the circuit surface, because the leakage flux density in the slot increases from zero close to the yoke to maximum close to the air gap.

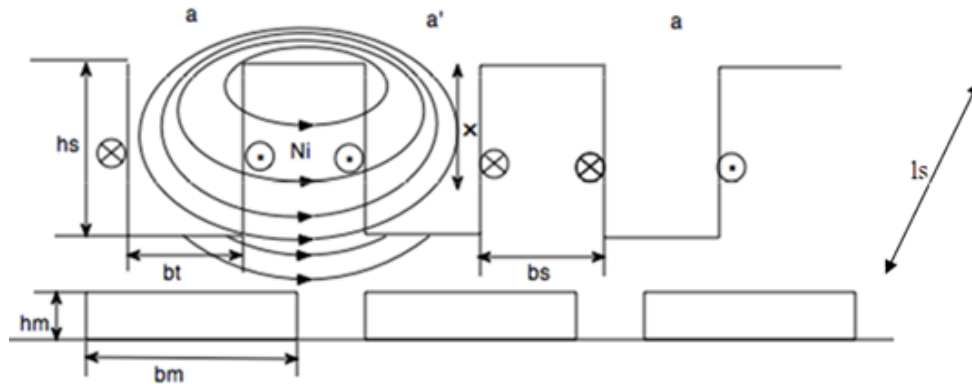


Figure 5-5 Leakage flux plot

So the magnetic field strength H and the flux density B at the slot are:

$$H = \frac{N_{slot}xi}{b_s h_s} \quad (5-8)$$

$$B = \mu_0 H = \frac{\mu_0 N_{slot}xi}{b_s h_s} \quad (5-9)$$

The flux linkage λ can be calculated from the surface integral of the flux density:

$$\lambda = \iint \vec{B} \cdot \vec{n} dA = l_s \sum_x^{N_{slot}} \int_{h_s}^{h_s} \frac{\mu_0 N_{slot}xi}{h_s b_s} dx \quad (5-10)$$

Then the flux linkage as a function of x can be described as:

$$\lambda(x) = \frac{l_s \mu_0 N_{slot} i}{2 h_s b_s} (h_s^2 - x^2) \quad (5-11)$$

So the flux linkage λ becomes:

$$\begin{aligned} \lambda &= \frac{N_{slot}}{h_s} \int_0^{h_s} \lambda(x) dx = \frac{N_{slot}}{h_s} \times \frac{l_s \mu_0 N_{slot} i}{2 h_s b_s} \left(h_s^2 x - \frac{1}{3} x^3 \right) \Big|_{x=0}^{x=h_s} \\ &= \frac{l_s \mu_0 N_{slot}^2 i h_s}{3 b_s} \end{aligned} \quad (5-12)$$

Using the equation $\lambda = Li$, the leakage inductance is:

$$L_\sigma = \frac{l_s N_{slot}^2 \mu_0 h_s}{3 b_s} \quad (5-13)$$

And the slot leakage reluctance R_σ is:

$$R_\sigma = \frac{N_{slot}^2}{L_\sigma} = \frac{b_s}{\mu_0 l_s \frac{h_s}{3}} \quad (5-14)$$

5.1.5.2 Self-inductance

In this section, a magnet circuit model of the reference generator is derived from figure 5-4. Since we assume that the permeability of the tooth and the rotor stator back iron are infinite, the reluctances of them are neglected in this model which is shown in figure 5-6.

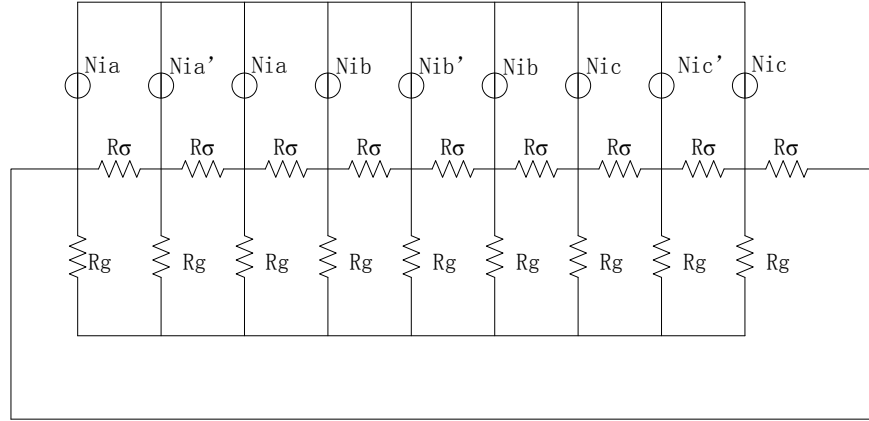


Figure 5-6 Magnet circuit model

In order to calculate the self-inductance easily, we put the phase *a* in the middle and only one tooth coil in phase *a* has current. Then we get a new magnet circuit model in figure 5-7.

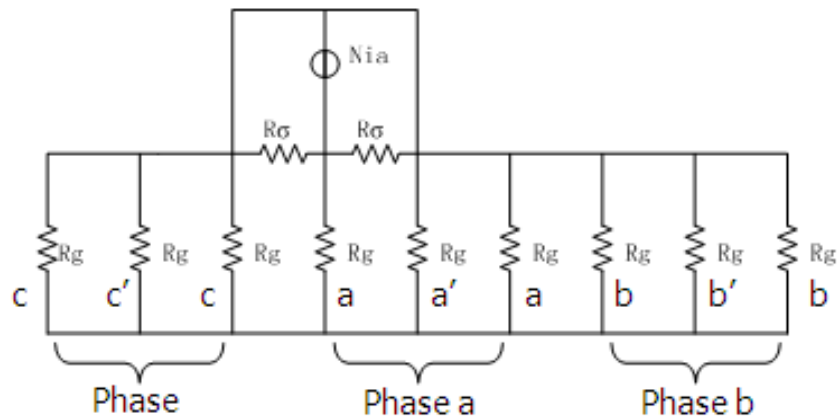


Figure 5-7 Magnet circuit Model when one tooth has current

From figure 5-7 a simplified magnet circuit model, which is shown in figure 5-8, was used to calculate the flux goes to each tooth under this condition.

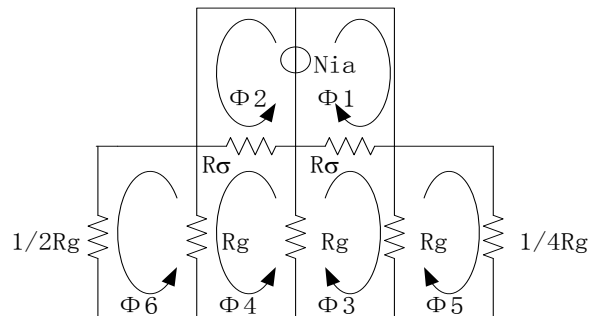


Figure 5-8 Simplified magnet circuit model

From figure 5-8, we get the following equations:

$$\left\{ \begin{array}{l} N_{slot} i_a = (\phi_1 - \phi_3) R_\sigma \\ N_{slot} i_a = (\phi_2 - \phi_4) R_\sigma \\ 0 = (\phi_3 - \phi_1) R_\sigma + (\phi_3 - \phi_5) R_g + (\phi_3 + \phi_4) R_g \\ 0 = (\phi_4 - \phi_2) R_\sigma + (\phi_4 - \phi_6) R_g + (\phi_4 + \phi_3) R_g \\ 0 = \phi_5 \frac{1}{4} R_g + (\phi_5 - \phi_3) R_g \\ 0 = \phi_6 \frac{1}{2} R_g + (\phi_6 - \phi_4) R_g \end{array} \right. \quad (5-18)$$

Using this set of equations, we can calculate the flux goes to every other tooth due to tooth a is:

$$\phi = \frac{N_{slot} i_a}{9 R_g} \quad (5-19)$$

Then we consider the whole phase a in this model together, which is shown in figure 5-9. Phase a have current and other teeth of phase b and phase c get flux from phase a .

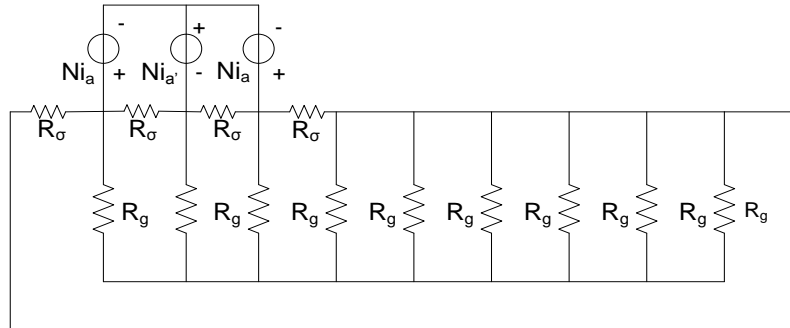


Figure 5-9 Magnet circuit Model when phase a has current

Using equation (5-19) we can know the flux on each tooth in this 9-8 combination. It is illustrated in figure 5-10.

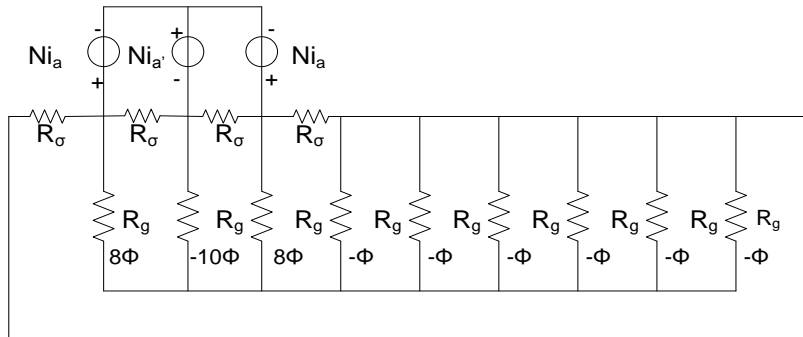


Figure 5-10 Magnet circuit Model with flux

From figure 5-9, we can also see that the leakage flux between tooth a and a' is doubled than the leakage flux between tooth a and tooth b or tooth c . Both leakage fluxes are calculated as:

$$\phi_{ab} = \phi_{ac} = \frac{N_{slot} i_a}{R_\sigma} \quad (5-20)$$

$$\phi_{aa'} = \frac{2N_{slot} i_a}{R_\sigma} \quad (5-21)$$

So the flux linkage of phase a in this model is:

$$\begin{aligned} \lambda &= N\phi = N_{slot} (8\phi + \phi_{ab} + 10\phi + \phi_{aa'} + 8\phi + \phi_{ac}) \\ &= N_{slot} \left(\frac{26N_{slot} i_a}{9R_g} + \frac{10N_{slot} i_a}{R_\sigma} \right) \end{aligned} \quad (5-22)$$

Taking other teeth in the same phase account, equation for phase self-inductance L_s is:

$$L_s = \frac{\lambda}{i_a} \times \frac{N_s}{3N_{slot}} = \frac{N_s N_{slot} (26R_\sigma + 90R_g)}{27R_\sigma R_g} \quad (5-23)$$

Substitute equations (5-1) and (5-15) in equation (5-23), we can get the value of self-inductance.

5.1.5.3 Mutual-inductance

For mutual inductance calculation, we use a similar way. From figure 5-9, we find out that the mutual flux of phase b is:

$$\phi_{ba} = 3\phi = \frac{N_{slot} i_a}{3R_g} \quad (5-24)$$

So the flux linkage of phase b due to phase a is:

$$\lambda_{ba} = N\phi_{ba} = N_{slot} \times 3\phi = N_{slot} \frac{N_{slot} i_a}{3R_g} \quad (5-25)$$

Finally, take other teeth in the same phase into account and the phase mutual inductance of is calculated as:

$$M = \frac{\lambda_{ba}}{i_a} \times \frac{N_s}{3N_{slot}} = \frac{N_{slot} N_t}{9R_g} \quad (5-26)$$

5.1.5.4 Finite element analysis

In this thesis, the finite element method is used to verify the magnetic circuit and compute the inductance values.

By using FEMM program, we draw the 8 poles-9 tooth combination with the same dimension parameters in previous calculation and set the periodical boundary condition for both left and right side boundaries. In order to get self inductance easily, we turn off the magnet and only energize phase b with current. Check the flux plot and calculation result from FEM which are shown in Figure 5-11.

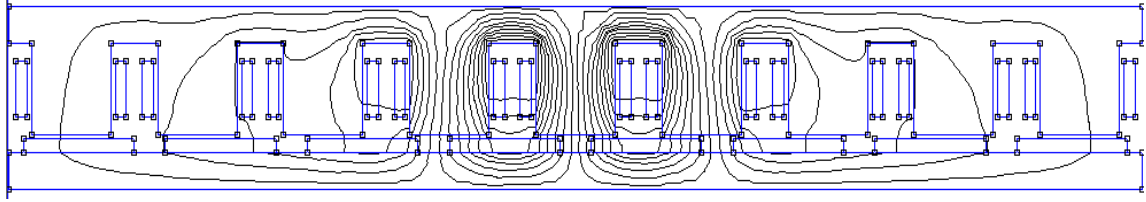


Figure 5-11 flux plot when phase b has current, when $i_b=320A$

From the results, we can get flux linkage on phase b is:

$$\lambda_b = 0.0268681Wb \quad (5-27)$$

and the self inductance of phase b in this 9-8 combination is calculated as:

$$L_b = \frac{\lambda_b}{i_b} = 8.39627 \times 10^{-5} H \quad (5-28)$$

Because the total number of teeth in one phase is:

$$\frac{N_s}{N_{slot}} = \frac{72}{3} = 24 \quad (5-29)$$

Total number of this 8-9 combination group in this generator is:

$$n = \frac{24}{3} = 8 \quad (5-30)$$

Therefore, total self inductance of phase b is:

$$L_{phase} = L_b \times 8 = 6.72 \times 10^{-4} H \quad (5-31)$$

Mutual inductance can be also calculated from FEM in a similar way. When phase b has current, it causes a flux linkage on the other two phases. Here we use phase a for the mutual inductance calculation. Flux linkage of each tooth in phase a due to phase b is:

$$\begin{aligned}
\lambda_{a_1b} &= -0.000714784Wb \\
\lambda_{a'b} &= 0.0000736774Wb \\
\lambda_{a_2b} &= -0.00129556Wb
\end{aligned}
\tag{5-32}$$

The mutual inductance of phase *a* in this 9-8 combination is the sum of these three flux linkages divided by the current on phase *b*:

$$M_a = \frac{\lambda_{a_1b} + \lambda_{a'b} + \lambda_{a_2b}}{i_b} = 8.585 \times 10^{-6} H \tag{5-33}$$

Then taking other teeth in the same phase into account, we can get the mutual inductance of one phase:

$$M_{phase} = M_a \times 8 = 6.87 \times 10^{-5} H \tag{5-34}$$

Finally we compare these results from FEMM program with the analytical results which are listed in table 4.

Table 4 Results comparison

	L (H)	M (H)
FEMM	6.72×10^{-4}	6.87×10^{-5}
Analytical	7.1×10^{-4}	6.4×10^{-5}

We can see that for mutual inductance, the analytical calculation is very close to the FEM result. But for self inductance, it is a little bit higher than FEM result. This is probably because we assume the permeability of the tooth and the rotor stator back iron is infinite.

5.1.6 Design parameters

After optimization, we can get the dimensions of the generator and some other parameters which are given in table 5.

Table 5. Machine Parameter Table

Parameter	Description	Values
r_{out}	Outside radius of the generator	0.6722 m
r_i	Inner radius of the generator	0.598 m
r_s	Airgap radius	0.65 m
l_s	Axial length of generator	0.295 m
m	No. of phases	3
p	No. of pole pairs	32
L_g	Air Gap	2 mm
τ_p	Pole Pitch	63.8 mm
l_m	Magnet height	5.2 mm

h_s	Slot Height	37 mm
b_s/τ_s	Ratio $B_s\tau_s$	0.37
b_p/τ_p	Ratio $b_p\tau_p$	0.78
h_{sy}	Height of stator yoke	15 mm
h_{ry}	Height of rotor yoke	15 mm
b_s	Slot width	21 mm
b_t	Tooth width	35.7 mm
b_{t1}	Tooth width inner	32.5 mm
b_m	Magnet width	49.8 mm
B_r	Remanent flux density of magnet	1.15T
N_{slot}	Number of turns per slot	3
Weight of the generator		
Total Weight of generator		639 kg
Weight of copper		117 kg
Weight of iron		486 kg
Weight of PM		36 kg
Losses in the generator		
Total Losses (rated)		7.2 kW
Iron Losses (rated)		1.43 kW
Copper Losses (rated)		5.77 kW
Other Parameter		
Current Density		4.3 A/mm ²
Actual Force density		15.67 kN/m ²
Power factor		0.8427
No load phase voltage E_{pnom}		128.7 V
Rated phase current I_{snom}		333.6 A
Rated terminal voltage U_s		102.7 V
Efficiency (rated power)		93.5%
Material Cost		5756 euros
Annual Energy Yield		355.2 MWh
Dissipation per m ²		6 kW/m ²

5.1.7 Resulting performance

The rotational speed of generator, and the phase voltage, the phase current, the power delivered to the grid, the losses and the generator efficiency as a function of the wind 8speed are depicted in figure 5-13.

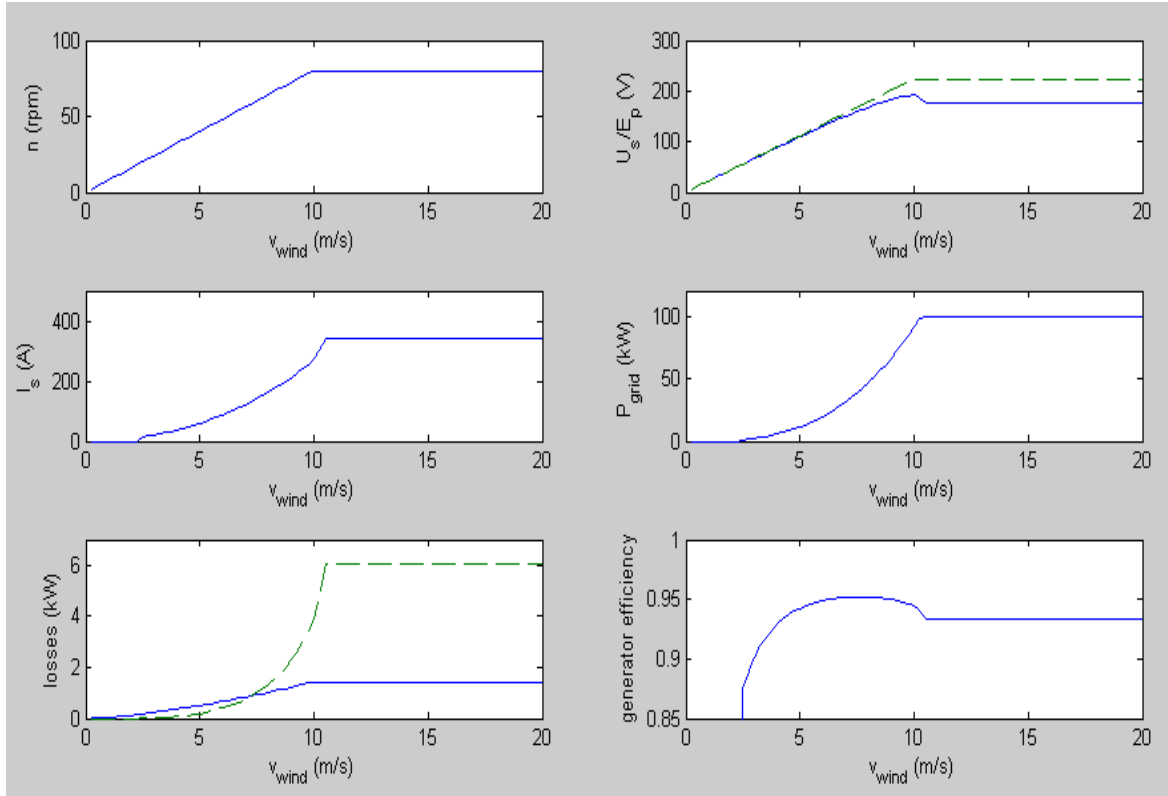


Figure 5-12 Rotational speed, terminal and no-load voltage (--), current, grid power, iron and copper losses (--) and the generator efficiency as a function of the wind speed

5.2 Fault tolerant generator design

One thing which is important to make a generator fault tolerant is the one per unit self inductance. First we need to find out the value of this designed inductance. Then possible ways to achieve this value will be given in the following sections.

5.2.1 Designed inductance

In order to gain the tolerance to a short circuit fault, the generator is designed with a one per unit phase inductance to limit the induced current in the event of a phase short circuit. So the value of this one per unit inductance per phase should be calculated first.

From the short circuit operation diagram of the generator, which is shown in figure 5-13, the terminal voltage is zero when there is a short circuit.

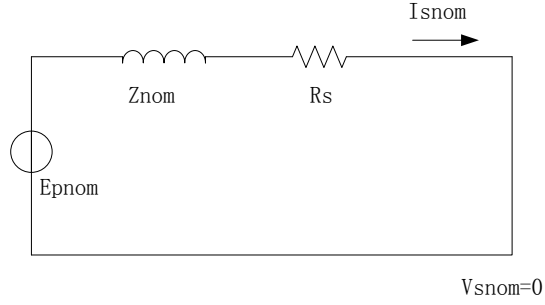


Figure 5-13 Short-circuit operation

An equation for this designed one per unit inductance can be derived from equation A-15 in appendix A:

$$L_{design} = \frac{\sqrt{E_p^2 - (I_{snom} R_s)^2}}{I_{snom} \omega_{enom}} = 0.0014H \quad (5-35)$$

5.2.2 Add slot opening

From the results of inductance calculation in table 4, it is obvious that the phase self inductance is not high enough to reach the 1 per unit current. So Stator topology with narrow slot opening is introduced which is shown in the figure 5-14 below.

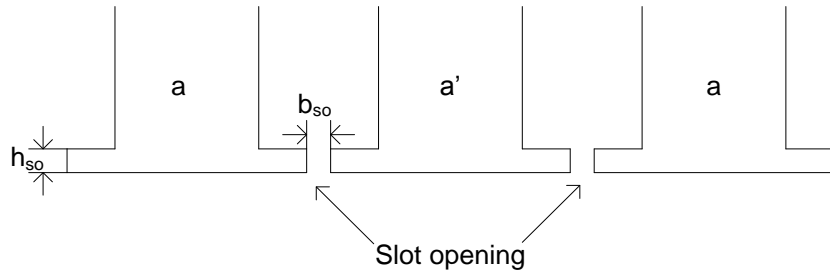


Figure 5-14 Stator tooth with narrow slot opening

In this configuration, h_{so} is the slot opening height and b_{so} is the slot opening width. The narrow slot opening results in a large amount of cross slot flux leakage, which gives the one per unit phase self inductance required for fault tolerance.

5.2.3 Finite element results

This kind of stator tooth will result in a large amount of cross slot flux leakage, which can give a large phase self inductance required for fault tolerance. So we use the similar way as we did in section 5.1.5.4 to check the inductances by FEM.

A 8-9 combination system with the tooth slot opening is drawn in FEMM program. The physical size of the generator is kept constant. We change the generator dimensions

with a narrow slot opening and verify them to gain the designed inductance. We use the slot opening height $h_{so}=0.006$, and the slot opening width $b_{so}=0.003$ in the FEM. Turn off the magnet and check the flux linkage on phase b when only phase b has current. Flux plot of this new generator is given in figure 5-15.

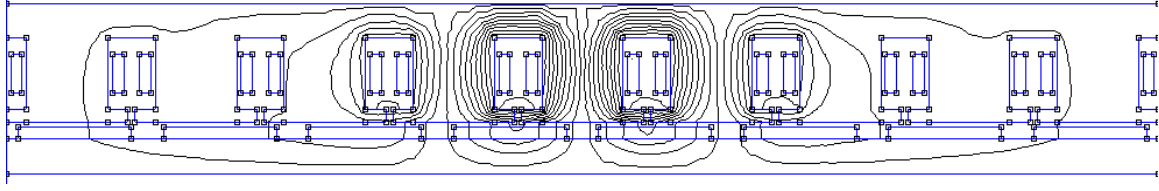


Figure 5-15 flux plot and flux linkage when $i_b=320A$

Due to the current on phase b , flux linkage of phase b is:

$$\lambda_{bb}' = 0.0581237Wb \quad (5-36)$$

then the self inductance of phase b can be calculated as:

$$L_b' = \frac{\lambda_{bb}' - \lambda_{bm}'}{i_b} = 1.8 \times 10^{-4} H \quad (5-37)$$

So total self inductance of phase b of the generator is:

$$L_{phase}' = L_b' \times 8 = 0.0014H \quad (5-38)$$

Compare this self inductance L_{phase}' with the self inductance of the reference generator L_{phase} , we can find that adding slot opening is helpful to increase the self inductance value.

Meanwhile the mutual inductance is also important and is checked here. The way of calculation is the same as we did in previous calculation. As a result, we can get the mutual inductance of each tooth in the same phase:

$$\begin{aligned} M_{a_1b} &= \frac{\lambda_{a_1b} - \lambda_{a_1m}}{i_b} = 1.14 \times 10^{-5} H \\ M_{a_2b} &= \frac{\lambda_{a_2b} - \lambda_{a_2m}}{i_b} = 2.94 \times 10^{-6} H \\ M_{a_3b} &= \frac{\lambda_{a_3b} - \lambda_{a_3m}}{i_b} = 1.64 \times 10^{-6} H \end{aligned} \quad (5-39)$$

Then the total mutual inductance of phase a is the sum of these three inductance, and take the other teeth in the same phase into account:

$$M_{ab} = (M_{a_1b} + M_{a_2b} + M_{a_3b}) \times 8 = 1.28 \times 10^{-4} H \quad (5-40)$$

5.2.4 Analytical calculation

In order to check the analytical results of this generator with slot opening tooth, we need to calculate the inductance again. For this type of generator, there is an additional reluctance part which is the reluctance of the extra slot opening tooth width. So a new magnet circuit model is derived and shown in figure 5-16.

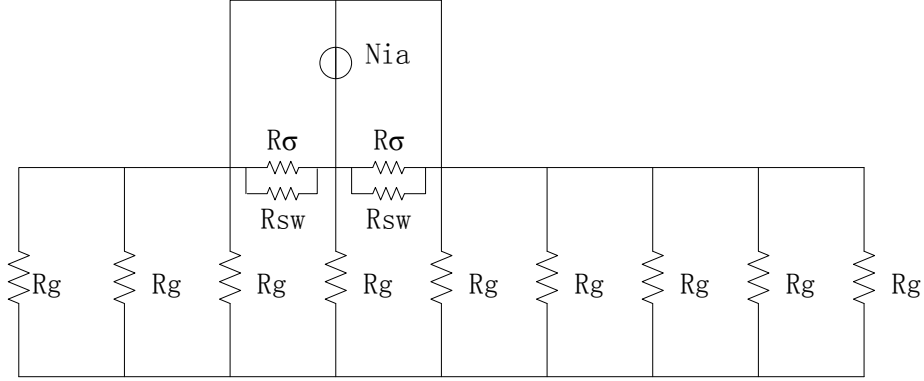


Figure 5-16 Magnet circuit Model of generator with slot opening tooth

The self inductance calculation is the same as we did for reference generator. But here we use a parallel reluctance of leakage reluctance and slot opening width reluctance instead of the leakage reluctance. And the slot opening dimensions are taking into account.

$$R_{\sigma} \Rightarrow R_{parallel} = \frac{R_{\sigma} R_{sw}}{R_{\sigma} + R_{sw}} \quad (5-41)$$

The leakage reluctance R_{σ} here is:

$$R_{\sigma} = \frac{b_s}{\mu_0 l_s \frac{h_s - h_{so}}{3}} \quad (5-42)$$

The reluctance of the slot opening width is:

$$R_{sw} = \frac{b_{so}}{\mu_o l_s h_{so}} \quad (5-43)$$

So, the self inductance becomes:

$$L_s = \frac{N_s N_{slot} (26 R_{parallel} + 90 R_g)}{27 R_{parallel} R_g} \quad (5-44)$$

But for mutual inductance, there are more fluxes cross the tooth slot opening. These fluxes increase the mutual inductance, so the mutual inductance is recalculated as follows:

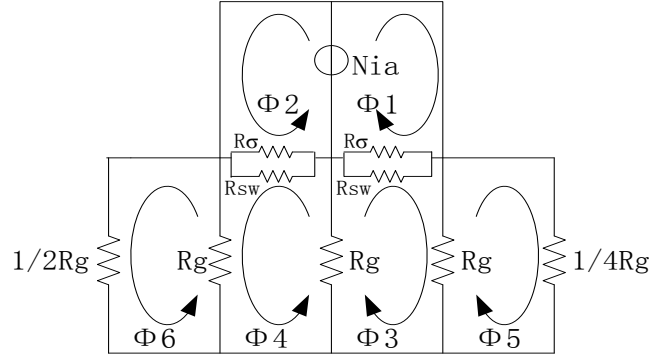


Figure 5-17 magnet circuit model of generator with tooth slot opening

From figure 5-17 we can get a set of equations from the new magnet circuit model of the fault tolerant generator which has the tooth slot opening.

$$\left\{ \begin{array}{l} N_{slot} i_a = (\phi_1 - \phi_3) R_{parallel} \\ N_{slot} i_a = (\phi_2 - \phi_4) R_{parallel} \\ 0 = (\phi_2 - \phi_1) R_{parallel} + (\phi_3 - \phi_5) R_g + (\phi_3 + \phi_4) R_g \\ 0 = (\phi_4 - \phi_2) R_{parallel} + (\phi_4 - \phi_6) R_g + (\phi_4 + \phi_3) R_g \\ 0 = \phi_5 \frac{1}{4} R_g + (\phi_5 - \phi_3) R_g \\ 0 = \phi_6 \frac{1}{2} R_g + (\phi_6 - \phi_4) R_g \end{array} \right. \quad (5-45)$$

From these equations we can derive the mutual flux:

$$\phi_4 - \phi_6 = \frac{N_{slot} i_a}{9 R_g} \quad (5-46)$$

$$\phi_2 - \phi_4 = \frac{N_{slot} i_a}{R_{parallel}} \quad (5-47)$$

Since most of the fluxes go through the adjacent tooth due to the narrow slot opening and the flux linkages due to the other two teeth are canceled out, we consider that the total mutual flux Φ_{total} of phase c is:

$$\phi_{mutual} = \frac{N_{slot} i_a}{9 R_g} \times 3 + \frac{N_{slot} i_a}{R_{parallel}} = \frac{N_{slot} i_a (3 R_g + R_{parallel})}{3 R_g R_{parallel}} \quad (5-48)$$

Therefore, the mutual inductance can be derived as:

$$M = \frac{N\phi}{i} = \frac{N_{slot} i_a (9R_g + R_{sw})}{9R_g R_{sw}} \times \frac{N_{slot}}{i_a} \frac{N_s}{3N_{slot}}$$

$$= \frac{N_s N_{slot} (9R_g + R_{sw})}{27R_g R_{sw}} \quad (5-49)$$

Using the new equations for self inductance and mutual inductance, we can calculate the inductance values of this new generator. Result comparison from both analytical calculation and FEM is shown in table 6.

Table 6 results of generator with slot opening tooth

	L (H)	M (H)
FEMM	0.0014	1.28×10^{-4}
Analytical	0.0013	1.4×10^{-4}

Compare the analytical calculation with the FEM analysis results, we can find out that the self inductance increased a lot and the analytical value of self inductance is similar to the FEM result. However, the rated current becomes to a complex number, this is because a passive rectifier is used. In order to get the fault tolerant generator with designed inductance value, we decided to load the generator with an active rectifier instead.

5.2.5 Passive rectifier to Active rectifier

We want to keep a rated current when a short circuit fault occurs, so a relatively large inductance is required. For passive rectifier, there is a maximum power which is shown on circle in figure 5-18. In the same figure, the dotted red line describes the situation when there is a short circuit current. But under this situation, the generator cannot operate at steady state.

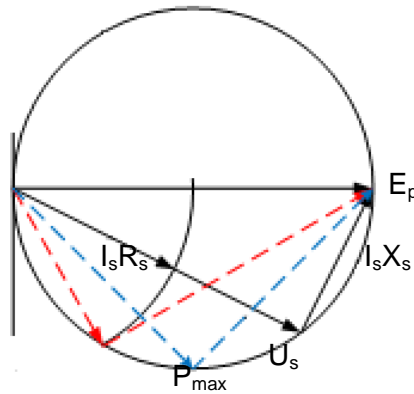


Figure 5-18 analyze the phasor diagram of generator with passive rectifier

So we change the passive rectifier into the active rectifier. When the generator is loaded with an active rectifier, it is assumed that this active rectifier keeps the current phasor in

between the phasor of the electromotive force and the terminal voltage as shown in figure 5-19.

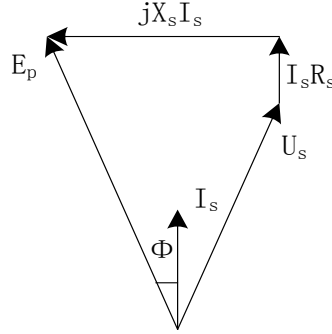


Figure 5-19 Phasor diagram of generator with active rectifier

Equations for rated current and rated voltage calculation are different than before due to this change. So these parameters are calculated from the phasor diagram as follows:

$$I_{snom} = \frac{P_{genom} - P_{Fesnom}}{mE_{pnom} \cos \phi} \quad (5-50)$$

$$U_{snom} = \sqrt{(E_{pnom} \cos \phi - I_{snom} R_s)^2 + \left(\frac{\omega L_s I_{snom}}{2}\right)^2} \quad (5-51)$$

$$\phi = \frac{1}{2} \delta \quad (5-52)$$

$$\delta = \arcsin \frac{(P_{genom} - P_{Fesnom}) \omega L_s}{mE_{pnom}^2} \quad (5-53)$$

Then using these equations to calculate the inductance, and vary some parameters of the generator. Finally we can make the self inductance equal to the designed self inductance:

$$L = L_{design} = 0.0015H \quad (5-54)$$

And the mutual inductance is:

$$M = 1.58 \times 10^{-4} H \quad (5-55)$$

Dimensions and some parameters are shown in table 7. We can compare the weight, the cost and the performance of the generator with the normal type of generator.

Table 7 New parameter table of generator loaded with active rectifier

Parameter	Description	Values
r_{out}	Outside radius of the generator	0.6722 m
r_i	Inner radius of the generator	0.593 m
r_s	Airgap radius	0.65 m
l_s	Axial length of generator	0.2950 m
m	No. of phases	3
p	No. of pole pairs	32
g	Air Gap	2 mm
τ_p	Pole Pitch	63.8 mm
l_m	Magnet height	5.2 mm
h_s	Slot Height	42 mm
h_{so}	Slot opening height	8 mm
b_s/τ_s	Ratio $B_s\tau_s$	0.43
b_p/τ_p	Ratio $b_p\tau_p$	0.78
h_{sy}	Height of stator yoke	15 mm
h_{ry}	Height of rotor yoke	15 mm
b_s	Slot width	24.4 mm
b_{so}	Slot opening width	2 mm
b_t	Tooth width	32.3 mm
b_{t1}	Tooth width inner	28.6 mm
b_m	Magnet width	49.8 mm
B_r	Remanent flux density of magnet	1.15T
N_{slot}	Number of turns per slot	3
Weight of the generator		
Total Weight of generator		652 kg
Weight of copper		126 kg
Weight of iron		490 kg
Weight of PM		36 kg
Losses in the generator		
Total Losses (rated)		6.86 kW
Iron Losses (rated)		1.87 kW
Copper Losses (rated)		4.99 kW
Other Parameter		
Current Density		3.85 A/mm ²
Actual Force density		18.8 kN/m ²
Power factor		0.8491
No load phase voltage E_{pnom}		132.8 V

Rated phase current I_{snom}	319.6 A
Rated terminal voltage U_s	128.4 V
Efficiency (rated power)	94.7%
Material Cost	5898 euros
Annual Energy Yield	355 MWh
Dissipation per m^2	6 kW/ m^2

Therefore, this generator can still keep operating when there is a short circuit. Because it will not induced a high short circuit current, the generator can operate safely and output power. The resulting performance is depicted in figure 5-20.

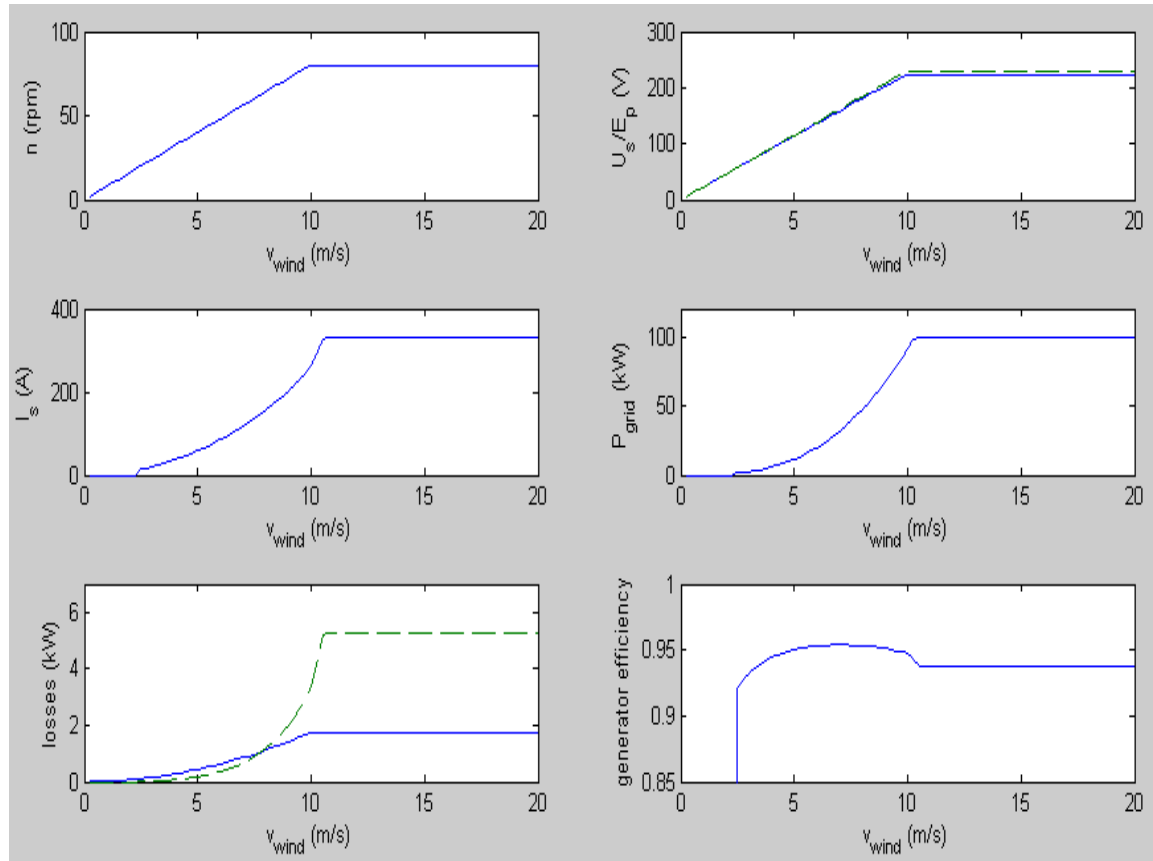


Figure 5-20 Rotational speed, terminal and no-load voltage (—), current, grid power, iron and copper losses (—) and the generator efficiency as a function of the wind speed

5.2.6 Spacer tooth

Although we have obtained the one per unit phase self inductance, from equation (5-55) we can see that the mutual inductance has also increased a lot, and it is about 10% of the self inductance. This is another issue for fault tolerant generator, because any one phase should have minimal impact upon the others. So it is important to find out a way to minimize the mutual inductance, and allow the other phases to continue operate unaffected in the case of one phase failure.

Then we can look at a possibility of adding spacer tooth to achieve a minimal mutual inductance. We consider two 8-9 combination systems as a new configuration part of the generator. In order to keep balance, the spacer teeth are placed in between each tooth as shown in figure 5-21.

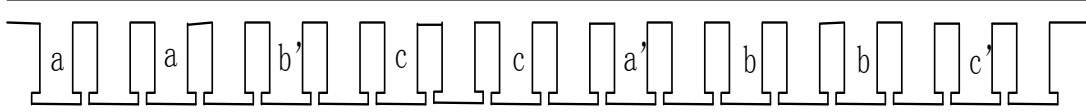


Figure 5-21 configuration of 16 poles - 18 tooth

Each tooth has a two times number of coils on it, so the self inductance should be increased. And the mutual inductance of this configuration should be very low because most of the flux will on the spacer tooth. It can be checked in FEM. We use the same dimensions as the system in section 5.2.3 ($h_{so}=0.006$, $b_{so}=0.003$). We get the flux linkage of phase b when it has current and the flux plot is given in figure 5-22.

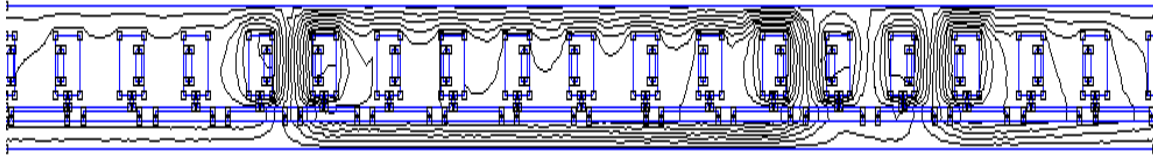


Figure 5-22 Flux plot and result of 18-16 combination, when $i_b=320A$

From the result, the flux linkage of phase b is:

$$\lambda_b = 0.168952Wb \quad (5-56)$$

So the self inductance of phase b in this 18-16 combination is:

$$L_b = \frac{\lambda_b}{i_b} = 5.28 \times 10^{-4} H \quad (5-57)$$

For the whole generator there are four 18-16 combination systems. So the total self phase inductance is:

$$L_{total} = L_b \times 4 = 0.0021H \quad (5-58)$$

Then the mutual inductance of each tooth in the same phase is:

$$M_{a_1b} = \frac{\lambda_{a_1b} - \lambda_{a_1m}}{i_b} = 0.35 \times 10^{-6} H$$

$$M_{a'b} = \frac{\lambda_{a'b} - \lambda_{a'm}}{i_b} = 9.92 \times 10^{-6} H \quad (5-59)$$

$$M_{a_2b} = \frac{\lambda_{a_2b} - \lambda_{a_2m}}{i_b} = 6.79 \times 10^{-6} H$$

Then the total mutual inductance of phase a in this generator is:

$$M_{ab} = (M_{a_{b1}} + M_{a'b} + M_{a_2b}) \times 4 = 0.68 \times 10^{-4} H \quad (5-60)$$

This mutual inductance is decreased a lot, and it only takes 3% of the self inductance. For instance, if there is a fault on one phase, it will not affect the other phases. So adding spacer tooth is a good way to gain a minimum mutual inductance.

In order to calculate inductances analytically, we also make a magnetic circuit model which is shown in figure 5-23.

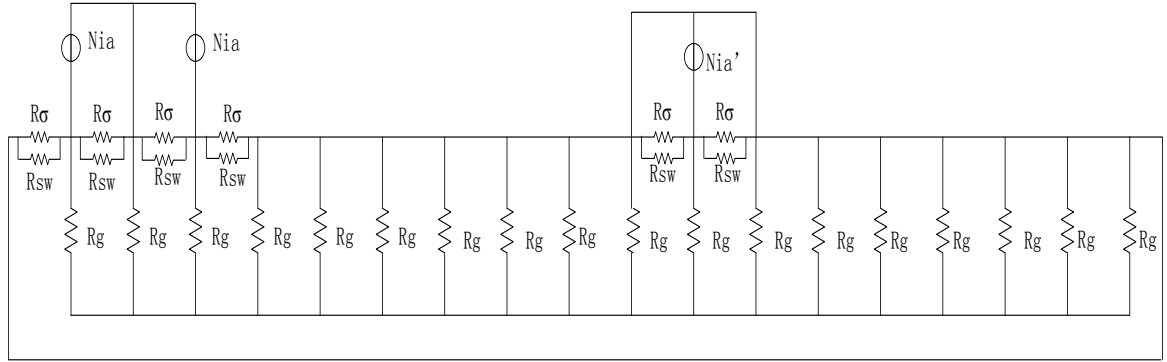


Figure5-23 magnetic circuit model for the generator with spacer tooth

Similarly, when we consider the phase a is energized, each tooth gets a flux from phase a which is calculated out:

$$\phi_1 = \frac{N_{slot} i_a}{18 R_g} \quad (5-61)$$

And each teeth also has a large part of flux goes through the slot opening width. So add this part of flux which is:

$$\phi_2 = \frac{N_{slot} i_a}{R_{parallel}} \quad (5-62)$$

Finally, we get the self inductance of one phase is:

$$\begin{aligned}
L &= \frac{(\phi_1 + \phi_2)N_{slot}}{i_a} \times \frac{N_s}{N_{slot}} \\
&= \frac{N_{slot}N_s(53R_{parallel} + 108R_g)}{54R_gR_{parallel}}
\end{aligned} \tag{5-63}$$

For mutual inductance, total mutual flux on the tooth of the other phase due to phase a is:

$$\phi_{mutual} = \frac{N_{slot}i_a}{18R_g} \times 3 = \frac{N_{slot}i_a}{6R_g} \tag{5-64}$$

Therefore, the phase mutual inductance of this 18-16 combination with spacer tooth generator is:

$$M = \frac{\phi_{mutual}}{i_a} \times \frac{N_s}{3N_{slot}} = \frac{N_sN_{slot}}{18R_g} \tag{5-65}$$

Result comparison from analytical and FEM is given in table 8.

Table 8 results of generator with slot opening tooth

	L (H)	M (H)
FEMM	0.0021	0.68×10^{-4}
Analytical	0.0021	0.74×10^{-4}

This comparison shows that the analytical calculation results are more or less the same as the FEM results and this 18-16 combination generator has a larger self inductance. Some parameters like slot opening and slot height can be varied to make the generator with 1 per unit self inductance.

Chapter 6 Comparisons

Reference generator and fault tolerant generator were designed in chapter 5. This chapter will list some energy conversion systems which are made of both generators. We will compare them based on the cost, performances and energy yield.

6.1 Normal energy conversion system

For wind turbine application, the generator is direct driven to avoid using a gearbox. In this thesis, the radial flux generator with concentrated winding (8 poles-9 tooth) is used as a reference generator. As mentioned in [18] that this type of generator has many advantages such as ease of assembly, construction, repair and segmentation. This can make the generator attractive for wind turbine application. The reference generator is loaded with a three phase converter which is shown in figure 6-1.

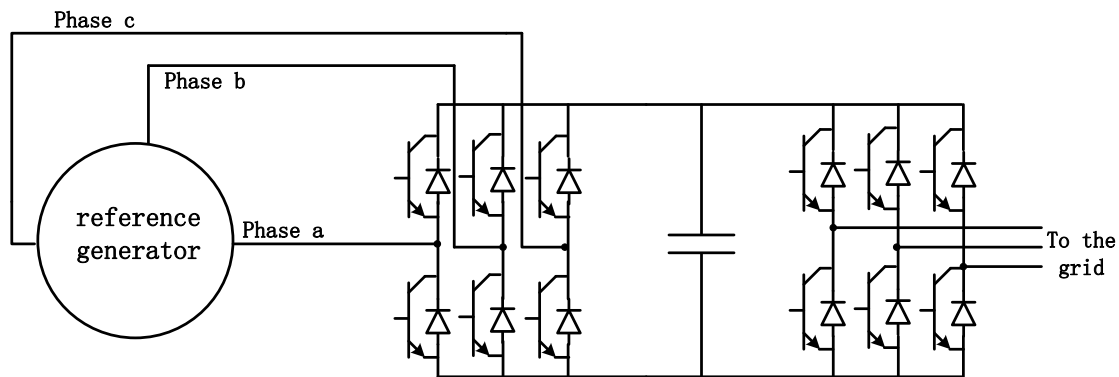


Figure 6-1 electrical arrangement of normal energy conversion system

6.2 Fault tolerant energy conversion system

Using both reference generator and fault tolerant generator, there are four possible ways to make the energy conversion system fault tolerant.

- a) Previous research by a variety of authors has been carried out a modular generator in which each phase may be regarded as a single modular.

Here we use three single phase converters which are connected to three phase respectively. This system is shown in figure 6-2. It can only tolerate an open circuit or a power converter fault. When there is a fault, this system can still out put $2/3$ power.

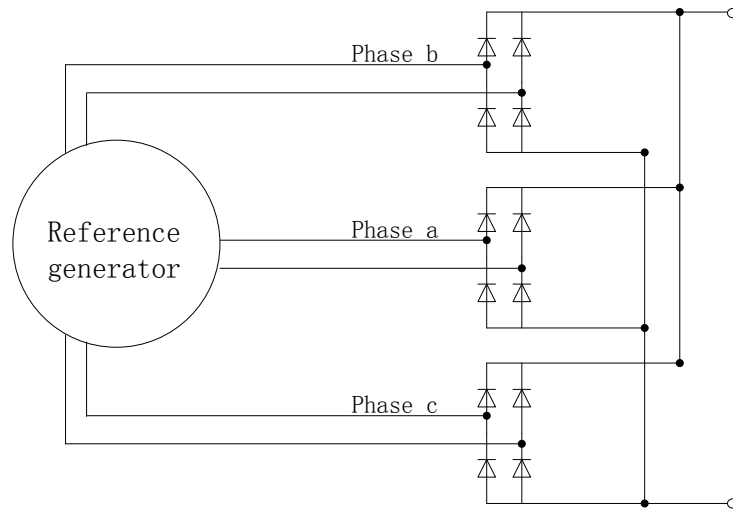


Figure 6-2 electrical arrangement of fault tolerant energy conversion system I

- b) Then we divide the reference generator into several parts. Initially 4 segments are considered. Each segment has two 8 poles-9 tooth combination systems. This kind of system can only tolerate winding open circuit fault or power converter fault. If one segment has such a fault, the other segments can still output three fourth of the total power. Hence 4 three-phase active rectifiers are needed in total to connect each segment which is shown in figure 6-3.

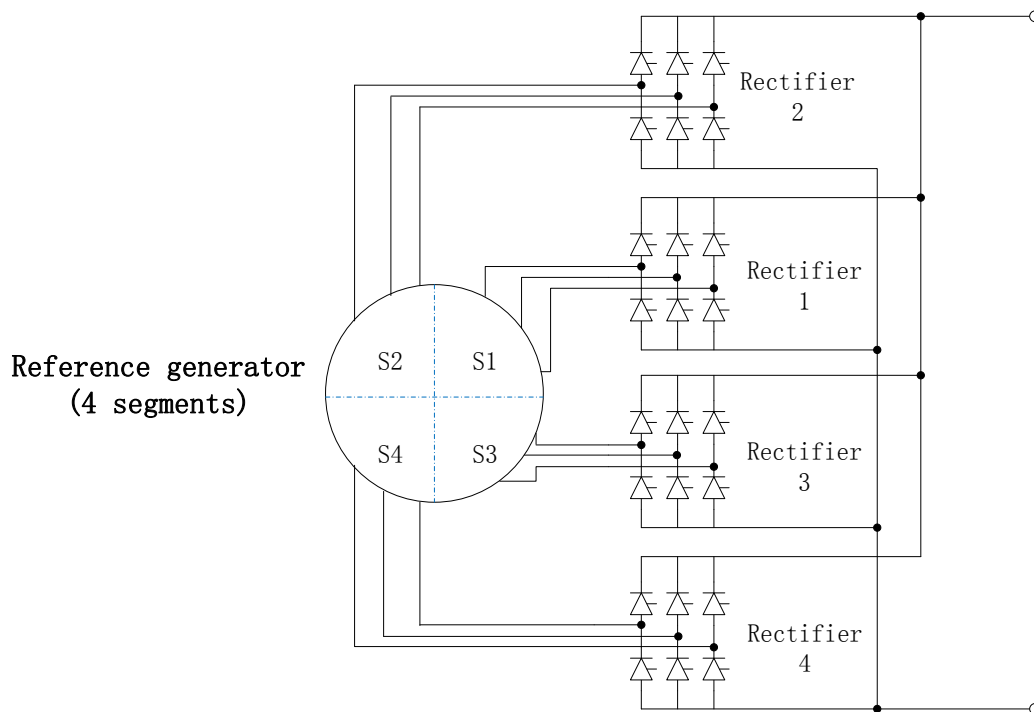


Figure 6-3 electrical arrangement of energy conversion system II

After the fault tolerant generator design, some dimensions of this reference generator have been changed to achieve the one per unit phase inductance. So the generator is capable to stand a short circuit fault. So for the fault tolerant generator, we can do the same thing.

- c) One system can be made of a fault tolerant generator and three single phase converter, see figure 6-4. This system can only tolerate short circuit fault and power converter fault.

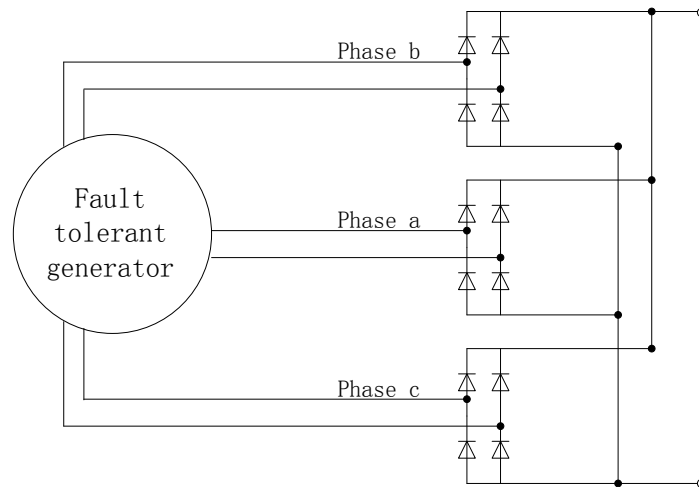


Figure 6-4 electrical arrangement of energy conversion system III

- d) Another system can be made of a fault tolerant generator which is divided into 4 segments, and 4 three phase converters. As a result, it can also stand an open circuit fault. So this system can keep operating in the case of short circuit, open circuit and power converter fault, and output 3/4 of the total power. This system is illustrated in figure 6-3.

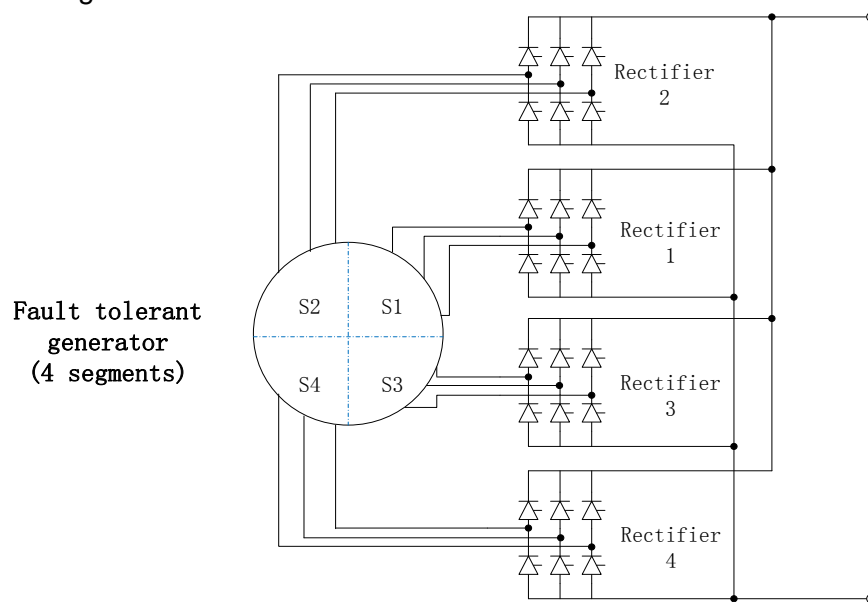


Figure 6-5 electrical arrangement of energy conversion system IV

6.3 Cost and performance

From the performance results of reference generator and fault tolerant generator, we can see some differences between these two generators due to some dimension parameter changes. Table 8 is redrawn from table 4 and table 7 to make the differences more clear.

Table 8 varified dimensions and resulting differences

Parameters	Conventional generator	Fault tolerant generator
Slot height h_s	37 mm	42 mm
Ratio $b_s_tau_s$	0.37	0.43
Slot width b_s	21 mm	24.4 mm
Tooth width b_t	35.7 mm	32.3 mm
Total weight	639 kg	652 kg
Weight of copper	117 kg	126 kg
Weight of iron	486 kg	490 kg
Weight of PM	36 kg	36 kg
Total losses (rated)	7.2 kW	6.86 kW
Iron losses (rated)	1.43 kW	1.87 kW
Copper losses (rated)	5.77 kW	4.99 kW
Rated current I_{snom}	333.6 A	319.6 A
Rated no-load voltage E_p	128.7 V	132.8 V
Rated terminal voltage U_s	102.7 V	128.4 V
Phase self inductance L	7.1×10^{-4} H	0.0015 H
Phase mutual inductance M	6.4×10^{-5} H	1.58×10^{-4} H
Efficiency(rated power)	93.5%	94.7%
Material cost	5756 euros	5898 euros
Annual energy yield	355.2 MWh	355.8 MWh

Conventional generator is loaded with passive rectifier. It is mainly because the passive rectifier is cheaper and more robust than active rectifier. But from the analysis in section 5.2.5 the fault tolerant generator cannot use the passive rectifier. Instead it uses an active rectifier which causes some different results in table 8.

From table 8 we can find that:

- 1) Compare to the reference generator, total material weigh of the fault tolerate generator increased. This is because both of the weight of iron and copper increased after the tooth dimension changes. As a result, the cost of fault tolerant generator is higher than the reference generator.
- 2) Total losses of the fault tolerant generator are lower than the reference generator. Iron losses in the fault tolerant generator are increased a little, but the area of copper is increased with a larger slot width, so the copper losses are decreased due to a smaller copper resistance.

- 3) Due to the lower losses, the fault tolerant generator has a higher efficiency than the reference generator.
- 4) The annual energy yield is slightly higher than the reference generator.

Comparing the five energy conversion system mentioned above, we find that the fault tolerant energy conversion systems have extra cost for fault tolerate generator, converters due to more segments and the cost for active rectifier.

Obviously normal system is the cheapest one. Because of the cost of fault tolerant generator and more converters are needed, the system IV (fault tolerant generator with 4 segments) is the most expensive one among these five systems.

6.4 Reliability and energy yield

The most important characteristic of fault tolerant generator is the capability of continued operation in the event of a short circuit fault happen. Furthermore the segmentation of the generator allows for continued operation in the event of a phase open circuit or a power device failure.

Meanwhile, failure rates of some electrical related components have been calculated in chapter 3. We can use the failure rates of windings and converters to check how the resulting energy yield will be affected of each system.

As a matter of fact, the downtime of generator is much larger than power converter. For the energy yield calculation and comparison in this thesis, we use downtime values of generator (DT_{gen}) and converter (DT_{con}) from reference [11], which are 7.2 days/failure and 1.8 days/failure respectively. We assume that these wind turbines are used for 30 years.

Annual energy yields of normal generator and fault tolerant generator are:

$$P_{annual_nom} = 355.2MWh \quad (6-1)$$

$$P_{annual_FT} = 355.8MWh \quad (6-2)$$

So energy yield per day are:

$$P_{day_nom} = \frac{P_{annual_nom}}{365} = 0.973MWh \quad (6-3)$$

$$P_{day_FT} = \frac{P_{annual_FT}}{365} = 0.975MWh \quad (6-4)$$

6.4.1 Converter fault

From table 3 we know that the failure rate of converters is 0.315 failures per year per wind turbine. So failure number of one converter during 30 years is:

$$f_{con} = 30 \times 0.315 \approx 9 \text{ times} / 30 \text{ years} \quad (6-5)$$

6.4.1.1 Normal system

When a power converter fails, the normal system cannot output power any more since the generator is connected to a three phase rectifier. So total energy yield is calculated as:

$$P_{total_nom} = P_{ann_nom} \times \text{years} - P_{day_nom} \times DT_{con} \times f_{con} \quad (6-6)$$

6.4.1.2 Fault tolerant systems

System II and system IV have been divided into four segments and each segment is connected to a three phase rectifier. So the other three segments can continue output power when there is a fault on one of the four rectifiers. The nominal generator power is:

$$P_{gennom_2,4} = \frac{3}{4} P_{gennom} = \frac{3}{4} \times 110 = 82.5 \text{ KW} \quad (6-7)$$

The generated power of a wind turbine is determined by the wind speed. Since the wind speed is modeled using the Weibull distribution which is shown in figure 6-6, the annual energy yield of the generator when one segment fails is calculated are given as follows.

$$P_{an_fail_2} = 317.7 \text{ MWh} \quad (6-8)$$

$$P_{an_fail_4} = 318.9 \text{ MWh} \quad (6-9)$$

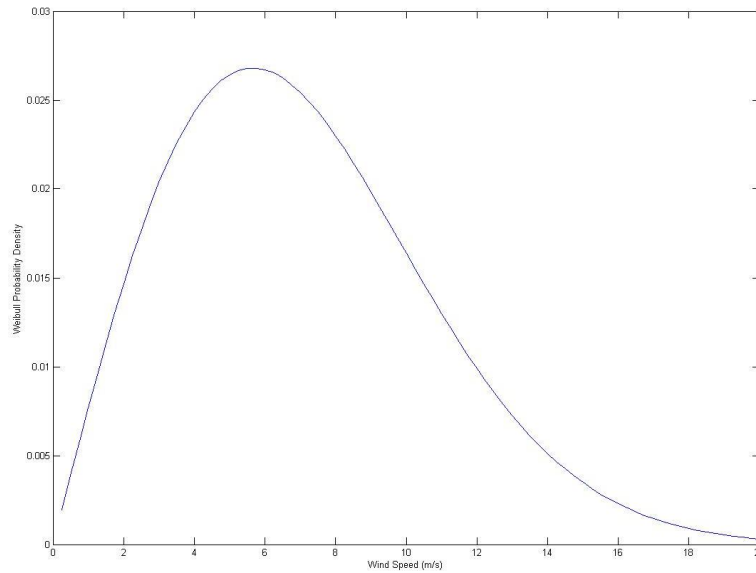


Figure 6-6 A Weibull distribution for average wind speed of 7.1m/s

System I and III are connected to three single phase converter, so if one converter fails, the other two segments can continue output power. The nominal generator power is:

$$P_{gennom_2,4} = \frac{2}{3} P_{gennom} = \frac{2}{3} \times 110 = 73.3KW \quad (6-10)$$

The annual energy yield of the generator when one segment fails is:

$$P_{an_fail_1} = 298.8MWh \quad (6-11)$$

$$P_{an_fail_3} = 300MWh \quad (6-12)$$

However, more rectifier means there is a higher failure rates. According to the converter failure rates, total energy yields of fault tolerant system II and IV are:

$$P_{total2} = P_{ann_nom} \times years - DT_{con} \times f_{con} \times 4 \times (P_{day_nom} - \frac{P_{an_fail_2}}{365}) \quad (6-13)$$

$$P_{total4} = P_{ann_FT} \times years - DT_{con} \times f_{con} \times 4 (P_{day_FT} - \frac{P_{an_fail_4}}{365}) \quad (6-14)$$

Total energy yields of fault tolerant system I and III is:

$$P_{total1} = P_{ann_nom} \times years - DT_{con} \times f_{con} \times 3 (P_{day_nom} - \frac{P_{an_fail_1}}{365}) \quad (6-15)$$

$$P_{total3} = P_{ann_FT} \times years - DT_{con} \times f_{con} \times 3 (P_{day_FT} - \frac{P_{an_fail_3}}{365}) \quad (6-16)$$

6.4.2 Winding open circuit fault

From table 3 we only know the failure rate of generator winding is 0.088 failures per year per wind turbine. But the ratio of open circuit or short circuit is unknown. Here we assume that each winding fault takes half of the failure rates. So the failure rate of open circuit is 0.044. The failure number of open circuit fault during 30 years is:

$$f_{open} = 30 \times 0.044 \approx 1 \text{ times} / 30 \text{ years} \quad (6-17)$$

6.4.2.1 Normal system

If there is an open circuit fault on a phase, system I will stop operating and will not output power to the grid. Then the total energy yield of conventional generator is:

$$P_{total_nom} = P_{ann_nom} \times years - P_{day_nom} \times DT_{gen} \times f_{open} \quad (6-18)$$

6.4.2.2 Fault tolerant systems

For the fault tolerant system I and III, the output power is 2/3 of the total power. Because the rest two phases will not be affected by the phase with open circuit. So total energy yields of fault tolerant system I and III is:

$$P_{total1} = P_{ann_nom} \times years - DT_{open} \times f_{open} \left(P_{day_nom} - \frac{P_{an_fail-1}}{365} \right) \quad (6-19)$$

$$P_{total3} = P_{ann_FT} \times years - DT_{open} \times f_{open} \left(P_{day_FT} - \frac{P_{an_fail-3}}{365} \right) \quad (6-20)$$

For the fault tolerant system II and IV, they can still give 3/4 of the total power in the presence of an open circuit fault. This is because only one segment of the generator has a fault, and the other three segments do not have impact from that fault phase. Using the winding failure rate, the total energy yields of fault tolerant system II and IV can be calculated as:

$$P_{total2} = P_{ann_nom} \times years - DT_{open} \times f_{open} \left(P_{day_nom} - \frac{P_{an_fail-2}}{365} \right) \quad (6-21)$$

$$P_{total4} = P_{ann_FT} \times years - DT_{open} \times f_{open} \left(P_{day_FT} - \frac{P_{an_fail-4}}{365} \right) \quad (6-22)$$

6.4.3 Winding short circuit fault

The failure rate of short circuit is also 0.044 from our assumption. The failure number of short circuit fault during 30 years is:

$$f_{short} = 30 \times 0.044 \approx 1 \text{ times} / 30 \text{ years} \quad (6-23)$$

6.4.3.1 Normal system

When there is a short circuit failure on a phase, normal system will have a very large short circuit current and the generator will be stopped without output. So total energy yield is calculated as:

$$P_{total_nom} = P_{ann_nom} \times years - P_{day_nom} \times DT_{short} \times f_{short} \quad (6-24)$$

6.4.3.2 Fault tolerant systems

For system I and II, the reference generator will stop working when there is a short circuit fault in one phase. So total energy yields of fault tolerant system I and II is:

$$P_{total1} = P_{total2} = P_{annual_nom} \times years - P_{day_nom} \times DT_{short} \times f_{short} \quad (6-25)$$

For system III and IV, because a fault tolerant generator is used, the one per unit phase inductance can limited the short circuit current. So the generator can continue working, but output power is lower than the rated power.

Total energy yield of system III is:

$$P_{total3} = P_{ann_FT} \times years - DT_{short} \times f_{short} (P_{day_FT} - \frac{P_{an_fail_3}}{365}) \quad (6-26)$$

For system IV, the remaining three segments can work normally and the segment with the short circuit fault can also keep working, but the output power becomes lower. When there is a one phase short circuit the output power is:

$$P_{genom_4_short} = \frac{3}{4} P_{genom} + \frac{1}{4} \times \frac{2}{3} P_{genom} = 100.8KW \quad (6-27)$$

So when there is a short circuit fault, the annual energy yield is calculated as:

$$P_{an_short_4} = 350MWh \quad (6-28)$$

Therefore, the total energy yields of fault tolerant system IV is:

$$P_{total4} = P_{ann_FT} \times years - DT_{short} \times f_{short} (P_{day_FT} - \frac{P_{an_short_4}}{365}) \quad (6-29)$$

Then we put all these energy yield results of each system based on three fault types in table 9.

Table 9 Total energy yield of 30 years of each system

Energy yield (MWh) \ Fault type	Winding Open circuit	Winding Short circuit	Converter failure
Systems			
Normal system	10649	10649	10640
Fault tolerant System I	10654	10649	10648
Fault tolerant System II	10655	10649	10649
Fault tolerant System III	10672	10672	10666
Fault tolerant System IV	10673	10673.9	10667

From table 9, we can find that fault tolerant system IV is the most efficient among these five energy system. Whichever fault happens, this system will give most output power than the others. However the cost of it is higher than the normal system.

These results are calculated using the downtime of onshore wind turbines. If the downtime of offshore wind turbines is taken in, the fault tolerant system will save much more energy.

Therefore if the wind turbines are planned to be used for a long time period, especially for offshore, system IV will save a lot of output power due to all kinds of fault. So this fault tolerant system is a good choice to increase the reliability of wind turbines.

Chapter 7 Conclusion and future work

Based on the work and results we got in previous chapters. This last chapter gives conclusion of this thesis project in section 7.1 and future work in section 7.2.

7.1 Conclusion

From the background of wind energy, we first studied wind turbine technology. Considering the existing issues, much attention has been paid to the reliability improvement. After analyzing failure data of some components, generator is a crucial component in electrical part of wind turbine. Its failure rate is not so high, but resulting large downtime will lose a lot of energy.

In order to make a reference generator capable to tolerate some machine faults, some efforts are made to achieve the 1 per unit phase inductance:

- Increasing slot height, slot width and some other dimensions of the generator results in a larger self inductance, but this increase is limited. The inductance value for fault tolerant design is even higher.
- Then we change the stator configuration with narrow slot opening. The narrow slot opening results in a large amount of cross slot flux leakage. So this method can increase the self inductance a lot to our designed value so that the generator can tolerate winding short circuit fault.
- Although the mutual inductance is not high in the generator, if we want to decrease it further, we can add spacer tooth between every two wound teeth in the generator. In this thesis we made a 16 poles-18 teeth combination with spacer tooth based on the 8 poles-9 teeth combination.

After finishing the fault tolerant generator design, we compare this generator with the reference generator. Efficiency and annual energy yield of the fault tolerant generator are higher than the reference generator. However, in order to gain fault tolerance, the cost and the weight of the generator also increased.

Then we build two energy conversion systems with this fault tolerant generator. One is loaded with single phase converters and the other one is divided into 4 segments (each segment is loaded with a three phase converter). Both of two systems can stand power converter fault, short circuit and open circuit fault.

In the same way, we made another two energy conversion systems but use the reference generator. However, these two systems cannot stand short circuit fault in the generator.

We can tell the best one among these systems and the normal energy conversion system by comparison. For each system, we introduce the failure rate and downtime data of converter and generator to calculate the total energy yield in a certain time period. Finally, the 4 segments-fault tolerant generator system can output the most power than other systems.

7.2 Future work

We have designed the fault tolerant generator in this thesis, but for generator with 18 teeth-16 poles combination, we did not get an ideal result, for instance, the efficiency is decreased and current density is quite high. So redesign of this type of generator, such as changing dimensions or number of turns, would be interesting and helpful.

It is also interesting to implement and test this fault tolerant generator system. Then it is possible to compare the performance and efficiency of the generator to the expected result by a series of tests. Another issue for this fault tolerant generator is the space harmonics. It may results in high eddy current losses in magnet and back iron. Therefore, thin laminations could be introduced to solve this problem.

Although the availability of wind turbines increased, the failure rates of some components are still high compare to other matured technologies. Especially for those unknown failures of components in wind turbine, their failure rates are even higher than other sub-components. If we have more information about the unknown failures, it is possible to make improvement of these subassemblies technology by specifically design for the wind turbine application or a stronger fault tolerant system which can stand most of the faults. As a result, the most effective method to increase the reliability can be figured out.

References

- [1] G.J.W van Bussel and Chr. Schontag, Operation and Maintenance aspects of large offshore wind farms. In proceedings of the 1997 European Wind Energy Conference, Dublin, Ireland, 1997. pp. 272-279.
- [2] G.J.W van Bussel and M. B. Zaaijer, Dowec concept study, reliability, availability and maintenance aspects. In Proceedings of the Marine Renewable Energy Conference (MAREC), Newcastle, UK, 2001.
- [3] P.J. Tavner, F. Spinato, G.J.W van Bussel, E Koutoulakos, Reliability of Different Wind Turbine Concepts with Relevance to Offshore Application, 2008
- [4] P.J. Tavner, J. Xiang, F. Spinato, Reliability analysis for wind turbines. 2006
- [5] E. Echavarria, B. Hahn, G.J.W van Bussel, T. Tomiyama, Reliability of wind turbine technology through time, 2008
- [6] Various authors, Wind energy report deutschland. Technical report, ISET, Institut für Solare Energieversorgungstechnik, Kassel, Germany, 2006.
- [7] Eggersgluß, W., Windenergie I-XIX Praxisergebnisse, Landwirtschaftskammer Schleswig Holstein, 1995-2004.
- [8] WindStats Newsletter, 12(4)-14(3), Denmark, 1999-2001
- [9] J. Ribrant, Reliability Performance and Maintenance - A Survey of Failures in Wind Power Systems, MS thesis, KTH School of Electrical engineering, Stockholm, 2006
- [10] F. Spinato, The Reliability of Wind Turbines, PhD Thesis, Durham University, 2008
- [11] Berthold Hahn, Michael Durstewitz, Kurt Rohrig, Reliability of Wind Turbines Experiences of 15 years with 1,500 WTs, Institut für Solare Energieversorgungstechnik (ISET), Germany
- [12] E. Koutoulakos, Wind turbine reliability characteristics and offshore availability assessment, MSc Thesis, Delft University and Technology, 2008
- [13] H. Polinder, Fault tolerances in generator system for wind turbines, Technical report, 2008
- [14] Hahn, B., et al., Wind Energy Report Germany 2006, Annual Evaluation of WMEP. 2006, Institut für Solare Energieversorgungstechnik (ISET): Kassel.
- [15] ISET. Renewable Energy Information System on the Internet. [cited 04-02-2008]; Available from: <http://reisi.iset.uni-kassel.de/>.

- [16] A.Jassa, Design of 2.25 MW Permanent Magnet direct drive generator for wind energy applications with concentrated windings and reduction of eddy current losses in the rotor back iron, Master thesis, TU Delft 2008.
- [17] Richter R. Elektrische Maschinen, Erster Band (3rd edn). Birkhäuser: Basel, 1967.
- [18] G. Shrestha, H. Polinder, Report on Comparison of Different Permanent Magnet Generator Topologies for Wind Turbine Application, 2009

Appendix A Design equations

(1) Sizing equation for permanent magnet machines

$$F_d = \sum B_g i \approx \frac{1}{2} \hat{B}_g \hat{A}_g \quad (\text{A-1})$$

$$P = T \omega_m = r_s F \omega_m = 2 \omega_m \pi r_s^2 l_s F_d \quad (\text{A-2})$$

$$V_r = \pi r_s^2 l_s = \frac{P}{2 \omega_m F_d} \quad (\text{A-3})$$

From the given speed n , the mechanical angular frequency:

$$\omega_m = 2\pi n / 60 \quad (\text{A-4})$$

Electrical angular frequency:

$$\omega_e = p \omega_m \quad (\text{A-5})$$

Where p is the number of pole pairs.

The force density $F_d = 25\text{-}50\text{ kN/m}^2$. Using this sizing equation, basic generator dimensions can be found out.

(2) Dimensional Parameters

Pole pitch:

$$\tau_p = \frac{\pi r_s}{p} \quad (\text{A-6})$$

Slot pitch:

$$\tau_s = \frac{\pi r_s}{pmq} \quad (\text{A-7})$$

Tooth width:

$$b_t = \tau_s - b_s \quad (\text{A-8})$$

Radius of rotor:

$$r_r = r_s - g \quad (\text{A-9})$$

Number of series connected coils:

$$N_s = N_{slot} 2p \frac{9}{8m} q \quad (A-10)$$

Number of pole pairs:

$$p=32 \quad (A-11)$$

Number of slots per pole per phase:

$$q=1 \quad (A-12)$$

Number of conductors in one slot:

$$N_{slot} = 3 \quad (A-13)$$

(3) No Load Voltage

The no load voltage of induced emf is:

$$E_p = \sqrt{2} N_{slot} l_s k_{ws} \omega_m r_s \hat{B}_{gm} \quad (A-14)$$

The terminal voltage is:

$$U_{snom} = \sqrt{E_p^2 - (I_{snom} Z_{nom})^2} - I_{snom} R_s \quad (A-15)$$

(5) Current per phase

$$I_q = \frac{P_g}{m E_p} \quad (A-16)$$

$$I_s = \frac{I_q}{\cos \delta} = 2 \frac{I_q}{\cos(\sin^{-1}(\frac{2 I_q X_s}{E_p}))} \quad (A-17)$$

(6) Flux density

The no load air gap flux density is given by,

$$B_g = \frac{l_m}{\mu_{rm} g_{eff}} B_r \quad (A-18)$$

The fundamental component of the flux density at air gap is:

$$\hat{B}_{gm} = \frac{l_m}{\mu_{rm} g_{eff}} B_r \frac{4}{\pi} \sin\left(\frac{\pi b_p}{2\tau_p}\right) \quad (A-19)$$

(7) Inductances

Self inductance:

$$L_s = \frac{N_s N_{slot} (26R_\sigma + 90R_g)}{27R_\sigma R_g} \quad (A-20)$$

Mutual inductance:

$$M = \frac{N_{slot} N_t}{9R_g} \quad (A-21)$$

Reluctance of air gap:

$$R_g = \frac{g_{eff}}{\mu_0 l_s (b_t + b_s)} \quad (A-22)$$

Reluctance of slot leakage:

$$R_\sigma = \frac{b_s}{\mu_0 l_s \frac{h_s}{3}} \quad (A-23)$$

The detailed calculation of inductances was separately done in chapter 5.

(8) Copper losses

$$P_{cu} = m R_s I_s^2 \quad (A-24)$$

Resistance per phase:

$$R_s = \frac{\rho_{Cu} l_{Cus}}{A_{Cus}} \quad (A-25)$$

Copper area:

$$A_{Cus} = \frac{A_s k_{sfill}}{N_{slot}} = \frac{b_s (h_s - h_{so})}{2} \quad (A-26)$$

Fill factor of the stator slot:

$$k_{sfill} = 0.6 \quad (A-27)$$

Current Density:

$$J_s = \frac{I_s}{A_{Cus}} \quad (A-28)$$

(9) Iron losses

$$P_{Fe} = 2P_{Fe,spec} \left(\frac{\omega_e}{2\pi f} \right)^{\frac{3}{2}} \left[M_{Fest} \left(\frac{\hat{B}_{st}}{1.5T} \right)^2 + M_{Fesy} \left(\frac{\hat{B}_{sy}}{1.5T} \right)^2 \right] \quad (A-29)$$

Specific iron losses at 1.5T, 50 Hz:

$$P_{Fe,speci} = 3.3 \text{ W/kg} \quad (A-30)$$

Mass of stator tooth:

$$M_{Fest} = \rho_{m,Fes} V_{Fest} \quad (A-31)$$

Mass of stator yoke:

$$M_{Fesy} = \rho_{m,Fes} V_{Fesy} \quad (A-32)$$

Mass density:

$$\rho_{m,Fes} = 7650 \text{ Kg} / m^3 \quad (A-33)$$

(10) Efficiency

$$\eta = \frac{P_{out}}{P_{out} + P_{genloss}} \quad (A-34)$$