Analysis and Control Aspects of Brushless Induction Machines with Rotating Power Electronic Converters

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Licentiate Thesis
Stockholm, Sweden 2012
Akademisk avhandling som med tillstånd av Kungl Tekniska högskolan framlägges till offentlig granskning för avläggande av teknologie licentiatesexamen i måndagen den 1 Oktober 2012 klockan 10:00 i Sal H1, Kungl Tekniska Högskolan, Teknikringen 33, Stockholm.

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Tryck: Universitetsservice US AB
Abstract

This thesis deals with the steady-state, dynamic and control aspects of new type of brushless configuration of a doubly-fed induction machine in which the slip rings and carbon brushes are replaced by rotating power electronics and a rotating exciter. The aim is to study the stability of this novel configuration of the generator under mechanical and grid disturbances for wind power applications.

The derivation, development and analysis of the steady-state model of the brushless doubly-fed induction machine with a rotating excitor and the power electronic converters mounted on the shaft and rotating with it, is studied. The study is performed at rated power of the generator between $\pm 20\%$ slip range. Moreover unity power factor operation between $\pm 20\%$ speed range is also discussed.

Furthermore dynamic modeling and control aspects of the generator are also analyzed. The controllers were designed using Internal Model Control principles and vector control methods were used in order to control the generator in a closed-loop system. It is shown that through the use of proper feedback control, the generator behaves in a stable state both at super-synchronous and sub-synchronous speeds.

Moreover Low Voltage Ride Through of the generator during symmetrical and unsymmetrical voltage dips is also investigated. Passive Resistive Network strategy is employed for Low Voltage Ride Through of the generator during symmetrical voltage dips. On the other hand, Extended Vector Control is used in order to control the negative sequence currents during unsymmetrical voltage dips. Suppression of negative sequence currents is important as they cause extra heating in the windings and affects the lifetime of the mechanical and electrical components of the generator and system due to oscillations in power and torque.

In addition to the above studies a steady-state model of a single-fed induction machine is also developed and investigated where the rotating exciter is removed and the rotor windings are short-circuited through the two rotating power electronic converters. In this way the slip power circulates in the rotor and with the help of the two rotating electronic converters, rotor current is used to magnetize the induction machine thereby improving the power factor. The steady state model is verified through experimental results.

Index Terms: Doubly-fed induction generator, extended vector control, induction machine, internal model control, Lindmark concept, low voltage ride through, passive resistive network, rotating power electronic converter, rotating exciter, symmetrical faults, synchronous machine, unity power factor, unsymmetrical faults, vector control, wind turbines.
Acknowledgements

This project was funded by the Vindforsk Research Program who are gratefully acknowledged.

First of all, I would like to thank my supervisor Professor Chandur Sadarangani for all the support, encouragement, guidance and equipping me with the technical insight during the project.

Further, I would like to thank the members of the steering committee for this project; Dr. Jouko Niiranen, Dr. Robert Chin and Dr. Muhamad Reza for their valuable feedback and fruitful discussions.

I would also like to thank Dr. Alija Cosic for his assistant with the equipment in the laboratory while I was working with the experimental setup. Mats Leksell too, is acknowledged for helping me with some of the problems I faced during this period. Furthermore, I would like to thank Dr. Oskar Wallmark for the valuable feedback related to the control aspects of the project.

I am grateful to my colleagues at KTH who have helped me in several ways especially Henrik Grop, Alexander Stening, Kashif Khan, Shafiqh Nategh, Andreas Krings, Noman Ahmed, Tomas Modeer, Yanmei Yao, Kalle Ilves and my former colleague Rathna Chitroju.

Special thanks to E2C financial administrator Eva Petterson, system administrator Peter Lönn and technician Jan-Olov Brännvall for helping me with the financial, computer and lab issues respectively.

Finally, I would like to express my deepest gratitude to my parents for their tremendous support and encouragement. I would also like to thank my cricket friends Zaheer, Mati, Adnan, Wahab and Ghalib.

Stockholm 2012
Naveed ur Rehman Malik
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Chapter 1

Introduction

1.1 Background and Objective

In recent years, electricity generation through harnessing wind power has gained considerable momentum especially in Europe [1, 2]. This momentum has resulted because of the increased threat of global warming due to excessive carbon dioxide (CO$_2$) emissions from the fossils fuels [1]. In addition, insecurity of energy supply in the future due to limited supply of fossil fuels has further motivated the research in the renewables [1]. As a result, interest has arisen for utilization of the renewable energy sources such as sun, wind and waves for the purpose of harnessing energy. The major advantage of these resources are that they are environment friendly and do not pose any risk to living beings unlike nuclear power. With more challenging European Union targets, it is expected that the share of renewable resources in power generation will increase rapidly [1, 2]. It is also expected that wind power will play a major role among the renewable resources [2].

Currently, for the purpose of exploiting wind power, different types of generator technologies are in use in the wind industry. Doubly-Fed Induction Generators (DFIG) are one of the most common and famous in the family of wind generators [3–7]. This is because these generators employ partially rated power electronic converters which are rated around 30% of the power rating of the generator for a ±25% speed range making them suitable for wind power applications. In this type of generator, the stator is directly connected to the grid while the rotor is connected to the grid via two power electronic converters. Most of the power flows through the stator while a fraction of the power i.e. slip power flows through the rotor-connected power electronic converters to the grid. As a result efficiency of the system is improved as only a fraction of the electric power is processed by the converter resulting in a reduction of the converter losses [3–8].
CHAPTER 1. INTRODUCTION

However, DFIG suffers from several disadvantages. One of the major disadvantages is that these generators employ slip rings and carbon brushes in order to recover slip power from the rotor and deliver it to the grid. In order to do so, one of the power electronic converters is connected to the rotor via slip rings while the second power electronic converter is connected to the grid. Carbon brushes are known to have limited life span and therefore are replaced every couple of months [4]. Moreover, slip rings also wear out due to conduction of high rotor currents and therefore also need replacement after every few years. Furthermore, carbon dust generated due to wearing out of the carbon brushes is very often blown into the generator windings by the cooling fan and therefore affects the lifetime of the insulation of the generator. This is because carbon dust is conducting in nature and when trapped in the generator windings it will increase the risk of sparking between the winding conductors [9] which could result in the weakening of the insulation and therefore a reduction of system reliability. Due to these factors, overall maintenance costs are increased especially for offshore wind turbines where maintenance is dependent upon weather conditions as turbine units are not accessible during certain time periods of the year. Due to aforementioned reasons it is of vital importance that the doubly-fed generators are designed in a manner so as to recover slip power utilizing more reliable means than carbon brushes and slip rings.

In the past, several authors have studied and developed doubly-fed machines without slip rings and carbon brushes. One of the well-known topologies is the Brushless Doubly-Fed Induction Generator. A brief overview of the development and use of this topology from early 1900 is covered in Chapter 2. Despite the fact that the brushless version of the doubly-fed induction generator has been present for more than 100 years, its use in the market has been limited due to several reasons. One of the main reasons is the lower efficiencies and larger sizes of the machine since it employs two induction machines [4]. Moreover, it has been shown in [10] that sizes of the power electronic converters increase if there is a requirement of unity power factor at the stator terminals of the generator. Therefore, in order to overcome these disadvantages, a newer topology is being investigated in this thesis where the power electronic converter is rotating (non-stationary) unlike conventional brushless and slip-ring doubly fed machines. The aim is to exploit the rotor windings directly via rotating power electronic converters in order to obtain similar or better performance of the machine compared to that obtained previously through conventional brushless doubly-fed machines. There are basically three aims of this thesis.

- Recover slip power and improve the efficiency.
- Obtain unity power factor.
1.2 Outline of the thesis

The chapters in this thesis are outlined as follows:

Chapter 2 gives a brief overview of different topologies of induction machines for variable speed control using slip recovery and rotor voltage injection methods. In addition a brief overview on the development of the Brushless Doubly-Fed Induction Generator (BDFIG) is also presented.

Chapter 3 presents the explanation of the basic working principle of the novel topology of the brushless induction machine referred to as Rotating Power Electronic Brushless Doubly-Fed Induction Generator (RPE-BDFIG) in this thesis. It also introduces the derivation, development and analysis of the steady-state and dynamic model of the RPE-BDFIG. It is seen that this generator shows stable operation at different speeds which are above and below the synchronous speed. Moreover it is seen that the RPE-BDFIG re-establishes the steady-state point of operation after being subjected to mechanical transients such as changes in torque and mechanical speed.

Chapter 4 discusses an overview of the closed-loop control of the RPE-BDFIG. Mathematical treatment of the current, speed and DC-link voltage controllers of the generator is given and explained.

Chapter 5 gives an analysis of the operation of the RPE-BDFIG when subjected to symmetrical and unsymmetrical voltage sags due to different types of faults in the grid. Passive Resistive Network (PRN) and Extended Vector Control (EVC) strategies for Low Voltage Ride Through (LVRT) of the generator is also investigated.

Chapter 6 presents the development of the steady-state model of a single-fed induction machine with the rotating power electronic converters. Unity power factor operation is shown. The model is verified through experiments.

Chapter 7 summarizes the project and presents several possibilities for future research.

- Achieve low-voltage ride through of the generator during various types of voltage sags.
1.3 Main Contributions of this Thesis

Thus far, this thesis has contributed in the following ways:

- This thesis introduces and explains a novel topology of Brushless-Doubly Fed Induction Generator and explains the basic working principles and control aspects of the generator. A steady-state model of the generator is derived and analyzed for variable speeds and unity power factor operation.

- A thorough analysis of the dynamics of the generator is presented and a first attempt has been made to develop and analyze the dynamic model and control of the generator. It is found that through proper closed-loop control, the generator shows stable behavior at variable speeds and variable torque. Moreover, it is shown that through the use of a rotating exciter, the slip power recovery scheme can be made successful.

- Impact of the symmetrical voltage dips with various magnitudes is investigated and a successful Low Voltage Ride Through of the generator is presented.

- Analysis of the Low Voltage Ride Through of the generator using Extended Vector Control method during unsymmetrical voltage dips is presented. The simulation results show that using the adopted method, the generator successfully operates during unsymmetrical conditions with considerably reduced oscillations in the mechanical and electrical components of the generator.

1.4 Publications

So far, publications originating from this project are:


- Malik, Naveed ur Rehman; Sadarangani, C.; “Dynamic modeling and control of a brushless doubly-fed induction generator with a rotating power electronic converter,” accepted and to be published in ICEM 2012 being held in Marseille, France, September 2-5, 2012.

- Malik, Naveed ur Rehman; Sadarangani, C.; “Behavior of a brushless doubly-fed induction generator with a rotating power electronic converter
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during symmetrical voltage sags,” accepted and to be published in ICEM 2012 being held in Marseille, France, September 2-5, 2012.

- **Malik, Naveed ur Rehman; Sadarangani, C.;** “Extended vector control of a rotating power electronic brushless doubly-fed induction generator under unsymmetrical voltage sags ,” accepted and to be published in IECON 2012, Annual Conference on IEEE Industrial Electronics Society being held in Montreal, Canada , October 25-28, 2012.


The following publication deals with the research, most of it which was done during the masters thesis.

- **Malik, Naveed ur Rehman; Sadarangani, C.; Cosic, A.; Lindmark, M. ,** “Induction machine at unity power factor with rotating power electronic converter,” published in International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM 2012), 20-22 June 2012.
Chapter 2

Variable Speed Control of Induction Machines

Various topologies of induction machine for variable speed control together with their working principles are discussed. The focus is given to those topologies in which rotor frequency and voltage is exploited for variable speed and power control. Moreover a brief review on the development of the brushless version of the doubly-fed induction generator is also presented.

2.1 Different Topologies of Induction Machine for Variable Speed Operation

This section presents an overview of some of the different topologies of an induction machine for variable speed control which has been in use in the past 100 years or so. Induction machines differ from synchronous machines in that the currents and voltages in the rotor windings have frequencies that depend on the speed of the rotor. Thus, the induction machine acts as a rotatable transformer with variable voltage and frequency. Through proper manipulation of the frequency of the rotor voltage while the frequency of the stator voltage is kept fixed, speed of the induction machine can be varied. Furthermore through proper adjustment of the phase and magnitude of the rotor voltage, power factor at the stator terminals can be improved. Some of the ways to change the speed of the induction machine are given below [11]:

- By changing the frequency of the stator field.
• By changing the pole-pairs of the stator windings. One of the ways of achieving this goal is via the use of the Dahlander connection where speeds of ratio of 2:1 are obtained [12].

• By changing the rotor slip through injection of voltage vector to the rotor windings e.g. through the use of external variable resistor banks connected to the rotor.

• By connecting a frequency changing device (such as power electronic converter or a rotary converter) to the rotor of the induction machine.

2.1.1 Stator Connected Converter

One of the several ways of changing the speed of an induction machine is by varying the magnitude of the stator voltage and the frequency. This can be achieved by connecting a full scale power electronic converter to the stator of the induction machine. This type of topology has the advantage that the speed of the machine can be varied over the whole speed range i.e. from zero to synchronous speed. This is a robust topology since it results in brushless operation of the drive and a squirrel cage induction machine can be used which is reliable and cheap. Moreover the machine is better isolated from the grid disturbances since it is connected to the grid through the power electronic converter. This is an advantage particular for Low Voltage Ride Through (LVRT) control of the generator as it becomes simpler. However one of the drawbacks of such a scheme is that the power rating of the converter is at least the same size as that of the power rating of the induction generator. In fact the power rating of the converter is larger than the generator, since the converter also needs to supply reactive power together with the active power. Moreover utilization of a full scale converter becomes expensive for higher power drives since the relative cost of the power electronic converter increases as the the power range increases. As a result, topologies favoring reduction in sizes of the power electronic converters are preferred especially for limited speed range applications.

2.1.2 Rotor Connected Converter

A more attractive method for variable speed control within limited speed range is by changing the electrical frequency of the rotor. This can be done either by employing variable resistors or through the power electronic converter. The use of variable resistor banks is inefficient for high power drives since energy is wasted in the resistors as losses. Moreover efficiency of the machine reduces because slip increases thereby deteriorating speed regulation at higher loads with reduced speeds [13]. Due
2.1. DIFFERENT TOPOLOGIES OF INDUCTION MACHINE FOR VARIOUS SPEED OPERATION

to above mentioned reasons, connection of the power electronic converter to the rotor of the generator for variable speed operation is preferred. In this way, power is recovered from the rotor and delivered to the grid resulting in improved efficiency. Moreover with the use of proper control strategies, the active and reactive power can be controlled independently. One of the major advantages of this topology is that the sizes of the power electronic converters are reduced since the rotor converter handles slip power only.

There are two types of configurations with regard to slip power recovery schemes and its utilization. Scherbius drive is the name given to a configuration where slip power is recovered and delivered to the grid electrically. In contrast Kramer drive is a type of configuration where slip power is converted into mechanical power and then is added to the common shaft. The two types of configurations will be explained in the subsequent sections.

2.1.3 Kramer Drive

The Kramer drive used during the time of its origin employed mechanical means to recover slip power as shown in Fig. 2.1. A DC machine was used as an auxiliary machine and shared the shaft with the induction machine. Slip power from the rotor of the induction machine was recovered via slip rings and fed to the DC machine where it was converted into mechanical power. The generated mechanical power was added back to the shaft thereby utilizing the slip power mechanically rather than electrically resulting in improved efficiency [14, 15]. In the original Kramer drive a rotary synchronous converter was used to convert the AC current from the rotor of the induction machine into the DC current before feeding it to the DC machine [14, 15]. Later on with the advent of mercury arc rectifiers, the rotary synchronous converter was replaced with the mercury arc rectifier [13, 15].

With the advent of solid state power electronic devices, a modified version of the Kramer drive was introduced around 1960’s which is known as "Static Kramer Drive" where the DC machine was replaced by a thyristor bridge and the synchronous rotary converter by a diode bridge thereby delivering power back to the grid in a manner similar to Scherbius drives [16, 17]. One of the limitations of the Static Kramer Drive was that they could operate in one mode of operation only usually sub-synchronous mode for motor operation.

2.1.4 Scherbius Drive

Scherbius drive is an outgrowth of the conventional Kramer drive where the DC machine was replaced by an auxiliary induction machine which delivered slip power back to the grid using the induction principle [11, 18] as shown in Fig. 2.2. The
excitation of the rotor of the main induction machine was controlled by the regulating machine (regulating frequency converter) which was coupled to auxiliary induction machine (squirrel cage) whose stator was connected to the grid [11,18]. The slip power from the rotor of the induction machine was fed to the rotor as well as to the stator of the regulating machine. Therefore the rotor and stator of the regulating machine operated at the slip frequency. As a result the Scherbius drive was unable to operate at synchronous speed since the slip frequency dropped to zero and therefore the regulating machine was unable to provide excitation to the rotor of the main induction machine. In order to drive the main induction machine over the synchronous speed, a variable frequency rotatable converter commonly referred to as Ohmic Drop Exciter was used which was mounted on the same shaft as that of the main induction machine [11,18]. The speed change of Scherbius drive was achieved by varying the magnitude of the rotor voltage through variable transformer. The Scherbius drive is capable of operation in both the super-synchronous
2.1. DIFFERENT TOPOLOGIES OF INDUCTION MACHINE FOR VARIABLE SPEED OPERATION

Figure 2.2: Scherbius drive.

and sub-synchronous modes.

With the advent of power electronic converters, the Scherbius drive was also modified. The rotary converter and the auxiliary induction machine was replaced by controllable thyristor bridge or nowadays with IGBT power electronic converter [19–21]. This type of drive is referred to as "Static Scherbius Drive" and allows operation of the machine in sub-synchronous mode as well as in super-synchronous mode since power flow in the rotor is bi-directional. As a result, for the same power rating of the converter, speed range is doubled as compared to the Kramer drive. Through proper control of the power electronic converter, the speed and power factor of the induction machine can be changed with considerable ease. These types of drives are nowadays very common in wind industry where IGBT power electronic converters are employed.
2.1.5 Schrage Brush Shifting Motor

The Schrage motor as shown in Fig. 2.3 was invented by Karl H. Schrage from Sweden. The motor operates in an inverted configuration where the primary winding are located on the rotor and are connected to the grid via slip rings [11, 22]. The secondary three phase winding of the motor are located on the stator and each of the two terminals of the winding are connected to the two separate brushes. The two brushes constitute one set. Similarly the windings for the remaining two phases are connected to the other two sets of brushes. The three sets of brushes are spaced apart by $120^\circ$. Each brush from each set moves together with the other corresponding brushes from the other two sets. In this way it is ensured that the spacial angle between the three sets of brushes always remains $120^\circ$. However the two brushes within each set can move relative to each other in both directions. These three sets of brushes are then connected to the rotating commutator which is further connected to another winding known as tertiary winding. The tertiary winding is also located on the same rotor as that of the primary winding and receives excitation from the primary winding in a manner similar to a transformer. When the two
brushes in each set are aligned with each other the stator winding is short circuited and thus the motor behaves as a normal short-circuited induction machine. When the two brushes in each set are separated from each other in a direction such that the foreign voltage vector introduced from the stator windings opposes the induced voltage vector from the rotor windings, the rotor speed reduces and is less than the synchronous speed. On the other hand, when the direction of separation of the two brushes is swapped and are separated in a direction such that the foreign voltage vector supports the induced voltage vector from the rotor, then the motor speed increases and is higher than the synchronous speed [11]. The power factor of the machine can be varied by angularly displacing all the three sets of brushes which in turn changes the phase of the injected foreign voltage vector relative to the rotor induced voltage vector. In this way Schrage motor is capable of operation at variable speeds over a range of 3:1 and also provides power-factor regulation [11].

2.2 Review on the Basic Development of the Brushless Doubly-Fed Induction Machine

Several researchers have come up with solutions which propose slip power recovery from the doubly-fed generators without slip rings and carbon brushes. Such generators are known as Brushless Doubly-Fed Induction Generators (BDFIG) and one of its configuration is shown in Fig. 2.4. The concept dates back to 1890’s when Görges in Germany and Steinmetz in America independently found the solution of controlling the machine at different speeds by employing a second induction machine connected in a cascade fashion [23]. They connected the stator of the second induction machine to the rotor of the first induction machine and the rotor of the second induction machine was short circuited directly or via resistances. In this way at least three different speeds were obtained which are listed below:

- When stator of the first machine was connected to the mains while its rotor was short-circuited.
- When the stator of the second machine was connected to the mains supply and its rotor was short-circuited.
- When the two machines were connected in a cascade manner. The stator of the first machine was connected directly to the mains while its rotor was connected to the stator of the second machine. The rotor of the second machine was short-circuited. Synchronous speed of the cascade machine is equivalent to the speed of a machine which has pole-pairs equal to the sum of pole-pairs of the two individual machines used in the cascade configuration. In a cascade connection the machines are coupled electrically as well as mechanically. The
rotor of the first machine and stator of the second machine carries the same currents and in essence the rotor of the first machine is the source of supply for the second machine.

The interest in these machines grew in early 1900’s due to a strong desire in the mining industry to use induction machines which can operate at different speeds without employing carbon brushes and slip rings [24]. Therefore around 1907, L.J. Hunt from Great Britain worked quite extensively on the design of the cascade version of the induction machines [23–25] and he realized that the rotor of the first machine needs not to be connected to the the stator of the second machine but instead can be connected to the rotor of the second machine thereby eliminating the slip rings and carbon brushes. He worked further on improving the rotor design and came up with the common rotor for the two stators in order to improve the efficiency of the machine and reduce the flux leakages. Furthermore Hunt adopted an idea which was originally conceived by F. Lydall in 1902 of utilizing the same slots for the primary and secondary stator windings [23]. The fluxes of the two stator windings were inductively decoupled by choosing different numbers of pole-pairs of the two stator windings as was also done by Lydall before Hunt. This is necessary as the primary and the secondary stator windings should not couple directly but through the rotor in order to produce electro-mechanical torque. In this way a brushless doubly-fed induction machine utilizing the same stator frame...
2.2. REVIEW ON THE BASIC DEVELOPMENT OF THE BRUSHLESS DOUBLY-FED INDUCTION MACHINE

could be realized. Moreover cascade operation resulted in a low speed operation since machines were mechanically and electrically coupled. This implied that pole-pairs of the induction machine summed up if the two rotor fields rotate in opposite direction to each other (provided that second machine is in inverted configuration). The inherent low speed property of the cascade machine was exploited by the ship industry where it was used in a.c. ship propulsion systems for maneuvering purposes [26].

Later on around 1920’s F. Creedy continued in developing further Hunts cascade machine and studied in depth the rules formulated by Hunt with regard to pole-pair selection [27]. F. Creedy further refined the rules and came up with 3/1 pole-pair combinations of the primary and secondary windings of the machine which were previously not addressed by Hunt. In this way he was able to increase the cascade synchronous speed by 50% as compared to machines designed by Hunt [27]. Moreover, Creedy further studied different configurations of the windings and ways of connection in order to get different distinct speeds for variable speed operation and also to increase the efficiency.

The work done by Hunt and Creedy focused on utilization of the same slots for the two windings and therefore use of different pole-pairs for magnetically decoupling the two windings. In contrast early work carried out by Steinmetz and a patent filed by Professor Silvanus Thompson in 1901 dealt with magnetically decoupling the two rotor windings through spacial separation. They used alternating segments to place the two windings in separate slots [23]. In this way they were able to use same pole-pairs and increased the slot fill factor but at the expense of the increased machine size.

After Creedy’s work in 1920’s, no major contributions came in the cascade brushless machine field until 1966 when Smith performed an in depth mathematical analysis of the machine [28]. He also highlighted the synchronous mode of operation in which frequency of the secondary winding is adjusted such that the rotor speed is the difference of the two stator frequencies [29]. Moreover in [29], he also presented an overview of the steady state performance of the machine and development of the steady state equivalent circuit.

Later in 1970’s Broadway and Burbridge also investigated the steady state performance of the machine and presented the derivation of the equivalent circuit [30]. He also introduced a new design of the rotor which is popularly known as "nested loop design" [30]. This type of rotor has all the features of a squirrel cage casted rotor such as robustness, ease of construction, reliability and lower losses. Broadway defined the rules for the design of this new type of rotor and presented ways of reducing the leakages in the rotor. Introduction of the nested loop rotor was a leap forward towards practical application of the machine in the industry due to similarities with the cage rotor induction machine. Nowadays nested loop rotor
is one of the preferred choice for the BDFIG. Later on Broadway also introduced
cageless version of the brushless induction machine in which he replaced the cage
rotor with the laminated iron rotor [31]. He also utilized the magnetic properties of
the rotor for coupling the rotor field with the stator field. The machine is similar to
a reluctance machine in construction but also comprises asynchronous mode apart
from the synchronous mode. Therefore the rotor was designed in a manner that
the machine could also operate in an induction mode [31].

Later on major work focused on further analysis of the dynamic performance and
control of the Brushless Doubly-Fed Induction Machine with Cook and Smith develop-
ing the mathematical model and confirming it through experiments in 1979 [32].
Kusko and Sumoah in [33] performed the analysis and experimental verification on
the control of the generator by using a rectifier and thyristors for delivering slip
power back to the grid. In 1980’s further developments were done by researchers
at Oregon university where the design considerations, steady-state and dynamic
performance and control aspects of the machine were further refined and studied.
Improvements in the design of the generator by using different configurations of the
stator winding is shown in [34]. Improvements in the generator efficiency and re-
duction in the sizes of the converter has been shown experimentally in [35]. In [36],
a steady state and dynamic model taking into consideration different sets of pole-
pairs of two machines is presented. It is shown experimentally that this model is
quite useful for better design of the machine for different speeds and for improved
estimation of the converter ratings. An in depth study and analysis on the control
aspects and steady-state power flow analysis of the generator is described in [37–41]
where [37] deals with stator flux field oriented control of the BDFIG.

Despite the fact that a lot of research has been done in the last couple of decades
on BDFIG, this type of machine has not been able to achieve commercial success as
was expected. One of the primary reasons has been that it employs two induction
machines and therefore power density is low. Moreover the machine suffers from low
power factor. Therefore an alternate topology of the brushless configuration is being
studied and analyzed in this thesis where the second induction machine (auxiliary
machine) in the BDFIG is replaced by a synchronous machine and power electronic
converters are moved from the stator of the auxiliary machine to in between the
rotors of the two machines. It is expected that by doing so better power factor
control over a wide range with lower power rating of the power electronic converter
and smaller machine size can be achieved. Moreover it is expected that the newer
configuration will result in higher power density than the conventional BDFIG. The
details on different aspects of the new configuration are given in the subsequent
chapters.
Chapter 3

Steady-state and Dynamic Modeling of the RPE-BDFIG

This chapter explains the basic working principle of the Rotating Power Electronic Brushless Doubly-Fed Induction Generator and presents the development of the steady-state and dynamic model of the generator.

3.1 Principle of Operation

The basic working principle of operation of the Rotating Power Electronic Brushless Doubly-Fed Induction Generator (RPE-BDFIG) is based on the same principle as that of the conventional slip-ring Doubly-Fed Induction Generator (DFIG) but without the use of carbon brushes and slip rings i.e. means of recovering slip power is brushless in nature. This type of topology was originally proposed by L. Gertmar and A. Nysveen [42]. The RPE-BDFIG consists of two machines as shown in Fig. 3.1; one is the main machine which is a wound rotor induction machine (also referred to as Doubly-Fed Induction Generator (DFIG)) and the other machine is the exciter which is modeled as a synchronous machine. The two machines are coupled mechanically and therefore rotate with the same speed. However unlike conventional Brushless Doubly-Fed Induction Generator (BDFIG), rotors of the two machines are not coupled electrically but only through agency of the DC-link, i.e. the rotor windings of the two machines are connected with each other via two power electronic converters. Therefore the frequency and magnitude of the currents and the voltages are different in the two rotors. This is in contrast to the BDFIG where rotors of the two machines must have currents of same frequency for stable operation of the drive. In addition mechanical means are employed to recover the slip power (unlike BDFIG where slip power recovery is electrical in nature) which
CHAPTER 3. STEADY-STATE AND DYNAMIC MODELING OF THE RPE-BDFIG

Figure 3.1: Configuration of the Rotating Power Electronic Converter Brushless Doubly-Fed Induction Generator.

This implies that the exciter acts as a power transfer device transferring power from the rotor of the induction machine (electrical in nature) to the common shaft (mechanical in nature) and vice versa. The mechanical power which is added/subtracted to/from the shaft contributes again for generating the electrical power and the process continues in a cyclic manner as shown in Fig. 3.2a and 3.2b. This implies that the input turbine mechanical power produces electrical power which is delivered to the grid and the slip power which is compensated by the exciter in a cyclic fashion either by generating mechanical or electrical power, which ultimately is, delivered to the grid in the form of electrical power. The fact that the mechanical power supplied by the turbine is equal to the generated power delivered to the grid (for a lossless generator) implies that slip power recovery scheme is successful. Please note that from now on the notation “Doubly-Fed Induction Generator (DFIG)” or “Induction Machine (IM)” will be used interchangeably through out this thesis to refer to the main machine of the RPE-BDFIG.

As far as configuration of the RPE-BDFIG is concerned, the stator of the IM is directly connected to the grid while its rotor is connected to one of the power electronic converters, see Fig. 3.1. The second power electronic converter is connected to the three phase rotor windings of the exciter. The exciter operates in an inverted configuration with the three phase winding on the rotor and the DC winding on the stator. Slip power from the rotor of the induction machine is fed
3.1. **PRINCIPLE OF OPERATION**

to the rotor of the exciter through the two power electronic converters. Due to the operation of the exciter in an inverted configuration, frequency of the exciter side converter must always balance the rotational speed of the shaft but in the opposite direction in order to maintain DC values at the stator terminals of the exciter i.e. exciter rotor flux appears stationary with respect to the DC excitation flux in the stator at steady state conditions. Therefore for a ±25% speed range around synchronous speed, rotor of the exciter carries high frequency currents while rotor of the IM operates at a lower frequency. Conversion in frequency and magnitude of the currents and the voltages between the two rotors is performed by the two power electronic converters. Wireless means are to be used for switching of the power electronic converters.

The RPE-BDFIG also operates in two modes of operation similar to conventional BDFIG and slip-ring DFIG. The two modes of operation are explained below.

### 3.1.1 Super-synchronous Mode

Super-synchronous mode is the normal mode of operation for a generator where the rotational shaft speed is greater than the synchronous speed. The synchronous speed of the RPE-BDFIG is decided by the grid frequency. In this mode of operation power leaves the generator from both the stator as well the rotor terminals as shown in Fig. 3.2a. Slip power leaves the rotor of the main machine and enters the rotating exciter through the two power electronic converters. In this mode, exciter operates as a motor and adds torque to the common shaft of the generator. As a result electromechanical torque generated by the main machine is the sum of the torques supplied by the wind turbine and the exciter. Regarding the direction of the fluxes, the direction of the flux vector produced by the rotor current of the doubly-fed machine is opposite to the direction of rotation of the shaft. Furthermore, the frequency of the rotor currents is equal to the difference in magnitude of the shaft speed (in electrical radians per second) and the grid frequency. This is a necessary condition for stable operation of the drive. In addition, the frequency of the flux vector produced by the exciter rotor converter must equal the shaft speed but in opposite direction for stable operation. The direction of fluxes in the stators and rotors of the two machines in super-synchronous mode of operation is illustrated in Fig. 3.3a.

### 3.1.2 Sub-synchronous Mode

In sub-synchronous mode, power enters the rotor of the induction generator from the exciter via the rotor power electronic converters. Therefore the exciter operates
Figure 3.2: Active power flow diagram for the RPE-BDFIG.
3.1. PRINCIPLE OF OPERATION

(a) Direction of rotation of the magnetic field in the super-synchronous mode.

(b) Direction of rotation of the magnetic field in the sub-synchronous mode.

Figure 3.3: Modes of operation.

as a generator extracting the torque from the shaft and producing electrical power which is equivalent to slip power as shown in Fig. 3.2b. The net electromagnetic torque generated is the difference between the turbine and the exciter torque. Moreover the direction of the flux vector produced by the rotor current of the induction
machine is the same as the direction of the shaft. As a result, sum of the magnitude of the rotor flux frequency (i.e. slip frequency) and the shaft rotational speed is equal to the stator flux frequency. Regarding the exciter, the direction of the flux vector generated by the exciter rotor converter must always be in the opposite direction but with the same magnitude as the shaft speed in electrical radians per second. The direction of the fluxes in the stators and rotors of the two machines in sub-synchronous mode of operation is illustrated in Fig. 3.3b.

3.2 Steady-state Model of the RPE-BDFIG

The steady state model of the Rotating Power Electronic Brushless Doubly-Fed Induction Generator (RPE-BDFIG) was developed, implemented and analyzed both for the super-synchronous and sub-synchronous mode of operation. The detailed development and results of the model is presented in Publication I. It is shown that this type of generator is capable of operation both in sub-synchronous and super-synchronous speeds. Furthermore if the normal induction principles are used, then during the synchronous mode (where the rotor speed is equal to the stator frequency), it is seen that the generator loses synchronism. However synchronism of this type of generator can still be realized at synchronous speed by injecting DC voltage in the rotor. In this case, the generator works similar to a DC excited synchronous generator. In Publication I, however the synchronous mode is not considered and normal induction laws are used to derive the steady-state model. As a result, at synchronous speed, the slip becomes zero and hence slip voltage also reaches zero resulting in instability unless DC voltage is fed into the rotor in order to gain stability. It can be argued that the DC excited synchronous generator is a special case of a doubly-fed induction generator, consequently in this thesis the synchronous mode of operation is not considered. The analysis and implementation of the control of the generator has been done only for super and sub-synchronous modes of operation.

3.3 Dynamic Model of the RPE-BDFIG

The dynamic model of the RPE-BDFIG is developed and analyzed in Publication II and summarized in this section. The model incorporates the dynamics of the Doubly-Fed Induction Generator (DFIG), rotating capacitor and the exciter coupled on a single shaft. Note that the term stator used through out this thesis implies stator of the main machine i.e. Doubly-Fed Induction Generator (induction machine) and the RPE-BDFIG.

The dynamic model was developed using state space vector approach in a synchronously rotating dq coordinate system as explained in [43]. One of the advan-
3.3. DYNAMIC MODEL OF THE RPE-BDFIG

tages of such a model is that variation of the inductances with rotor position are eliminated [43]. Moreover by aligning the \(dq\) reference frame using grid flux orientation where the \(d\)-axis is aligned with the grid flux vector, reactive power and active power can be controlled independently by changing the \(d\)-axis and \(q\)-axis currents respectively. Since the rotors of the two machines are not coupled electrically due to the rotating DC capacitor between the two rotating power electronic converters, two independent \(dq\) reference frames are chosen for the induction machine and the exciter part of the RPE-BDFIG. This is in contrast to BDFIG where the two rotors are mechanically as well as electrically coupled thereby leading to a common \(dq\) reference frame for the two machines. In case of the BDFIG, usually the \(dq\) reference frame is aligned with one of the stator variables of the main (primary) machine [38].

The dynamic model of the RPE-BDFIG is given by 3.1-3.18. The variables and coefficients used in the equations are defined in Appendix A.

\[
\frac{d\psi_{1d}}{dt} = v_{1d} - R_{1}i_{1d} + \omega_{1}\psi_{1q} \tag{3.1}
\]
\[
\frac{d\psi_{1q}}{dt} = v_{1q} - R_{1}i_{1q} - \omega_{1}\psi_{1d} \tag{3.2}
\]
\[
\frac{d\psi'_{2d}}{dt} = v'_{2d} - R'_{2}i'_{2d} + (\omega_{1} - \omega_{r})\psi'_{2q} \tag{3.3}
\]
\[
\frac{d\psi'_{2q}}{dt} = v'_{2q} - R'_{2}i'_{2q} - (\omega_{1} - \omega_{r})\psi'_{2d} \tag{3.4}
\]
\[
\frac{d\psi''_{3d}}{dt} = -v''_{3d} - R''_{3}i''_{3d} - \omega_{3}\psi''_{3q} \tag{3.5}
\]
\[
\frac{d\psi''_{3q}}{dt} = -v''_{3q} - R''_{3}i''_{3q} + \omega_{3}\psi''_{3d} \tag{3.6}
\]
\[
\frac{d\psi_{D}}{dt} = -R_{D}i_{D} \tag{3.7}
\]
\[
\frac{d\psi_{Q}}{dt} = -R_{Q}i_{Q} \tag{3.8}
\]
\[
\frac{d\psi_{4}}{dt} = v_{4} - R_{4}i_{4d} \tag{3.9}
\]

\[
\psi_{1d} = L_{1}i_{1d} + L_{m1}(i_{1d} + i'_{2d}) \tag{3.10}
\]
\[
\psi_{1q} = L_{1}i_{1q} + L_{m1}(i_{1q} + i'_{2q}) \tag{3.11}
\]
\[
\psi'_{2d} = L'_{2}i'_{2d} + L_{m1}(i_{1d} + i'_{2d}) \tag{3.12}
\]
\[
\psi'_{2q} = L'_{2}i'_{2q} + L_{m1}(i_{1q} + i'_{2q}) \tag{3.13}
\]
\[
\psi''_{3d} = (L''_{3d} + L''_{md2})i''_{3d} + L''_{md2}(i_{4d} + i_{D}) \tag{3.14}
\]
\[
\psi''_{3q} = (L''_{3q} + L''_{mq2})i''_{3q} + L''_{mq2}i_{D} \tag{3.15}
\]
\[
\psi_{4d} = (L_{4d} + L''_{md2})i''_{4d} + L''_{md2}(i_{3d} + i_{D}) \tag{3.16}
\]
CHAPTER 3. STEADY-STATE AND DYNAMIC MODELING OF THE RPE-BDFIG

\[
\psi_D = (L_D + L_{md2}''')i_D + L_{md2}'''i_{3d}'' + i_{4d}''
\]
\[
\psi_Q = (L_Q + L_{mq2}''')i_Q + L_{mq2}'''i_{3q}''
\]

(3.17) \hspace{1cm} (3.18)

The electro-magnetic torque produced by the exciter is given by (3.19) while the resultant electro-magnetic torque generated by the RPE-BDFIG is given by (3.20).

\[
T_{\text{exciter}} = \frac{3}{2} p_2 (\psi_{3d}'''i_{3q}'' - \psi_{3q}'''i_{3d}'')
\]

(3.19)

\[
T_e = \frac{3}{2} p_1 (\psi_{1d}i_{1q} - \psi_{1q}i_{1d})
\]

(3.20)

The mechanical dynamics of the generator are given by (3.21a)-(3.21b).

\[
\frac{d\omega_r}{dt} = \frac{p_1}{(J_1 + J_2)} (T_e - T_{\text{turbine}} - (b_1 + b_2)\omega_m + T_{\text{exciter}})
\]

(3.21a)

\[
\frac{d\theta_r}{dt} = \omega_r
\]

(3.21b)

From (3.21a) it is observed that the torque consumed or generated by the exciter is treated as a load disturbance and incorporated in the mechanical dynamics. Moreover since the shafts of the two machines are coupled, therefore speed of the exciter is controlled by the main machine. As a result, inertia of the exciter is added to the inertia of the main machine as depicted by (3.21a). Another interesting aspect to observe is that the pole-pairs of the two machines do not add which is contrary to the conventional brushless drives (BDFIG). This is because in conventional BDFIG, rotors of the two machines share currents of the same frequency i.e. the rotors are also coupled electrically, thereby leading to summation of pole-pairs.

The \textit{dq} dynamic equivalent circuit of the RPE-BDFIG is shown in Fig. 3.4a for \textit{d}-axis and in Fig. 3.4b for \textit{q}-axis. The rotor quantities are referred to the respective stator frames in terms of equivalent number of turns between the stator and the rotor. A complete analysis of the equivalent circuit is given in \textbf{Publication II} where it is shown that the RPE-BDFIG re-establishes the steady-state point of operation after being subjected to mechanical transients such as changes in torque and mechanical speed. Furthermore, it is shown that this generator has stable modes of operation at different speeds such as above and below the synchronous speed.
3.3. DYNAMIC MODEL OF THE RPE-BDFIG

Figure 3.4: $dq$ dynamic model of the RPE-BDFIG.
Chapter 4

Feedback Control Aspects of the RPE-BDFIG

This chapter explains the basics of the feedback control of the RPE-BDFIG. Design of the current controllers, speed controller and DC-link voltage controller is given. It is shown that RPE-BDFIG offers stable operation under mechanical transients.

4.1 Reference Frames

The control of the generator was implemented in synchronously rotating $dq$ reference frame. $d$-axis of the $dq$ coordinate system was aligned with the grid flux vector and vector control approach was used in order to realize the control of the generator. As a result, active and reactive power of the generator were decoupled and hence were controlled independently by controlling the $q$ and $d$-axis components of the rotor currents respectively.

The grid was modeled as an ideal three phase voltage source. Clarke’s transformation was used to transform the three phase voltages into an arbitrary reference frame called as $\alpha\beta$ coordinate system. This reference frame is fixed with the stator windings and quantities in a $\alpha\beta$ coordinate system produces the same effect in the generator as the quantities in a three phase $abc$ reference frame. However analysis of the generator becomes simpler in a $\alpha\beta$ coordinates since the three phase quantities are reduced to two phase quantities. The common practice of fixing the $\alpha\beta$ coordinates is by aligning the $\alpha$ axis with phase $a$ of the three phase windings. Clarke’s transformation is given by (4.1) [43, 44].

$$
T_{\alpha\beta} = \begin{bmatrix}
1 & -\frac{1}{2} & -\frac{1}{2} \\
0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2}
\end{bmatrix}
$$

(4.1)
where $K = \frac{2}{3}$ for amplitude invariant transformation which will be used throughout this thesis.

The variables in $\alpha\beta$ reference were further transformed to a synchronously rotating reference frame in order to realize the Proportional-Integral (PI) controller. This is because for the PI controllers the state variables of the generator should have DC values in steady-state. Therefore it becomes more convenient to use another two phase reference system rotating in synchronism with a state variable of the machine such as the stator flux or voltage vector. Doing so results in decomposition of the variable into DC quantities in steady state when seen from the synchronously rotating reference frame. As a result, implementation of PI controllers is realized with considerable ease. The transformation from $\alpha\beta$ reference frame to $dq$ reference frame is given by (4.2) which is a variant of Parks transformation [43,44]. The major advantage of this transformation is that since the two axis are in quadrature, therefore the torque producing current component and flux producing current component are decoupled when one of the axis is aligned with the flux vector. This in principle is similar to mimicking the DC machine which is the basic purpose of the vector control technique.

$$T_{dq} = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \tag{4.2}$$

The choice of $dq$ and $\alpha\beta$ reference frames is shown in Fig. 4.1. It is seen that the stator of the RPE-BDFIG is aligned with the $dq$ reference frame which is rotating synchronously with the grid frequency $\omega_1$. $\theta_1$ is the grid flux angle which is estimated using Phase-Locked Loop (PLL). The rotating power electronic converter of the exciter is also synchronized with another rotating $d_2q_2$ reference frame with the shaft speed $\omega_r$. $\theta_r$ is the rotor position.
4.2 Phase-Locked Loop (PLL) Type Estimator

The \( d \)-axis of the \( dq \) reference frame was aligned with the grid flux vector. Phase Locked Loop (PLL) estimator was used to estimate and track the position and speed of the grid flux vector and thereafter stator of the RPE-BDFIG was synchronized with the grid. PLL estimator was realized using methods described in [45] and is given by

\[
\frac{d\hat{\omega}_1}{dt} = \gamma_1 \epsilon \\
\frac{d\hat{\theta}_1}{dt} = \hat{\omega}_1 + \gamma_2 \epsilon
\]

where \( \epsilon \) is the error between the actual position (\( \theta_1 \)) and the estimated position (\( \hat{\theta}_1 \)) of the grid flux vector and is given by (4.4) [45]. \( K \) is an application specific constant [45] and \( m \) defines the polarity of the waveform. If the polarity is known then \( m = 1 \), otherwise \( m = 2 \) [45].

\[
\epsilon = K \sin(m(\theta_1 - \hat{\theta}_1))
\]

The non-linear equation can be linearized assuming that the estimated position is approximately equal to the actual position [45]. This results in a differential equation whose characteristic equation is given by (4.5a).

\[
c(s) = s^2 + \gamma_2 s + \gamma_1 \\
\gamma_1 = \rho^2 \\
\gamma_2 = 2\rho
\]

The choice of choosing the gains \( \gamma_1 \) and \( \gamma_2 \) according to (4.5b)-(4.5c) results in a well damped system since this gives \( s = -\rho \). \( \rho \) is placed in the left half of the \( s \)-plane and hence is a positive constant [45].
4.3 Control of the Induction Machine and the Exciter Rotor Side Converter

The main task of the Induction Machine Rotor Side Converter (IMRSC) is to control the speed, torque and power factor of the RPE-BDFIG. This is realized by implementing two controllers; one is the current controller which operates in an inner control loop while the second is a speed controller which works in an outer control loop. The bandwidth of the speed controller is lower than the current controller (at least a decade lower) since the mechanical dynamics are slower than the electrical dynamics [46,47]. On the other hand, the main task of the Exciter Rotor Side Converter (ERSC) is to control the DC voltage of the rotating capacitor and to deliver the slip power to/from the exciter in such a way that the stability of the generator is not compromised.

4.3.1 Internal Model Control Principles

Current and speed controllers were designed using Internal Model Control (IMC) principles which are well described in [47–49]. The basic idea behind IMC is that accurate control without any feedback can be realized only if the controller contains all the required characteristics of the system which needs to be controlled. However in reality closed loop representation of IMC is used since the knowledge of the system is not exactly known [47–49]. Fig. 4.3 shows the block diagram representation of the IMC where $G(s)$ is the representation of the system, $\hat{G}(s)$ is the model of the system $G(s)$ (it usually does not describe system exactly) and $F(s)$ is the internal model controller. Choosing $F(s)$ as a product of the low pass filter and the system model leads to better disturbance rejection and reduces the effects due to mismatch between the system and its model [48]. $F(s)$ is chosen according to (4.6) where $n$ is the order of the system and is chosen such that it makes $F(s)$ proper [46,47,50].

\[ F(s) = \left( \frac{1}{s^n} \right) \frac{G(s)}{\hat{G}(s)} \]
4.3. CONTROL OF THE INDUCTION MACHINE AND THE EXCITER
ROTOR SIDE CONVERTER

\[ F(s) = \left( \frac{\alpha}{s + \alpha} \right)^n \hat{G}^{-1}(s) \]  

(4.6)

For a first order system \( n = 1 \) and when \( G(s) = \hat{G}(s) \) the closed loop transfer function reduces to [46,47,50]

\[ G_{cl}(s) = F(s)G(s) = \left( \frac{\alpha}{s + \alpha} \right) \]  

(4.7)

As a result the IMC controller \( F(s) \) can be written in terms of proportional and integral terms as follows

\[ F(s) = \frac{\alpha}{s} G^{-1}(s) = k_p + \frac{k_i}{s} \]  

(4.8)

The following sections will present the design of the current, speed and DC-link controllers based on the IMC principles.

4.3.2 Current Controller

The rotor equation of the induction machine part of the RPE-BDFIG can be written in terms of the rotor voltage vector generated by the IMRSC and is given by (4.9)-(4.10). Similarly the rotor equation of the exciter can be written in terms of the rotor voltage vector generated by the ERSC and is given by (4.11)-(4.12).

\[ v'_{2d,cc} = R'_{2}i'_{2d} + \frac{d\psi'_{2d}}{dt} - \omega\psi'_{2q} \]  

(4.9)

\[ v'_{2q,cc} = R'_{2}i'_{2q} + \frac{d\psi'_{2q}}{dt} + \omega\psi'_{2d} \]  

(4.10)

\[ v''_{3d,cc} = R''_{3}i''_{3d} + \frac{d\psi''_{3d}}{dt} - \omega\psi''_{3q} \]  

(4.11)

\[ v''_{3q,cc} = R''_{3}i''_{3q} + \frac{d\psi''_{3q}}{dt} + \omega\psi''_{3d} \]  

(4.12)

Due to the presence of the cross-coupling term in the \( dq \) voltage components, an extra feedback term consisting of the leakage reactance is added in the system transfer function \( G_{c,y}(s) \) as shown in the Fig. 4.4. As a result, the resulting voltage vector injected into the rotor terminals of the induction machine and the exciter is given by (4.13)-(4.14) and (4.15)-(4.16) respectively.

\[ v'_{2d} = R'_{2}i'_{2d} + \frac{d\psi'_{2d}}{dt} \]  

(4.13)

\[ v'_{2q} = R'_{2}i'_{2q} + \frac{d\psi'_{2q}}{dt} \]  

(4.14)

\[ v''_{3d} = R''_{3}i''_{3d} + \frac{d\psi''_{3d}}{dt} \]  

(4.15)

\[ v''_{3q} = R''_{3}i''_{3q} + \frac{d\psi''_{3q}}{dt} \]  

(4.16)
Using the Laplace operator, the transfer function of the rotor of the induction machine from the output of the current vector to the input voltage vector (assuming same inductances in both the $d$ and $q$-axis) is given by (4.17). Similarly the transfer function of the rotor of the exciter from the current vector as an output to the rotor voltage vector as an input is given by

$$G_{c,IM}(s) = \frac{i_2'}{v_2'} = \frac{1}{(R'_2 + sL'_2)}$$  
$$G_{c,exciter}(s) = \frac{i_3''}{v_3''} = \frac{1}{(R''_3 + sL''_3)}$$  

Using IMC principles the induction machine rotor current controller can be written as in (4.19) while the exciter rotor current controller is given by (4.20). The induction machine and exciter rotor current controller parameters are given by (4.21) and (4.22) respectively.

$$F_{c,IM}(s) = \frac{\alpha_{c,IM}}{s} G_{c,IM}^{-1}(s) = k_{pc,IM} + \frac{k_{i,IM}}{s}$$  
$$F_{c,exciter}(s) = \frac{\alpha_{c,exciter}}{s} G_{c,exciter}^{-1}(s) = k_{pc,exciter} + \frac{k_{i,exciter}}{s}$$

$$k_{pc,IM} = \alpha_{c,IM}(L_1 + L'_2) \quad k_{ic,IM} = \alpha_{c,IM}(R_1 + R'_2)$$
$$k_{pc,exciter} = \alpha_{c,exciter}(L''_3) \quad k_{ic,exciter} = \alpha_{c,exciter}(R''_3)$$

The block diagram of the current controllers for the RPE-BDFIG is given in the Fig. 4.4. Two current controllers were used; one for the induction machine rotor side converter and the other for the exciter rotor side converter. This is illustrated by variable “$x$” and “$y$” in the block diagram where $x = 2$ and $y = IM$ represents variables for induction machine rotor current controller while $x = 3$ and $y = exciter$ represents variables for exciter rotor current controller.

### 4.3.3 Speed Controller

The speed controller is also designed using IMC principles and was implemented in a cascade configuration with the current controller. The purpose of the speed controller is to give the reference value of the $q$-axis rotor current in order to generate the required torque resulting in a smooth transition from one speed to another [51] for the same torque or for a different torque but at the same speed. It is essential that the bandwidth of the speed controller should be at least a decade lower than the current controller for the desired performance of the speed controller when used in a cascade configuration with the current controller [46, 47, 50].
According to the IMC principle, the speed controller was designed using the transfer function of the mechanical dynamics of the generator which is governed by (4.23).

\[
\frac{J_1 + J_2}{p_{p1}} \frac{dw_r}{dt} + \frac{b_1 + b_2}{p_{p1}} w_r = T_e - T_{turbine} + T_{exciter} (4.23)
\]

Applying Laplace transformation to (4.23) and rearranging it yields the transfer function of the mechanical dynamics of the RPE-BDFIG from the mechanical torque as an input to the speed as an output.

\[
G_s(s) = \frac{w_r/p_{p1}}{T_e - T_{turbine} + T_{exciter}} = \frac{1}{(b_1 + b_2) + s(J_1 + J_2)} (4.24)
\]

Applying the IMC principles to the mechanical model yields a speed controller given by (4.25) and its PI control parameters are given by (4.26) [50,51]. The block diagram of the speed controller is given in Fig. 4.5.

\[
F_s(s) = \frac{\alpha_s}{s} G_s^{-1}(s) = k_{ps} + \frac{k_{is}}{s} (4.25)
\]

\[
k_{ps} = \alpha_s(J_1 + J_2) \quad k_{is} = \alpha_s(b_1 + b_2) (4.26)
\]

The block diagram for the speed controller of the RPE-BDFIG is shown in Fig. 4.5 where the speed is an input of the controller while reference command of the electromechanical torque is an output.

**4.3.4 DC-Link Voltage Controller**

This section presents the DC voltage control of the rotating capacitor. The aim of the controller is to maintain the DC-link voltage of the rotating capacitor. In order to do so, the controller needs to balance the slip power generated/consumed.
CHAPTER 4. FEEDBACK CONTROL ASPECTS OF THE RPE-BDFIG

Figure 4.5: Block diagram of a speed controller for a RPE-BDFIG.

from the induction machine part of the RPE-BDFIG and the rotor power consumed/generated from the exciter. Therefore the DC-link controller should act such that in a case of a super-synchronous mode, the net slip power leaving the rotor of the induction machine should balance the power entering the rotating exciter. On the other hand, in a sub-synchronous mode, the rotor power generated from the exciter must balance the slip power entering the rotor of the induction machine. It should be observed that the DC-link voltage controller must work in conjunction with the current controller of the exciter and the reference slip power command from the induction machine part of the model. This is because in this case the DC-link controller is not static but rotating. Therefore the power balance should be maintained in such a manner so as not to affect the overall stability of the RPE-BDFIG.

The DC-link model and its voltage controller is developed using methods described in [52,53]. The power flow in the capacitor is the difference between the induction machine rotor slip power and the exciter rotor power and is given by (4.27a)-(4.27b).

\[
\frac{1}{2} C_{dc} s v_{dc}^2 = P_{r, exciter} - P_{r, IM} \tag{4.27a}
\]

\[
= 3v'''_{3q} i'''_{3q} - P_{r, IM} \tag{4.27b}
\]

Introducing the “active conductance” \( G_a \) which acts as an active damper and also moves the pole from the origin to the left half of the plane yields

\[
\frac{1}{2} C_{dc} s v_{dc}^2 = 3v'''_{3q} i'''_{3q} - 3v'''_{3q} G_a v_{dc}^2 - P_{r, IM} \tag{4.28}
\]

Rearranging the above equation and treating \( P_{r, IM} \) as an external disturbance results in the following transfer function of the DC-link model.

\[
G_v'(s) = \frac{v_{dc}^2}{i_{3q}^\text{ref}} = \frac{6v'''_{3q}}{sC_{dc} + 6v'''_{3q} G_a \tag{4.29}}
\]
4.3. CONTROL OF THE INDUCTION MACHINE AND THE EXCITER
ROTOR SIDE CONVERTER

This means that the poles of the DC-link model moves from \( s = 0 \) to \( s = -\frac{6G_a v''_{\text{dc}}}{C_{\text{dc}}} \) thereby improving the damping of the system. Furthermore for a first order system the transfer function of the closed loop system can be given by (4.30a) where \( \alpha_v \) is the bandwidth of the controller and specifies the position of the pole of the closed loop system in the left half plane. It is observed from (4.30b) that closed loop system constitutes the transfer function of the process model (in this case it is the DC-link voltage model) and the DC voltage controller designed in a cascade configuration.

\[
F_v(s) = \frac{\alpha_v}{s + \alpha_v} \quad (4.30a)
\]

\[
= \frac{F_v(s)G_v'(s)}{1 + F_v(s)G_v'(s)} \quad (4.30b)
\]

Applying the IMC principle, the DC-link voltage controller for a first order system in terms of DC-link system parameters is given by

\[
F_v(s) = \frac{\alpha_v}{s} G_v'^{-1}(s) = k_{pv} + \frac{k_{iv}}{s} \quad (4.31)
\]

Since the damping of the DC-link model is much slower than the closed loop system, therefore placing the poles of the DC-link voltage model at the same position as that of the pole position of the closed loop system results in the disturbance rejection of the inner feedback loop of the DC-link system at the same rate as that of the closed loop system [52]. Thus choosing the value of \( G_a \) according to (4.32) makes the inner feedback loop of the DC-link system as fast as the overall closed loop system.

\[
G_a = \alpha_v \left( \frac{C_{\text{dc}}}{6v''_{3q}} \right) \quad (4.32)
\]

The proportional and integral gains of the DC-link voltage controller are then given by (4.33).

\[
k_{pv} = \alpha_v \left( \frac{C_{\text{dc}}}{6v''_{3q}} \right) \quad k_{iv} = \alpha_v^2 \left( \frac{C_{\text{dc}}}{6v''_{3q}} \right) \quad (4.33)
\]

The block diagram of the DC-link voltage model and its controller is depicted in Figure 4.6 while the overall closed-loop control of the RPE-BDFIG is shown in Fig. 4.7. It includes the block diagrams for the two current controllers for controlling the two rotating power electronic converters, a DC-Link voltage controller for controlling the DC voltage of the rotating capacitor, a speed controller and a PLL for tracking the grid flux angle. Note that the dotted line in the RPE-BDFIG block in Fig. 4.7 represents the rotor of the exciter while the dashed line represents the rotor of the induction machine.
CHAPTER 4. FEEDBACK CONTROL ASPECTS OF THE RPE-BDFIG

Figure 4.6: Block diagram for a DC-link voltage model and its controller.

Figure 4.7: Block diagram for a closed-loop control of a RPE-BDFIG.
Chapter 5

Low Voltage Ride Through of the RPE-BDFIG

This chapter explains the types of voltage dips occurring in the power network due to different types of faults. Particular focus is laid on the impact of different types of faults on the behavior of the RPE-BDFIG. Furthermore Low Voltage Ride Through (LVRT) of the generator is implemented and analyzed and it is concluded that this type of generator is capable of withstanding severe voltage dips during symmetrical and unsymmetrical faults.

5.1 Grid Code Requirements for the Wind Turbines

With the increasing penetration of wind turbines in the power system, it is no longer feasible to disconnect the wind turbines from the grid during grid faults. On the contrary they should support the grid during the disturbances and in fact contribute with reactive power for voltage stability. Connection of wind turbines to the grid during a fault in the network is becoming a reality as the grid codes are becoming more stringent and transmission system operators are placing heavy demands on the wind turbine plants during the grid disturbances. Several Transmission System Operators (TSO) for example, E.ON in Germany have modified its grid codes for wind plants and have placed the demand requiring them to contribute with reactive current during a grid fault for a certain period of time [54–59]. In other words wind turbine plants are being treated in the same category as conventional power plants such as hydro and gas turbines. After modifications in the German and Danish grid codes where the percentage of penetration of wind power is one of the highest in the world, other grid operators such as those in Spain and United Kingdom have followed the same trend and therefore modified their grid codes. Due to
different grid code requirements in different countries, wind turbine manufacturers face challenges when designing wind turbines which have to be adapted according to the requirements of the countries where it will be installed [58]. Therefore in order to harmonize different grid codes, Europe is working on the development of generic grid codes under the platform of European Network of Transmission System Operators for Electricity (ENTSO-E) which comprises of 41 transmission system operators (TSOs) from 34 European countries. One of the aims of ENTSO-E is to develop grid codes which are applicable in the European countries [60]. This will result in better energy exchange between different countries, easier integration of renewable sources and secure operation of the transmission network [60]. The draft version on grid codes published by ENTSO-E also has the requirements for wind turbines to maintain connection to the grid and to provide reactive power during a fault period [61].

The limit curve for the magnitude and the corresponding duration of the voltage dip as illustrated in the E.ON grid code standard [57] is depicted in Fig. 5.1. In region I wind turbines are not allowed to be disconnected and should provide reactive current (at a rate of 2% of the rated current for each percent of the voltage dip) if the voltage drops below 90% of the nominal value at the generator terminals. In region II wind turbine units are allowed temporary disconnection from the grid and should re-synchronize again within 2 seconds after the fault clearance. In region III, wind turbine units are allowed to be disconnected from the grid.

Due to above mentioned reasons it has become a major challenge to design a system for wind generators especially Doubly-Fed Induction Generators that can maintain connection to the grid in case of faults in the power system. Low Voltage Ride Through (LVRT) of DFIG’s is a challenging task since the power electronic converter is rated for fraction of the power rating of the main generator. During a fault when the voltage drops at the stator terminals, the stator current starts to increase. Since the stator and rotor are mutually coupled, the rotor current will also increase and can exceed the rating of the converter thereby leading to its damage. Thus in order to save the converter from damage either the turbine has to be disconnected from the grid or some LVRT strategy needs to be adopted.

5.2 Existing Topologies for the LVRT of the Doubly-Fed Generators

One of the techniques of protecting the rotor converter from damage is to employ rotor crow bar concept in which a high resistance is connected in series with the rotor with the help of switches during the grid fault [8,62–68]. In this way, high rotor current is bypassed into the resistors and the generator acts similar to a
5.2. EXISTING TOPOLOGIES FOR THE LVRT OF THE DOUBLY-FED GENERATORS

Figure 5.1: E.ON grid code standard for low voltage ride through.

conventional short-circuit rotor induction generator. Use of rotor crowbar for LVRT has certain drawbacks such as the control of the generator is lost during the fault period and as a consequence it draws more reactive current from the grid thereby further deteriorating the voltage stability [62,63,66]. Besides during the crowbar operation, reactive power cannot be fed to the grid and therefore generator will no longer participate in voltage stability. An alternative approach is to use a chopper together with a resistance in parallel with the DC-Link voltage [68]. The chopper will be switched during the fault and will help in limiting the DC voltage by dissipating the power in the resistor. However this will result in over-dimensioning of the rotor converter since it needs to handle high rotor currents [68]. Another alternative option is to use an auxiliary converter referred to as series grid side converter operating together with the machine side and grid side converters and connected in series with the stator of the generator [69,70]. The aim of the converter is to maintain the voltage at the stator terminals irrespective of the voltage dip in the grid. The converter uses the same DC-link capacitor as the machine side converter. However addition of an extra converter increases the total cost of the system and large DC-link voltage is required in order to maintain voltage at the stator terminals for deeper voltage sags resulting in further increase in the size of the
40 CHAPTER 5. LOW VOLTAGE RIDE THROUGH OF THE RPE-BDFIG

converter. Due to these aforementioned limitations, a technique known as Passive Resistive Network first proposed in [71–73] has been adopted for LVRT of RPE-BDFIG during symmetrical voltage dips and is explained in Section 5.4. Extended Vector Control strategy [74,75] has been adopted for LVRT of RPE-BDFIG during unsymmetrical voltage dips and is explained in Section 5.5.

5.3 Types of Faults

Faults in the power system are a consequence of short circuits in some parts of the grid thereby resulting in voltage sags. Starting of large induction motors and energizing of transformers are also other factors for voltage sags in the power network [76–79]. There are various types of faults which can be classified as symmetrical faults and unsymmetrical faults.

Symmetrical faults are due to the three-phase faults and three-phase-to-ground faults [76–79]. They are the most severest fault but their frequency of occurrence is less. In these faults the magnitude of the voltage in each phase reduces by the same magnitude and phase angle between the three voltage vectors remains 120° [79–81].

Unsymmetrical faults are due to single-phase-to-ground faults, phase-to-phase faults and phase-to-phase-to-ground faults [76–79]. Single-Phase-to-Ground Faults (SPGF) are the most common faults occurring in the electrical network followed by phase-to-phase faults. However, severity of the SPGF in terms of the magnitude of the short-circuit currents is less than the three-phase faults [79–83]. In case of SPGF, magnitude of the voltage reduces in one phase only if the fault is solidly grounded. On the other hand, in case of the resistance grounded system, magnitude of the voltages in the other two phases increases because of an increase in the voltage at the neutral point due to the ground impedance [79–82].

5.3.1 ABC Classification of Voltage Dips

One of the simplest ways of classifying different types of faults together with magnitude and phase angle of voltage dips resulting from them is known as ABC classification [79,83,84]. The ABC classification is derived from the symmetrical component classification by assuming equal impedances for the positive, negative and zero sequences in the power system. Therefore ABC classification is a specific case of a symmetrical component classification [79,83]. According to ABC classification, there are seven types of voltage dips occurring due to different types of faults which are summarized in Fig. 5.2 [79–81,83]. According to the Fig. 5.2, it is seen that different fault types give rise to voltage vectors with different magnitudes and phase angles at the stator terminals of the generator. The magnitudes and phase angles of the voltage vectors depends upon the transformer impedance and distance of the
fault from the generator terminals [79]. Furthermore, if the voltage dip experienced by the load is due to the fault occurring in the transmission line and the load is connected directly to the transmission line, then in this case the phase angle jump in the voltage is small and therefore can be neglected [84].

5.4 LVRT of RPE-BDFIG during Symmetrical Voltage Dips using Passive Resistive Network

This section explains the symmetrical voltage dips and explains the technique used for the LVRT of the RPE-BDFIG in this thesis. The detailed analysis of the generator using Passive Resistive Network for LVRT is given in Publication III.

Symmetrical voltage dips are not very common in the power system. However their occurrence results in large magnitude of short circuit currents. These faults are much easier to handle since these faults do not give rise to negative sequence currents unlike unsymmetrical faults which is explained in Section 5.5. Several techniques are used to handle such faults such as rotor crowbar, series grid side converter, Passive Resistive Network, etc as explained in Section 5.2. The technique which has been adopted for LVRT of the RPE-BDFIG during symmetrical voltage dips is Passive Resistive Network (PRN) [71–73]. This is because in the case of RPE-BDFIG, due to its brushless nature, rotor terminals are not available for external connection unlike slip-ring DFIG. Therefore a strategy which can be used at the stator terminals of the RPE-BDFIG needs to be adopted for successful ride
through of the generator. PRN offers this advantage and therefore access to the rotor terminals is not required.

Passive Resistive Network consists of two resistors named as series resistor ($R_s$) and shunt resistor ($R_p$) for each phase. The series resistor ($R_s$) is connected in series with the stator terminals while the shunt resistor ($R_p$) is connected in parallel with the stator terminals as shown in Fig. 5.3. This implies that these two resistors operate as a voltage divider. A controllable switch ($S_A$) is connected in parallel with the series resistance ($R_s$) and a second switch ($S_B$) is connected in series with the shunt resistor ($R_p$) [71–73]. When the fault occurs in the power network, the switch ($S_A$) is opened while the switch ($S_B$) is closed. The value of ($R_s$) is chosen such that it draws the current from the generator with an amplitude which results in a voltage drop across the resister ($R_s$) equivalent to the difference between the grid pre-fault voltage and grid voltage during the fault. As a result the generator terminals do not experience a voltage dip. In this way the stator flux oscillations are damped resulting in reduced rotor currents thereby saving the power electronic converter from damage. In other words, the series resistance ($R_s$) helps in maintaining the connection to the grid and limits the excessive current being drawn from the generator [71–73]. The basic purpose of the resister ($R_p$) is to balance the input mechanical power and the generated electrical power [71–73].

One of the major advantage of using PRN strategy is that the rotor power electronic converter maintains its connection to the grid during the fault and therefore the active and reactive power can be controlled during this period. A comprehensive analysis of the LVRT of the RPE-BDFIG during symmetrical voltage dips is shown in Publication III. It is shown that RPE-BDFIG is able to successfully ride through different magnitudes of symmetrical voltage dips using PRN. Further details on the basic working principle of PRN, its equivalent circuit diagram and LVRT of the RPE-BDFIG using E.ON grid code standards is also given in Publication III.

5.5 LVRT of RPE-BDFIG during Unsymmetrical Voltage Dips

In this section, brief overview of the methods used for low voltage ride through of the generator during unsymmetrical voltage dips is presented. During unsymmetrical voltage dips, stator of the generator experiences voltages with different magnitudes and phase angle jumps in different phases. The unbalance in the generator voltages results in an extra heating of the generator windings due to negative sequence currents and an increase in the iron losses due to higher frequencies of these currents. Moreover oscillations in power, currents, torque and DC-link capac-
5.5. LVRT OF RPE-BDFIG DURING UNSYMMETRICAL VOLTAGE DIPS

Itor voltage results in a reduction in the lifetime of the electrical and mechanical components connected to the generator such as gearbox, generator shaft, DC-link capacitor, etc [85–87]. Therefore it is of immense importance that the resulting disturbances due to voltage unbalance are handled in a manner so as not to affect the normal operation of the generator.

The resultant voltage vector can be split into three balanced components using symmetric component theory i.e. positive, negative and zero sequence components. Zero sequence component can be disregarded since neutral point of the conductor of the three phase winding is not grounded.

During an unsymmetrical fault, the voltage vector at the stator terminals of the RPE-BDFIG in the stationary reference is given by (5.1).

\[ v_1(t) = |\bar{V}_{1p}|e^{j\omega_1t} + |\bar{V}_{1n}|e^{-j\omega_1t} \] (5.1)

Transforming (5.1) in a positive sequence synchronous reference frame results in (5.2). It is observed from (5.2) that the positive sequence quantities are seen as DC quantities in a positive sequence synchronous reference frame while the negative sequence quantities rotate with double frequency. This implies that in order to control the positive sequence currents, control strategy similar to controlling the currents during balanced operation can be used. However some form of control technique needs to be implemented for controlling the double frequency component in order to reduce the oscillations in power, torque, etc.

\[ v_1(t) = |\bar{V}_{1p}| + |\bar{V}_{1n}|e^{-j2\omega_1t} \] (5.2)

In the existing literature [74,88–94] several techniques have been investigated for mitigating the effect of the unbalance voltages on the conventional slip-ring induction generator. One of the ways proposed in [88] for successful ride through

![Figure 5.3: Single phase diagram of the Passive Resistive Network.](image-url)
of the DFIG under unsymmetrical voltages is to use Proportional Resonance (PR) controllers. This type of controller is directly implemented in stationary reference frame ($\alpha\beta$) and is tuned at grid frequency e.g. 50 Hz. This is because in the $\alpha\beta$ reference frame, the positive and negative sequence components rotate with the same magnitude but in the opposite direction as depicted by (5.1). As a result with the proper tuning of the controller, negative sequence currents can be controlled to a desired value. One of the advantages of using PR controller is that the dynamic performance is improved since conversion from $\alpha\beta$ to $dq$ reference frame is not required. Furthermore harmonic filters in order to separate positive and negative sequence currents are no longer required [88]. Moreover only one controller for handling positive and negative sequence components is needed.

Another approach for controlling the generator during voltage unbalance is to use Proportional Integral Resonance (PIR) controller which is proposed in [89]. This controller is implemented in positive sequence synchronously rotating reference frame. Thus the positive sequence currents and voltages appear as DC components in steady-state. However, the negative sequence currents appear as oscillation with twice the grid frequency i.e $2w_1$. As a result an extra term with the conventional PI controller is added and it is tuned at $2w_1$. In this way the negative sequence components can be controlled to a desired value.

The following section explains the strategy which is used in this thesis for controlling the negative sequence currents.
5.5. **LVRT OF RPE-BDFIG DURING UNSYMMETRICAL VOLTAGE DIPS**

5.5.1 **Extended Vector Control**

The approach which has been adopted in this thesis for controlling the RPE-BDFIG during unbalanced voltages is based on Extended Vector Control proposed in [74] for slip ring doubly-fed induction generators. A similar approach has also been proposed in [75] for the Pulse Width Modulated (PWM) converters. Further work on controlling the generator through decoupling the sequences in their respective positive and negative sequence reference frames has been analyzed in [90–94]. In [94] Delayed Signal Cancelation (DSC) technique instead of filters (low-pass or notch) is used to separate the positive and negative sequence $dq$ components for the DFIG and in [95] for the PWM converter. Delayed signal cancelation has much faster response than the bandpass or low-pass filters but at the cost of introducing large oscillations during the beginning and end of the voltage dip [94]. However in this thesis Butterworth low-pass filter has been used to filter the oscillations in the $dq$ positive sequence reference frame due to negative sequence components and vice versa.

Extended Vector Control (EVC) was adopted for the purpose of controlling the negative sequence currents due to its simplicity since it uses standard PI controllers. Using this technique, response of the generator is fully expressed using two synchronous reference frames i.e. Positive Sequence Synchronous Rotating Reference Frame ($d^+q^+$) which rotates with the positive sequence grid flux vector and the Negative Sequence Synchronous Rotating Reference Frame ($d^-q^-$) which rotates with the flux vector in the opposite direction to the positive sequence flux vector as shown in Fig. 5.4. The positive and negative sequence current and voltage components are separated using Butterworth low pass filter and are independently controlled in the two reference frames thereby resulting in reduction in oscillations in torque, power and rotor capacitor voltage. The mathematical treatment and analysis of the RPE-BDFIG using EVC during unsymmetrical faults is explained in detail in **Publication IV**. Basic expressions for power including the oscillating components are also given. The study in **Publication IV** is conducted for both the single-phase-to-ground fault and phase-to-phase fault.
Chapter 6

Unity Power Factor Operation of a Single-fed Induction Machine using Lindmark Concept

This chapter gives an overview of operation of the induction machine at unity power factor using rotating power electronics. Using suitable control strategy, the power electronics in the rotor is used to control the power factor of the induction machine at the stator terminals. It is shown that the sizes of the capacitor and power electronic converters is rated at fraction of the power rating of the machine for unity power factor operation.

6.1 Rotating Power Electronic Induction Drive

This section gives an overview of the Rotating Power Electronic Induction Drive (RPED). This type of drive uses controllable capacitors through the two power electronic converters mounted on the rotor of the induction machine in order to inject reactive current from the rotor to the stator as shown in Fig. 6.1. Using the two power electronic converters, the rotor current is controlled in such a way so as to attain unity power factor at the stator terminals. This concept was conceived and invented by Magnus Lindmark from Sweden [96] and is referred to as Lindmark concept in this thesis. His main idea was to use currents in the rotor to improve the power factor of the machine using power electronics and capacitors in the rotor with sizes which are a fraction of the power rating of the induction machine. In this way Lindmark was able to self-excite the machine without any external support such as grid or capacitor banks.
Self-excitation of the generator and hence unity power factor is a very desirable property to have not only for single-fed induction generators but also for single-fed induction motors because unity power factor operation results in a decrease in the reactive current at the stator terminals and therefore transmission lines. This results in reduction of copper losses in the transmission network and increases the overall efficiency of the power system. Furthermore, voltage stability of the grid is also enhanced.

It is well known that the induction generators are quite often employed in remote areas for stand alone operation. Stand alone use of the induction generators needs auxiliary equipment for self-excitation of the generator. RPED can also be employed in such application since this type of generator has capability of operating at unity power factor and even delivers reactive power. Besides, the Lindmark concept can be smartly exploited for designing induction machines with large pole-pairs. It is well known that the power factor of the induction machines deteriorates as the pole-pairs of the machine increases. However since the Lindmark concept employs controllable capacitors rated for fraction of the total power, therefore using the induction machine with large pole-pairs can be realized with unity power factor and high system efficiency. Moreover the rotating power electronic switches can be smartly placed on the periphery of the rotor since the machines with higher pole-pairs offers large airgap diameters due to mechanical reasons. This is similar to permanent magnet direct drive generators but instead replacing the permanent
magnets with the electronic switches. As a result direct drive induction generators with improved power factor can be conceived and realized.

## 6.2 Lindmark Concept

In the RPED, Lindmark concept is used which utilizes open end winding concept in the rotor instead of the stator as explained in detail in Publication V and Publication VI. This concept uses two power electronic converters in the rotor with a DC-link capacitor in between, for improving the power factor at the stator terminals of the induction machine. Each of the two terminals of the respective rotor windings are connected with one of the two power electronic converters and the two power electronic converters are connected with each other in a back-to-back configuration separated by a DC capacitor as shown in Fig. 6.2. The stator of the induction machine is directly connected to the grid. Purpose of the rotor power electronic converter and the rotor capacitor is to inject an extra voltage vector which will vary the magnitude and phase angle of the rotor current in such a manner so as to deliver reactive power from the rotor. The phase angle of the voltages produced by one of the converters can be shifted with respect to the other by an angles referred to as phase shift angle $\theta_{ps}$ which results in generation of an extra voltage vector named as phase-shift voltage vector across the rotor windings. The angle $\theta_{ps}$ can be varied between $\theta_{ps} = 0^\circ$ to $\theta_{ps} = 180^\circ$. When the phase shift angle is $\theta_{ps} = 0^\circ$, the rotor winding is short circuited and the currents follow the path as shown by Fig. 6.2a. On the other hand, when the phase shift angle is $\theta_{ps} = 180^\circ$, the rotor windings inductance is placed in series with the DC-link capacitor and therefore the current follows the path as shown by Fig. 6.2b.

For the sake of simplifying the analysis, in this thesis, the phase-shift angle between the corresponding phases of the two switches is fixed at $180^\circ$ during normal operation. Doing so places the rotating capacitor in series with the rotor windings, thereby increasing the effective capacitive reactance of the rotor windings. The change in the impedance of the rotor windings results in the movement of the rotor current vector (and hence the stator current vector) in such a manner so as to improve the overall power factor of the machine. Unity power factor is obtained when the equivalent rotor capacitive reactance is equal to the induction machine magnetization and stator leakage reactance. It is shown in Publication VI that the size of the rotor capacitor required at low slip (high speed) is quite small as it is normalized by a factor of slip squared. This means that the effective capacitive reactance of the rotor as seen from the stator is large for small values of slip thereby reducing the sizes of the power electronics and the capacitors.

Publication V deals with the derivation and development of the steady state analytical model of the RPED. Furthermore the analytical model is verified and
thus validated through experiments on an 11 kW induction machine and it is shown in \textit{Publication V} that the results from the analytical model are in close agreement with the performance of the RPED in real time. \textit{Publication VI} gives an in depth experimental analysis of the RPED at different speeds and studies the effects of variations in the slip on the power factor of the machine. The analysis presented is based on experimental measurements performed on a 1.8 kW induction machine. Furthermore the mathematical treatment of the machine using phasor analysis based on experimental results is also presented in \textit{Publication VI}. The phasor analysis shows how the stator current changes its position with change in torque when the voltage vector is injected through the electronic converters.
6.2. LINDMARK CONCEPT

(a) Direction of the current when $\theta_{ps} = 0^\circ$.

(b) Direction of the current when $\theta_{ps} = 180^\circ$.

Figure 6.2: Configuration of the Lindmark rotor. Red arrow indicates direction of the current.
Chapter 7

Conclusions

This chapter presents the summary of the work and gives suggestions for future work.

7.1 Summary

A novel topology of a brushless doubly-fed induction machine was introduced in which the slip rings and carbon brushes were replaced by the rotating power electronic converters and a rotating exciter. The basic principles behind the working of the generator were explained.

The steady-state model of the Rotating Power Electronic Generator was developed and implemented. It was shown that the generator shows stable behavior in both the sub-synchronous and super-synchronous modes of operation. Moreover it was shown that the rotating exciter together with the power electronic converters are capable of injecting reactive power from the rotor thereby improving the power factor of the generator. Unity power factor operation was also illustrated.

The dynamic model of the generator was also developed and it was shown that the generator is capable of withstanding transients and perturbations in torque at different speeds in the super-synchronous and sub-synchronous modes. Moreover it was shown that during an external mechanical disturbances, the DC voltage of the rotating capacitor is capable of maintaining its reference voltage and the overall power balance between the induction machine rotor power and the exciter rotor power in such a manner so as not to compromise the overall stability of the generator. Apart from this, it is also shown that by using the rotating exciter, the slip power recovery scheme is successful and the power is recovered via the stator of the RPE-BDFIG thereby increasing the efficiency of the generator.
Analysis of the LVRT of the generator for various magnitudes of voltage dips was performed and analyzed. It was shown that the generator is capable of withstanding approximately 20% of voltage dip after which an external safety strategy was required in order to save the converter from damage. Passive Resistive Network (PRN) strategy was employed for LVRT during the excessive symmetrical voltage dips. The behavior of the generator using PRN was analyzed and it was shown that the generator is capable of riding through extreme voltage dips of 85% of its nominal value using PRN.

Analysis of the RPE-BDFIG during unsymmetrical voltage dips was also conducted. Extended Vector Control (EVC) method was adopted in order to mitigate the affects of the negative sequence currents on the operation of the generator. It was shown that through the use of EVC control the generator showed stable behavior and the oscillations in power, current, torque and DC-link capacitor were reduced to a considerable extent.

Besides single-fed induction machine with unity factor operation was presented. Lindmark concept was used to attain unity power factor. The voltage vector produced from the power electronic converter was injected to the rotor terminals in a manner so as to move the rotor current. Movement of the rotor current also affected the stator current. Phase of the stator current with respect to the stator voltage was changed in a manner so as to improve the power factor of the machine. Using this technique an induction machine where the rotor took over the magnetization of the machine and delivered the reactive power was demonstrated. Steady state model of the machine was also developed and was verified through experimental tests.

7.2 Future Work

The developed steady-state and dynamic model of the RPE-BDFIG needs to be verified experimentally using the closed-loop control. It is of interest to see how well the experimental results agree with the derived models. Moreover, impact of the symmetrical and unsymmetrical voltage dips needs to be investigated experimentally and the increase in the rating of the converter with increasing voltage dip must also be verified.

Furthermore, once the models are verified through experiments, it would be an interesting study to compare the sizes of the exciter and the rotating power electronic converters with the sizes of the power electronic converters and auxiliary machine of the conventional BDFIG.

Another interesting aspect and investigation will be to evaluate the cost aspects of the rotating power electronic converters, wireless communication controllers and rotating exciter and compare it with the maintenance costs of the slip rings and
7.2. FUTURE WORK

carbon brushes. This will be the deciding factor in showing and proving the competitiveness of the RPE-BDFIG relative to the slip-ring DFIG.
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Appendix A

Glossary of Symbols and Abbreviations

Symbols

\( \psi \) \quad Flux
\( v \) \quad Voltage
\( v_{dc} \) \quad DC-link voltage
\( V \) \quad Voltage complex vector
\( i \) \quad Current
\( \omega \) \quad Electrical speed in radians per second
\( \theta \) \quad Electrical position in radians
\( R \) \quad Resistance
\( L \) \quad Inductance
\( L_{m1} \) \quad Induction machine magnetization inductance
\( L_{m2} \) \quad Exciter magnetization inductance
\( T_e \) \quad Electromagnetic torque of the RPE-BDFIG
\( T_{exciter} \) \quad Electromagnetic torque of the exciter
\( T_{turbine} \) \quad Torque provided by the turbine
\( p_{p1} \) \quad Pole-pairs of the induction machine
\( p_{p2} \) \quad Pole-pairs of the exciter
\( J_1 \) \quad Inertia of the induction machine
\( J_2 \) \quad Inertia of the exciter
\( b_1 \) \quad Friction coefficient of the induction machine
\( b_2 \) \quad Friction coefficient of the exciter
\( C_{dc}, C \) \quad Capacitance of the rotating capacitor
\( s \) \quad Laplace operator
\( \alpha \) \quad Bandwidth of the controller
Appendix A. Glossary of Symbols and Abbreviations

$\alpha_c$  Bandwidth of the current controller
$\alpha_s$  Bandwidth of the speed controller
$\alpha_v$  Bandwidth of the voltage controller

**Subscripts**

1  Stator of the induction machine or RPE-BDFIG, grid
2  Rotor of the induction machine
3  Rotor of the exciter
4  DC excitation winding (second stator) of the exciter
d  d-axis
q  q-axis
D  Damper winding in the d-axis
Q  Damper winding in the q-axis
r  Rotor
p  Positive
n  Negative
ps  phase shift
N  Number of winding turns

**Abbreviations**

BDFIG  Brushless Doubly-Fed Induction Generator
DFIG  Doubly-Fed Induction Generator
EVC  Extended Vector Control
ERSC  Exciter Rotor Side Converter
IMRSC  Induction Machine Rotor Side Converter
LVRT  Low Voltage Ride Through
PLL  Phase-Locked Loop
PWM  Pulse Width Modulation
PIR  Proportional Integral Resonance
PR  Proportional Resonance
PRN  Passive Resistive Network
RPE-BDFIG  Rotating Power Electronic Brushless Doubly-Fed Induction Generator