IMPROVED VECTOR CONTROL METHODS FOR BRUSHLESS DOUBLE FED INDUCTION GENERATOR DURING INDUCTIVE LOAD AND FAULT CONDITIONS

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ABSTRACT

A Brushless Double-Fed Induction Generator (BDFIG) has shown tremendous success in wind turbines due to its robust brushless design, less maintenance, smooth operation, and variable speed characteristics. These generators are composed of two back-to-back voltage source converters, a Grid Side Converter (GSC) and a Rotor Side Converter (RSC). Existing control techniques use a “trial and error” method that results in a poor dynamic response in machine parameters during the absence of load. The RSC control is used for reactive current control during the inductive load insertion. However, it is more suitable for stabilizing steady-state behaviour, but it suffers from slow response and introduces a double fundamental frequency component to the Point of Common Coupling (PCC) voltage. In addition, generally, a Low Voltage Ride Through (LVRT) fault is detected using a hysteresis comparison of the power winding voltage. The LVRT capability is provided by using fixed reference values to control the winding current. This approach results in an erroneous response, sub-optimal control of voltage drops at PCC, and false alarms during transient conditions. This thesis aims to solve the mentioned issues by using an improved vector control method. Internal Model Control (IMC) based Proportional-Integral (PI) gains calculation is used for GSC and RSC. These are controlled to enhance the transient response and power quality during no-load, inductive load, and fault conditions. Firstly, a GSC-based vector control method is proposed to suppress the PCC voltage fluctuations when a large inductive load is suddenly connected. The proposed technique is based on an analytical model of the transient behaviour of the voltage drop at the PCC. To block a double fundamental frequency component as a result of reactive current compensation, a notch filter is designed. Secondly, an RSC-based vector control method is proposed using an analytical model of the voltage drop caused by a short circuit. Moreover, using a fuzzy logic controller, the proposed technique employs the voltage frequency in addition to the power winding voltage magnitude to detect LVRT conditions. The analytical model helps in reducing the power winding voltage drop while the fuzzy logic controller leads to better response and faster detection of faults. However, the reference value for reactive current compensation is analysed using an analytical model of the voltage drop at the PCC in the event of a short-circuit fault. The results obtained from MATLAB/Simulink show that the GSC-based vector control method technique can effectively reduce about 10% voltage drop at PCCs. Total Harmonics Distortion (THD) is improved to 22.3% by notch filter in comparison with an existing technique such as instantaneous reactive power theory. The RSC-based vector control method can achieve up to 11% voltage drop reduction and improve the THD by 12% compared to recent synchronous control and flux tracking methods.

ABSTRAK

Penjana aruhan suapan-berganda tanpa berus (BDFIG) telah menunjukkan kejayaan yang luar biasa dalam turbin angin kerana reka bentuk tanpa berus yang teguh, kurang penyelenggaraan, operasi lancar dan ciri kelajuan berubah-ubah. Penjana ini terdiri daripada dua penukar sumber voltan belakang ke belakang, penukar sisi grid (GSC) dan penukar sisi rotor (RSC). Teknik kawalan sedia ada menggunakan kaedah "cuba dan ralat" yang menghasilkan gerak balas dinamik parameter mesin yang lemah semasa ketiadaan beban. Kawalan RSC digunakan untuk mengawal arus reaktif semasa kemasukan beban induktif. Walau bagaimana pun ia adalah lebih sesuai untuk penstabilan gerak balas keadaan mantap tetapi mempunyai gerak balas yang perlahan dan memperkenalkan komponen frekuensi asas berganda kepada voltan titik gandingan sepunya (PCC). Di samping itu, secara amnya, kerosakan pacu terus voltan rendah (LVRT) dikesan menggunakan perbandingan histerisis voltan belitan kuasa. Keupayaan LVRT disediakan dengan menggunakan nilai rujukan tetap untuk mengawal arus belitan. Pendekatan ini menghasilkan ralat gerak balas, kawalan suboptimal bagi susut voltan di PCC, dan penggeraan palsu semasa keadaan fana. Tesis ini bertujuan untuk menyelesaikan isu yang dinyatakan dengan menggunakan kaedah kawalan vektor diperbaiki. Pengiraan kawalan model dalaman (IMC) berasaskan kadar-kamir (PI) digunakan untuk GSC dan RSC. Pengawalan ini adalah bagi meningkatkan gerak balas fana dan kualiti kuasa semasa tanpa beban, berbeban induktif, dan keadaan kerosakan. Pertama, kaedah kawalan vektor berasaskan GSC dicadangkan untuk menyekat turun-naik voltan PCC apabila beban induktif yang besar tiba-tiba disambungkan. Teknik yang dicadangkan adalah berdasarkan model keanalisaan kelakuan fana susut voltan di PCC. Untuk menyekat komponen frekuensi dasar berganda hasil daripada pampasan arus reaktif, penapis takuk telah direka bentuk. Kedua, kaedah kawalan vektor berasaskan RSC dicadangkan menggunakan model keanalisaan turunan voltan yang disebabkan oleh litar pintas. Tambahan pula, dengan menggunakan pengawal logik kabur, teknik yang dicadangkan mengguna frekuensi voltan sebagai tambahan kepada magnitud voltan belitan kuasa bagi mengesan keadaan LVRT. Model keanalisaan membantu dalam mengurangkan susut voltan belitan kuasa manakala pengawal logik kabur membawa kepada gerak balas yang lebih baik dan pengesanan kerosakan yang lebih cepat. Walau bagaimanapun, nilai rujukan untuk arus pampasan reaktif dianalisis menggunakan model keanalisaan susut voltan di PCC ketika berlaku kerosakan litar pintas. Keputusan Simulasi MATLAB/Simulink menunjukkan bahawa teknik kaedah kawalan vektor berasaskan GSC dapat mengurangkan susut voltan dengan ketara menghampiri 10% di PCC. Herotan harmonik total (THD) dapat diperbaiki sebanyak 22.3% dengan menggunakan penapis takuk dibandingkan dengan teknik sedia ada seperti teori kuasa reaktif seketika. Kaedah kawalan vektor berasaskan RSC boleh mencapai sehingga 11% pengurangan susut voltan dan meningkatkan THD sebanyak 12% berbanding dengan kaedah terkini kawalan segerak dan pengesanan fluks.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

APF	-	Active Power Filters
BDFI	-	Brushless Doubly-Fed Induction Generator
BDFIM	-	Brushless Doubly Fed Induction Machine
CCA		Coupled Circuit Analysis
CW	-	Control Windings
DFIG	-	Doubly Fed Induction Generator
DC	-	Direct Current
DVR	-	Dynamic Voltage Restorer
DPC		Direct Power controller
DTC	-	Direct Torque Control
EESG	-	Electrically Excited Synchronous Generator
FL	-	Fuzzy Logic
FLC	-	Fuzzy Logic Controller
GB	-	Gearbox
GSC	-	Grid Side Converter
IEA	-	International Energy Agency
IMC	-	Internal Model Control
IRP	-	Instantaneous Reactive Power
ISC	-	Indirect Stator Quantities Control
LCL	-	Inductance-Capacitance-Inductance
LVRT	-	Low Voltage Ride through
NF	-	Notch Filter
OWF	-	Offshore Wind Farms
PCC	-	Point of Common Coupling
PE		Power Electronics
PI	-	Proportional Integral
PLL	-	Phase-Locked Loop
PMSG	-	Permanent Magnet Synchronous Generator
PW	-	Power Windings
RSC	-	Rotor Side Converter

RW - Rotor Winding

SCIG - Squirrel Cage Induction Generator

SG - Synchronous Generator

SMES - Super Conducting Magnetic Energy Storage

THD - Total Harmonic Distortion

VC - Vector Control

WECS - Wind Energy Conversion System

WPGS - Wind Power Generation System

WRIG - Wound Rotor Induction Generator

WRIM Wound Rotor Induction Machine

WTG - Wind Turbine Generator

LIST OF SYMBOLS

P_m	Mechanical Power
Vw	Wind Velocity
r	Rotor Radius
ρ	Air Density
Cp	Wind Energy Utilization Ratio
^	Tip Speed Ratio
Twt	Aerodynamic Torque
f_{PW}	PW Frequency
P_p, P_c, P_r	PW, CW, Rotor Pole-Pairs
$\omega_p, \omega_c, \omega_r$	PW, CW, Rotor Excitation Angular Frequencies
ω_n	Natural Frequency
u_{pa}, u_{pb}, u_{pc}	Three Phase Stator PW Voltage
u_{ca}, u_{cb}, u_{cc}	Three Phase Stator CW Voltage
u_{ra}, u_{rb}, u_{rc}	Three Phase Stator Rotor Voltage
u_a, u_b, u_c	Three Phase Stator PW Voltage at PCC
T_e	Rotor Torque
u_{dc}	DC-Link Voltage
v_{ra}, v_{rb}, v_{rc}	Three Phase RSC Voltage
v_{ga}, v_{gb}, v_{gc}	Three Phase GSC Voltage
i_{pa}, i_{pb}, i_{pc}	Three Phase Stator PW Current
i_{ca}, i_{cb}, i_{cc}	Three Phase Stator CW Current
i_{La}, i_{Lb}, i_{Lc}	Three Phase Load Current
i_{Ta}, i_{Tb}, i_{Tc}	Three Phase Grid Current
C_{dc}	DC-Link Capacitor
C_g	Capacitor Bank
L_s, L_L	Filter, Load Inductance
R_s, R_L	Internal, Load Resistance
R_p, R_c, R_r	Stator PW, CW, and RW Resistance
L_p, L_c, L_r	Stator PW, CW, and RW leakage inductance

L_{rp}, L_{rc}	Magnetizing Inductance of Rotor to PW and CW.
λ_p, λ_c	PW and CW flux
K_p^{PW} , K_i^{PW}	Gain Values for PW
K_p^{CW}, K_i^{CW}	Gain Values for CW
B_p, B_c	Frequency Bandwidth for PW and CW
B_{dc}	DC-Link Voltage Bandwidth
L_g	GSC Choke Inductance
R_g	GSC Choke Resistance
$H(z)$	Transfer Function
f_0	Centre Frequency
f_s	Sampling Rate

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

The increasing environmental pollution due to the emission of greenhouse gases from traditional power houses poses a massive threat to life on earth by causing global warming and other serious health issues. Furthermore, usage of electrical energy has exponentially increased during the last few decades due to the rapidly growing population. Due to this, a vast part of the population of the world lives without access to electricity. The report of the International Energy Agency (IEA) highlights the fact that 1.3 billion people still do not have access to electricity. This lack of energy access is largely due to the fact that many inhabitants of developing countries live in rural areas far from the primary utility grids [1]. Also, there seems to be a trend of fuel assets becoming rare in recent days, and therefore, the price of these assets is rapidly increasing due to their limited supply. Another significant issue is the increasing burden on the existing power system due to the continuously growing load, which causes the overloading of electric power generators, transmission lines, and distribution transformers [2].

To minimize the effects of the issues mentioned, deploying renewable energy sources into the existing power system has become essential to relieve the system from overloading and produce cheaper electricity with reduced carbon footprints and enhanced power quality. Amongst various renewable energy resources, wind energy is a viable source and becoming popular because of its environmentally friendly features and lowered costs. For these reasons, wind energy is the leading renewable energy source employed for power generation in Europe, with a share of 15.6% of total power capacity [3]. Denmark relies on renewable energy and has shifted its 43.4% load to wind energy which is expected to increase up to 50% by 2030 and has planned for zero fossil fuel energy by 2050 [4]. China is contributing towards renewable energy with the onshore market of 21200 MW in 2018 and the offshore market of 1800 MW in 2018. Interestingly, the worldwide wind power installations reached a total outlay of 51.3 GW in 2018 [5]. Hence, the world is witnessing faster development in the Wind Power Generation System (WPGS). A wind turbine control objectives are shown in Figure 1.1.

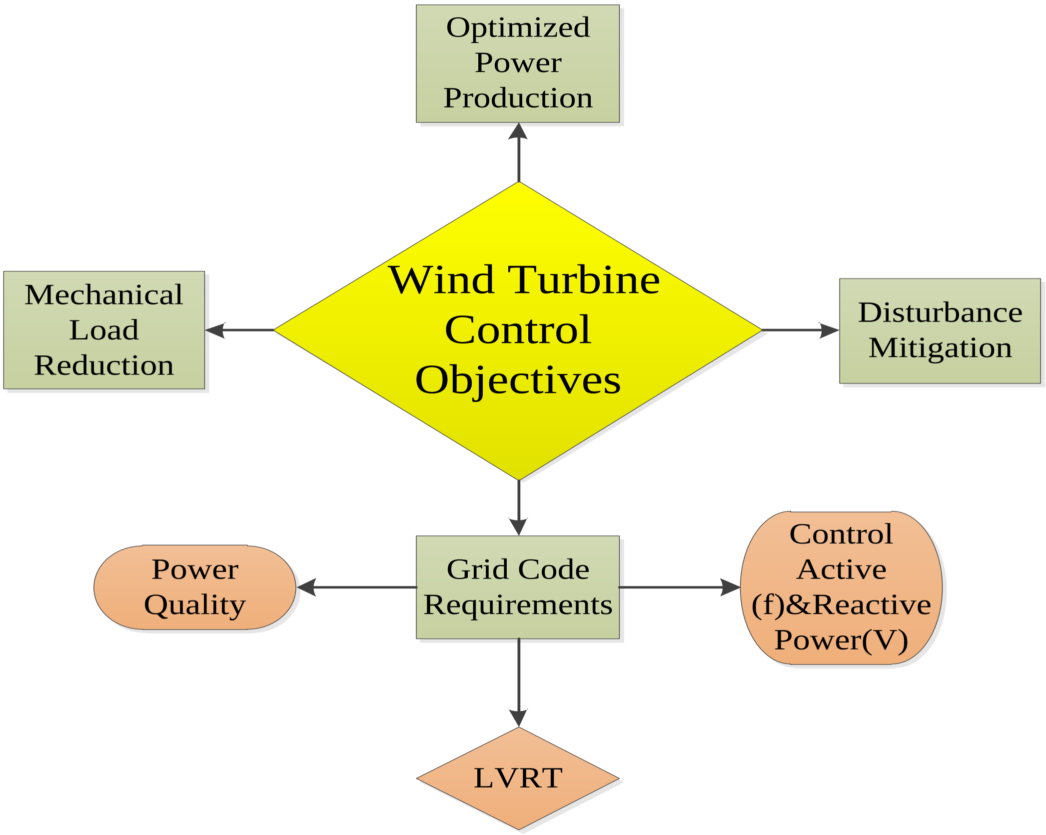

Figure 1.1 Wind turbine control

However, to utilize wind energy, one needs to install induction generators on the wind turbines, which makes interfacing wind turbines to the power grid more challenging, i.e., regulating and conditioning the power, voltage, and frequency with high efficiency and flexibility [6]. The power rating of generators utilized in wind turbine units has increased, ranging from a few kilowatts to 6-8 MW. However, there are power losses of several MWs in this generation process [7]. The high penetration of wind energy has introduced both opportunities and challenges for the smooth supply of energy which has eventually lead to the preparation of grid codes, advanced generator design, sophisticated power electronic topologies, and control strategies for smooth integration with the power grid [8]. It is, therefore, the concern of wind power generators to ensure the compliance of grid codes provided by the power utility. According to the grid codes, machines utilized in wind turbines should provide smooth power to the grid with enhanced dynamic response during its operation, such as no-load, inductive load, and fault conditions [2]. Low Voltage Ride Through (LVRT) is one of the most challenging requirements for wind generator units. LVRT keeps the wind turbine connected with the power grid without interruption for a specified period and supply reactive power during faults at the Point of Common Coupling (PCC).

Amongst wind generators, the Double Fed Induction Generator (DFIG is one of the popular machines installed across the globe. Its favorable characteristics include; variable speed operation, partial scale conversion and filtration, low maintenance, and high-power output. However, DFIG is very sensitive to grid faults and cannot meet the grid code requirements during fault conditions [9]. Furthermore, DFIG has poor LVRT and requires brushes and slip rings, making DFIG non-suitable for offshore WPGS. Various studies have explored and worked on the improved designs of DFIG both for the onshore and offshore wind farms. Different hardware and software-based control methods of DFIG under transient conditions have been reviewed. These studies concluded that DFIG could be controlled using tuned controllers; however, the addition of hardware for higher voltage dips is unavoidable [10]. These studies suggest an active crowbar for DFIG during voltage dips and have developed various control algorithms [11]. As DFIG has the addition of brushes and slip rings and suffers from high sensitivity to grid disturbances, brushless DFIG is an excellent alternative to the traditional DFIG because of its superb handling characteristics of LVRT. It has no carbon brushes and slips rings [12]. However Synchronous Generator uses the full rated power electronics converters that increases overall cost.

The Brushless Double Fed Induction Machine (BDFIM) development has its origins in the early twentieth century. During the 1980s, power electronics became a very common tool for controlling electric machines, and it became standard to use two cascaded slip ring induction motors for speed control of the machines. A unique rotor design was proposed by Hunt *et al.* [13] in 1907 with two machine windings in the stator. The machine achieved speed control through resistors connected to one of the stator windings, which avoided the need for slip rings, making it a more compact machine. Further development of the BDFIM design was made by Creedy *et al.* [14] in the early 1920s. In 1970, Broadway *et al.* [15] proposed a caged rotor design that would further enhance the performance of the BDFIM. The BDFIMs are still using the same design of rotor available previously in the 1920s. In addition, they advanced an equivalent circuit for the machine, its steady-state performance is analyzed, and observed its operation in a synchronized manner. The operation of a brushless induction motor is investigated as to control the speed of a slip-power pump that operates on a single frame [16]. All stator designs, including those developed by Hunt *et al.* and Creedy *et al.*, used a single stator winding that produced two different fields of pole numbers. According to Rochelle *et al.*, an analysis of the alternative winding designs for a stator in 1990 concluded that electrically isolated windings were more beneficial than other alternatives [17]. Subsequently, a study industrialized a dynamic model of the machine by Wallace *et al.* [18]. Simulation models were employed to investigate the phenomenon of machine control during the mid of 1980s [19]. Developing a two-axis model suitable for the study of dynamic systems is a contribution by Li *et al.* [20], and simulations of dynamic processes were presented [21].

The Brushless Doubly Fed Machine was modeled further at Cambridge University in the decades following its invention. In the later stage of the study, Williamson *et al.* developed a mathematical model that incorporated features of a machine operating in the synchronous mode [22]. A field-oriented control algorithm for the machine has been presented by Zhao *et al.* [23], which followed with a simplified version [24] of the field-oriented algorithm. In spite of this, these algorithms were heavily dependent on parameters related to the machine. Vector Control (VC) algorithms based on the Power Winding (PW) flux were introduced by Poza *et al.* in 2002 [25].

After extensive research on the design and control of Brushless Doubly Fed Induction Generator (BDFIG), the machine became an excellent choice to replace other machines in wind turbines. Like DFIG, BDFIG LVRT situations can be divided into hardware solutions and software solutions. The BDFIG does not need hardware-based control schemes/methods because of having inherent large leakage inductance, which helps fault current to minimize at the event of a fault. Hence, control strategies for BDFIG have been developed and proved experimentally that LVRT is possible even without a crowbar [26]. Researchers are focusing on improving the BDFIG LVRT characteristics without adding additional hardware like crowbar solutions and have applied software solutions in their research work.

1.2 Problem Statement

Several control strategies such as scalar control method, super-twisting sliding mode DPC, indirect torque control method, indirect stator-quantities control have been utilized in literature to accomplish the control objectives. The mentioned control strategies could not suppress the heavy transients and long oscillations in active power, reactive power, and speed during the starting and abrupt load changes. Besides, these control methods lack the independent control of machine parameters due to the unavailability of quadrature and the DC component within their structures. Another critical control strategy that has been extensively explored in literature for WECS is the Vector control (VC) method [11]. VC models are practical tools for independently regulating the speed and reactive power of a Brushless doubly-fed induction generator (BDFIG). VC methods can provide satisfactory outcomes if their Proportional Integral (PI) regulators are optimally selected. However, they utilize the conventional PI tuning approaches such as “trial and error” results in time constraints and complexity. Finally, it leads to the poor dynamic response of the machine during the parameter’s variations.

The standard BDFIG control approach has been demonstrated that the voltage level is at the verge of common coupling is prone to fluctuate when the inductive load variation is significant. Such variations affect other loads such as motors, transformers, and chokes connected to the PCC and introduce torque pulsations. Existing techniques use the RSC for reactive current control, with a prolonged response and lower bandwidth control due to sudden inductive load introduction. The existing methods on reactive current control through GSC are based on voltage-oriented control in the synchronous reference frame that compute constant *d*-axis and *q*-axis reference values. However, such traditional control approaches are designed with steady-state performance as the focus [12]. Thus, when an inductive load is instantaneously connected to the PCC, the conventional control method does not remain satisfactory as the transient load current may fluctuate instead of being constant. A harmonic component at the double of fundamental frequency has been observed during reactive current compensation with GSC, which is harmful to smooth electric supply. Recent literature has proposed the instantaneous reactive power theory, which increases the complexity and results in sub-optimal performance.

Existing techniques on improving the LVRT capability of BDFIGs can be categorized as hardware-based or control-based. Hardware-based techniques such as crowbar have been shown to successfully protect the generator from surge currents during faults. The hardware-based approaches lead to losses, electromagnetic torque oscillations, and an increase in operation and maintenance costs in addition to the initial hardware cost. It leads the authors to concentrate on control methods, especially during fault conditions. LVRT fault is improved in previous literature by using fixed control winding current reference values for reactive current control. It causes high voltage drop and Total Harmonics Distortion (THD) at PCC. Furthermore, a fault is usually detected using a hysteresis comparison of the power winding voltage [26]. However, this approach leads to two problems, firstly, the use of only voltage to detect faults results in an erroneous or slow response, and secondly, it results in false alarms during transient conditions.

The present techniques utilized during the control of BDFIG have produced satisfactory results to make the machine an attractive choice for wind turbines. The machine shows an excellent characteristic while being operated under different operating conditions such as inductive load and short circuit conditions. However, there is need to improve machine behaviour under these operating conditions more as compared to present techniques being utilized in recent literature.

1.3 Research Objectives

The objectives of the research work are as follows;

i. To develop an improved Vector Control method for Brushless Double Fed Induction Generator bases wind turbine to enhance the dynamic response of machine during no-load operation with Internal Model Control method-based Proportional-Integral gains.

ii. To develop a Grid Side Converter-based Vector Control method with a notch filter by analytically calculating the reference value for reactive current to reduce the voltage drop and harmonics at Point of Common Coupling, respectively, during inductive load insertion.

iii. To develop Rotor Side Converter-based Vector Control method with fuzzy logic controller using the analytical model to improve machine behaviour during short circuit conditions and to reduce the latency of detecting the onset of a fault

iv. To evaluate and compare the performance of the proposed Grid Side Converter and Rotor Side Converter-based Vector Control method with that of the conventional compensation control strategies in order to validate its effectiveness and significance.

1.4 Scope

The major scopes and limitations of this research are as follows:

i. The study focuses on improving the vector control of BDFIG parameters, which can be enhanced with the addition of a sensorless control method because no encoders are involved.

ii. All the simulations are carried out in MATLAB/Simulink for BDFIG under no load, abrupt inductive load change, and fault conditions.

iii. The type of fault considered in the thesis is symmetrical faults only and can be extended.

iv. Although using a fuzzy logic controller improves the rotor side converter's response to a fault, the proposed technique is sensitive to the rules in the knowledge base. Therefore, the knowledge base needs to be designed carefully to avoid sub-optimal results.

v. Utilizing the optimization techniques in the VC methods for BDFIG operations beyond the scope of this research work.

1.5 Research Significance

The potential practical applications of this research are;

i. The dynamic response of the BDFIG parameters is improved with IMC based PI gains calculations in VC method.

ii. The developed GSC and RSC-based VC method with notch filter and fuzzy logic respectively enhance the power quality of BDFIG and easily makes the machine fulfil the grid code requirements.

iii. The other loads connected to the grid do not suffer any adverse effects, and the torque pulsations on BDFIG are minimized.

iv. As a result of the proposed VC method for GSC and RSC, the BDFIG could be considered an attractive option for onshore wind farms and remote offshore wind farms.

v. The control method in the thesis does not use any hardware approach for the BDFIG that leads to a low-cost and straightforward design. Therefore, it can benefit developing countries since they may not have the necessary infrastructure to implement more advanced technologies.

1.6 Thesis Organization

In CHAPTER 2, the related research work in the literature has been extensively studied, and a critical review has been done. This chapter portraits the different types of electrical machines used for wind turbines with their power electronics converters. In particular, this literature review focuses on control methods for improving the BDFIG behaviour on no-load, inductive load, and, most importantly, the LVRT improvement. It also focuses on reactive current compensation techniques for BDFIG based VC method. Finally, the recent development in the behaviour of BDFIG generator in wind turbine during its operation has been highlighted.

CHAPTER 3 presents the methodology of the proposed VC method -based BDFIG operation with the IMC method for PI gains. Both of the power electronics converters, i.e., RSC and GSC, are discussed, including the system's overall structure and architecture modelling with its mathematical foundation and the system configuration. Moreover, the methodology for the usage of Notch Filter (NF) and Fuzzy Logic (FL) design in BDFIG is also represented.

CHAPTER 4 is dedicated to the results and discussion of the proposed VC method -based BDFIG using simulations in MATLAB/Simulink. The machine is tested for improved dynamic behaviour under no load by using a PI calculation based on IMC at the initialization stage. The various performance aspects for the voltage/current waveforms, active/reactive power waveforms, stability, and the voltage drop at PCC and THD are discussed during the inductive load insertion and LVRT. Moreover, a comprehensive comparison with existing techniques in recent literature is also presented.

Finally, in CHAPTER 5, the conclusions for this thesis and highlights for the future recommendations are presented.

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