Improvement of Fault Ride Through Capability of Wind Turbines by Fault Current Limiters

by

Seyed Behzad Naderi, M.Sc.

submitted in fulfilment of the requirements for

the Degree of Doctor of Philosophy

School of Engineering

College of Science and Engineering

University of Tasmania

March 2018

Declaration of Originality

This thesis contains no material which has been accepted for a degree or diploma by the University or any other institution, except by way of background information and duly acknowledged in the thesis, and to the best of my knowledge and belief no material previously published or written by another person except where due acknowledgement is made in the text of the thesis, nor does the thesis contain any material that infringes copyright.

Seyed Behzad Naderi

Date: 20/03/2018

Authority of Access

This thesis is not to be made available for loan or copying for two years following the date this statement was signed. Following that time, the thesis may be made available for loan and limited copying and communication in accordance with the Copyright Act 1968.

Seyed Behzad Naderi

Date: 20/03/2018

Statement of Co-Authorship

The following people and institutions contributed to the publication of work undertaken as part of this thesis:

Candidate = **Seyed Behzad Naderi, School of Engineering, College of Science and Engineering, University of Tasmania**

Author 1, Supervisor = **Michael Negnevitsky, University of Tasmania**

Author 2 = **Frede Blaabjerg, Aalborg University, Denmark**

Author 3 = **Mehrdad Tarafdar Hagh, University of Tabriz, Iran**

Author 4 = **Amin Jalilian, University of Tabriz, Iran**

Author 5 = **Kashem M Muttaqi, University of Wollongong, Australia**

Author 6 = **Pooya Davari, Aalborg University, Denmark**

Author 7= **Dao Zhou, Aalborg University, Denmark**

Author 8= **Mehdi Jafari, Michigan Technological University, MI, USA**

Author 9 = **Amir Zandnia, Michigan Technological University, MI, USA**

Author 10 = **Ali Rostami, South Tehran Branch, Azad University, Tehran, Iran**

Author 11 = **Marzieh Bagheri, Sharif University of Technology, Tehran, Iran**

Author details and their roles:

Paper 1. "Optimum resistive type fault current limiter: An efficient solution to achieve maximum fault ride-through capability of fixed speed wind turbines during symmetrical and asymmetrical grid faults," ***IEEE Trans. Ind. Appl***.

Located in Chapter 2

Candidate was the primary author of the paper and contributed 80% in writing, simulation, analysing the proposed method and preparing the paper. The contribution of authors 1, 4, 3 and 5 was individually 5%.

Paper 2. "Efficient fault ride-through scheme for three phase voltage source inverter-interfaced distributed generation using DC link adjustable resistive type fault current limiter," ***Elsevier Renewable Energy***.

Located in Chapter 3

Candidate was the primary author of the paper and contributed approximately 55% in writing, simulation, analysing the proposed method and preparing the paper. The contribution of authors 1, 4 and 3 was individually 15%.

Paper 3. "Controllable DC-link bridge-type FCL for low voltage ride-through enhancement of converter interfaced DG systems," ***Elsevier International Journal of Electrical Power and Energy Systems***.

Located in Chapter 3

The contribution of author 4 as primary author was 50% and contribution of the candidate was 30% in preparing and writing the paper. The contribution of authors 1 and 3 was individually 10%.

Paper 4. "Controllable DC-link fault current limiter augmentation with DC chopper to improve fault ride-through of DFIG," ***IET Renewable Power Generation.***

Located in Chapter 4

The contribution of author 4 as primary author was 50% and contribution of the candidate was 30% in preparing, analysing the proposed method and writing the paper. The contribution of author 1 was 10% and authors 3 and 5 was individually 5%.

Paper 5. “Low voltage ride-through enhancement of DFIG-based wind turbine using DC link switchable resistive type fault current limiter,” ***Elsevier International Journal of Electrical Power and Energy Systems***.

Located in Chapter 4

Candidate was the primary author of the paper and contributed 50% in writing, simulation, analysing the proposed method and preparing the paper. The contribution of authors 1 and 4 was individually 20% and authors 3 and 5 was individually 5%.

Paper 6. “A review on fault current limiting devices to enhance fault ride-through capability of doubly fed induction generator-based wind turbine,” Submitted to ***Electric Power Components and Systems,*** Under Review.

Located in Chapter 4

Candidate was the primary author of the paper and contributed approximately 60% in writing, literature review and preparing the paper. The contribution of authors 6, 7, 1 and 2 was individually 10%.

Paper 7. “A Modified DC Chopper for Limiting the Fault Current and Controlling the DC Link Voltage to Enhance Fault Ride-Through Capability of Doubly-Fed Induction Generator Based Wind Turbine,” Submitted to ***IEEE Trans. Ind. Appl.,*** Under Review.

Located in Chapter 4

Candidate was the primary author of the paper and contributed 80% in writing, simulation, analysing the proposed method and preparing the paper. The contribution of authors 1 and 5 was individually 10%.

Paper 8. “Optimum resistive type fault current limiter: an efficient solution to achieve maximum fault ride-through capability of fixed speed wind turbines during symmetrical and asymmetrical grid faults,” in *Proc.* ***the 50th IEEE IAS Annual Meeting***, Addison (Dallas area), Texas, USA.

Located in Chapter 2

Candidate was the primary author of the paper and contributed 80% in writing, simulation, analysing the proposed method and preparing the paper. The contribution of authors 1, 4, 3 and 5 was individually 5%.

Paper 9. “Fault ride through improvement of fixed speed wind turbine using CR-FCL with its modified control strategy,” in *Proc.* ***Australasian Universities Power Engineering Conference (AUPEC)***, QLD, Australia.

Located in Chapter 2

Candidate was the primary author of the paper and contributed 70% in writing, simulation, analysing the proposed method and preparing the paper. The contribution of authors 1, 4 and 3 was individually 10%

Paper 10. “Improving fault ride-through of three-phase voltage source inverter during symmetrical fault using DC link fault current limiter,” in *Proc*. ***Australasian Universities Power Engineering Conference (AUPEC)***, NSW, Australia.

Located in Chapter 3

The contribution of author 3 as primary author was 50% and the contribution of the candidate and author 4 was individually 20% in preparing, analysing the proposed method and writing the paper. The contribution of authors 1 and 5 was individually 5%.

Paper 11. “Voltage sag compensation of point of common coupling for low voltage ride-through enhancement of inverter interfaced DG using bridge type FCL,” in *Proc*. ***Australasian Universities Power Engineering Conference (AUPEC)***, NSW, Australia.

Located in Chapter 3

Candidate was the primary author of the paper and contributed 60% in writing, simulation, analysing the proposed method and preparing the paper. The contribution of authors 1, 4, 3 and 5 was individually 10%.

Paper 12. “Non-controlled fault current limiter to improve fault ride through capability of DFIG-based wind turbine,” in *Proc*. ***IEEE Power and Energy Society General Meeting***, Boston, MA, USA.

Located in Chapter 4

Candidate was the primary author of the paper and contributed approximately 70% in writing, simulation, analysing the proposed method and preparing the paper. The contribution of authors 1, 4 and 3 was individually 10%

Paper 13. "A modified DC chopper for limiting the fault current and controlling the DC link voltage to enhance ride-through capability of doubly fed induction generator-based wind turbine," in *Proc*. ***the 52th IEEE IAS Annual Meeting***, OH, USA.

Located in Chapter 4

Candidate was the primary author of the paper and contributed 80% in writing, simulation, analysing the proposed method and preparing the paper. The contribution of authors 1 and 5 was individually 10%.

Paper 14. "Study on application of new approach of fault current limiters in fault ride through capability improvement of DFIG-based wind turbine," Accepted for publication in ***IEEE Power and Energy Society General Meeting***, Portland, OR, USA.

Located in Chapter 4

Candidate was the primary author of the paper and contributed 70% in writing, simulation and preparing the paper. The contribution of authors 6 and 7 was individually 10% and authors 1 and 2 was individually 5%.

Paper 15. "A Novel Passive Islanding Detection Scheme for Distributed Generations Based on Rate of Change of Positive Sequence Component of Voltage and Current," in *Proc*. ***Australasian Universities Power Engineering Conference (AUPEC)***, Melbourne, Australia.

The contribution of author 10 as primary author was 50% in preparing and writing the paper and the contribution of candidate and authors 4, 1, 6 and 2 was individually 10%.

Paper 16. "A Novel Islanding Detection Scheme for Synchronous Distributed Generation Using Rate of Change of Exciter Voltage over Reactive Power at DG-Side," in *Proc*. ***Australasian Universities Power Engineering Conference (AUPEC),*** Melbourne, Australia.

The contribution of author 10 as primary author was 50% in preparing and writing the paper and the contribution of candidate and authors 11, 1, 4 and 2 was individually 10%.

Paper 17. "Investigation on Capacitor Switching Transient Limiter with a Three Phase Variable Resistance", in *Proc*. Australasian Universities Power Engineering Conference (AUPEC), Melbourne, Australia.

Candidate was the primary author of the paper and contributed 50% in writing, simulation and preparing the paper. The contribution of authors 8 and 9 was individually 15%, and the contribution of authors 4, 6, 1 and 2 was individually 5%.

Paper 18. "Soft and fast starting induction motors using controllable resistive type fault current limiter," in *Proc*. ***IEEE Power and Energy Society General Meeting***, Denver.

Candidate was the primary author and contributed 80% of writing, preparing and analysing the proposed method. Author 1, supervisor, contributed 20% of the preparation of the paper.

We the undersigned agree with the above stated "proportion of work undertaken" for each of the above published (or submitted) peer-reviewed manuscripts contributing to this thesis:

Signed: ______________________ ______________________

Michael Negnevitsky
Supervisor, School of Engineering
College of Science and Engineering
University of Tasmania

Andrew Chan
Head of School
School of Engineering
College of Science and Engineering
University of Tasmania

Date: 20.03.2018 21/3/2018

Acknowledgement

Firstly, I would like to express my sincere gratitude to my supervisor Prof Michael Negnevitsky for the continuous support of my Ph.D. study and related research, for his patience, motivation, and immense knowledge. His guidance helped me in all the time of research. I could not have imagined having a better supervisor and mentor for my Ph.D. study.

Besides my supervisor, I would like to thank Prof Mehrdad Tarafdar Hagh from University of Tabriz and Prof Kashem Muttaqi from University of Wollongong for their insightful comments and encouragement during my Ph.D., but also for the hard questions which incented me to widen my research from various perspectives.

My sincere thanks also goes to Prof Frede Blaabjerg and Associate Prof Pooya Davari from Aalborg University, Denmark, who provided me an opportunity to join their team as a visiting Ph.D. student, and who gave access to the laboratory and research facilities. Without they precious support it would not be possible to conduct this research.

I thank James Lamont, Technical officer in helping me for the preparing experimental set-up, and for his friendship during my first year of Ph.D.

Last but not the least, I would like to thank my family: my parents, my partner and my sister for supporting me spiritually throughout writing this thesis and my life in general. They are the most important people in my world and I dedicate this thesis to them.

List of Contents

Declaration of Originality iii

Authority of Access iv

Statement of Co-Authorship v

Acknowledgement xi

List of Contents xii

List of Figures xv

List of Tables xxii

List of Abbreviations and Acronyms xxiii

Preface 1

Abstract *1*

Thesis Outline *3*

Supporting Publications *3*

Chapter 1: Introduction 1

1.1 Wind Power *1*

1.2 Different Types of Wind Energy Conversion Systems *2*

1.2.1 Fixed speed wind turbine 3

1.2.2 Variable speed wind turbine 3

1.3 Fault Ride Through Requirements *5*

1.4 Project Objectives *7*

Chapter 2: Fault Ride Through Capability of Fixed Speed Wind Turbines 9

2.1 Introduction *9*

2.2 Operation and Modelling of Fixed Speed Wind Turbine *11*

2.3 The Optimum Resistive Type Fault Current Limiter (OR-FCL) Approach *12*

2.3.1 Utilising the proposed OR-FCL to obtain maximum FRT of the FSWT . 17

2.3.2 Design considerations of the OR-FCL 20

2.3.3 Simulation results and discussions on the operation of the OR-FCL 22

2.4 Controllable Resistive Type Fault Current Limiter Approach *32*

2.4.1 Maximum FRT of the FSWT with the CR-FCL 35

2.4.2 Technical consideration of the CR-FCL 36

2.4.3 Simulation results and discussions on the operation the CR-FCL 37

2.5 Conclusion *44*

Chapter 3: Fault Ride Through Scheme for Three Phase Voltage Source Inverter-Interfaced Distributed Generation 45

3.1 Introduction *45*

3.2 Bridge Type Fault Current Limiter (B-FCL) Approach *48*

3.2.1 Power loss calculation in the B-FCL 50

3.2.2 Simulation results with the B-FCL: including the symmetrical and asymmetrical faults 50

3.3 DC Link Resistive Type Fault Current Limiter (DC-RFCL) Approach *60*

3.3.1 Principle of operation of the DC-RFCL 61

3.3.2 Analytical analysis of the proposed scheme 63

3.3.3 Power losses calculation of the DC-RFCL 67

3.3.4 Design considerations of the DC-RFCL 68

3.3.5 Simulation results and discussion on the operation of the DC-RFCL 72

3.4 Conclusion *78*

Chapter 4: Fault Ride Through Capability of Doubly Fed Induction Generator-Based Wind Turbine 80

4.1 Introduction *80*

4.2 Operation and Modelling of Doubly Fed Induction Generator-Based Wind Turbine *84*

4.3 Modified DC Chopper Approach *86*

4.3.1 The operation of the DFIG-based wind turbine with the modified DC chopper in normal condition 87

4.3.2 The operation of the DFIG-based wind turbine with the modified DC chopper during the fault condition.. 88

4.3.3 Technique for determination of the value of $R_{chopper}$ in the modified DC chopper.. 91

4.3.4 Simulation results and discussions on the operation of the modified DC chopper.. 93

4.4 Non-Controlled Fault Current Limiter Approach.. 97

4.4.1 Simulation results and discussions on the operation of the non-controlled FCL 99

4.5 DC Link Resistive Type Fault Current Limiter Approach 103

4.5.1 Advantages of the DC link DC-RFCL as the proposed FRT scheme and its comparison with other FCLs.. 107

4.5.2 Analytical technique for analysis of the proposed FRT scheme............. 110

4.5.3 Power loss calculation of the proposed DC-RFCL 118

4.5.4 Design considerations of the DC-RFCL in the DFIG-based wind turbine 119

4.5.5 Simulation results and discussions on the operation of DC-RFCL in the DFIG-based wind turbine 120

4.5.6 Experimental results of the operation of the DC-RFCL 129

4.6 Conclusion 136

Chapter 5: Conclusion and Future Works 138

5.1 Thesis Summary 138

5.2 Future Studies 142

References 143

List of Figures

Fig. 1.1 Fixed Speed Wind Turbine (FSWT) 3

Fig. 1.2 Variable speed wind turbine with fully rated back-to-back converters 4

Fig. 1.3 Doubly Fed Induction Generator (DFIG)-based wind turbine as variable speed wind turbine with partially scaled back-to-back converters 5

Fig. 1.4 The grid code requirement for the FRT of wind turbine in different countries [6, 23] 6

Fig. 1.5 Limits curve for the FRT requirement of the “E.ON” grid code 7

Fig. 2.1 Single phase equivalent circuit of the double squirrel cage induction generator 12

Fig. 2.2 Single line diagram of the investigated system 13

Fig. 2.3 Single phase power circuit topology of the proposed OR-FCL 13

Fig. 2.4 Steady state currents and the self-turnoff switching pulse during the fault condition 15

Fig. 2.5 The fault current level limited by the proposed OR-FCL for both the exact equation, (2.9), and the simplified one (2.10) 17

Fig. 2.6 Optimum resistance variation, $Rac,opt.$, with respect to PG and k 21

Fig. 2.7 Dedicated control circuit of the proposed OR-FCL 22

Fig. 2.8 The generated impedance of the proposed OR-FCL for the wind speed of 13 m/s during the LG fault 25

Fig. 2.9 The rotor speed for the wind speed of 13 m/s during the LG fault 25

Fig. 2.10 The fault phase current, A phase, for the wind speed of 13 m/s during the LG fault 25

Fig. 2.11 The PCC voltage, A phase, for the wind speed of 13 m/s during the LG fault26

Fig. 2.12 The output active power of the FSWT for the wind speed of 13 m/s during the LG fault 26

Fig. 2.13 The generated impedance of the proposed OR-FCL for the wind speed of 13 m/s during repetitive transient LG faults 27

Fig. 2.14 The rotor speed for the wind speed of 13m/s during repetitive transient LG faults 27

Fig. 2.15 The fault phase current, A phase, for the wind speed of 13m/s during repetitive transient LG faults 27

Fig. 2.16 The output active power of the FSWT for the wind speed of 13m/s during repetitive transient LG faults 28
Fig. 2.17 The generated impedance of the proposed OR-FCL for the wind speed of 10m/s during the LG fault 29
Fig. 2.18 The rotor speed for the wind speed of 10m/s during the LG fault 29
Fig. 2.19 The fault phase current, A phase, for the wind speed of 10m/s during the LG fault 29
Fig. 2.20 The output active power of the FSWT for the wind speed of 10 m/s during the LG fault 30
Fig. 2.21 The rotor speed for the wind speed of 13 m/s during the LLG fault 31
Fig. 2.22 The rotor speed for the wind speed of 10 m/s during the LLG fault 31
Fig. 2.23 The rotor speed for the wind speed of 13 m/s during the LLLG fault 32
Fig. 2.24 The rotor speed for the wind speed of 10 m/s during the LLLG fault 32
Fig. 2.25 The three-phase power circuit topology of the proposed CR-FCL 34
Fig. 2.26 The line current and the DC side current trends before and after the fault 34
Fig. 2.27 Optimum resistance variation respect to Pg 37
Fig. 2.28 Single line diagram of the investigated system 38
Fig. 2.29 The induction generator current without using the proposed CR-FCL 40
Fig. 2.30 The rotor speed without using the proposed CR-FCL 40
Fig. 2.31 The transferred and generated active powers during the fault without using the proposed CR-FCL 40
Fig. 2.32 Inserting the optimum resistance value by the CR-FCL for case study 1 (a) the induction generator current, (b) the fault line current (line 1) with the DC current of the CR-FCL, (c) the healthy line current (line 2) 41
Fig. 2.33 The rotor speed using the optimum resistance value for case study 1 42
Fig. 2.34 The consumed active power by the CR-FCL and the transferred and generated active powers for case study 1 42
Fig. 2.35 The produced optimum resistance value by the CR-FCL and the self-turnoff switching pattern with D=51% 42
Fig. 2.36 The rotor speed for two values of the duty cycle 43
Fig. 2.37 The electrical torque of the induction generator with respect to the rotor speed for two values of the duty cycle by the CR-FCL 43
Fig. 3.1 The proposed B-FCL topology 49
Fig. 3.2 Control circuit of the proposed B-FCL 49

Fig. 3.3 The simulated power system including the proposed B-FCL 51
Fig. 3.4 The AC output currents of the inverter during LLLG fault.............................. 52
Fig. 3.5 The DC side current of the inverter during LLLG fault................................... 52
Fig. 3.6 The PCC voltage during LLLG fault... 52
Fig. 3.7 A phase line current including the B-FCL's DC current and shunt resistance current during the LLLG fault... 53
Fig. 3.8 The DC current of the inverter with the B-FCL operation................................ 53
Fig. 3.9 During LLLG fault with the B-FCL operation (a) the PCC voltage (b) the voltage drop on the B-FCL 54
Fig. 3.10 The AC output current of the inverter during LG fault.................................. 55
Fig. 3.11 The PCC voltage during the LG fault.. 55
Fig. 3.12 The AC output currents of the inverter including the B-FCL's DC current and shunt resistance current during LG fault (a) in A phase, (b) in B phase, (c) in C phase 56
Fig. 3.13 During LG fault with the B-FCL operation (a) the PCC voltage (b) the voltage drop on the B-FCL 57
Fig. 3.14 The AC output currents of the inverter during LLG fault.............................. 58
Fig. 3.15 The PCC voltage during LLG fault 58
Fig. 3.16 The AC output currents of the inverter including the B-FCL's DC current and shunt resistance current during the LLG fault (a) in A phase, (b) in B phase, (c) in C phase... 59
Fig. 3.17 During the LLG fault with the B-FCL operation (a) the PCC voltage (b) the voltage drop on the B-FCL.. 60
Fig. 3.18 Power circuit topology of the proposed fault ride-through configuration for the VSI 62
Fig. 3.19 Control circuit of the proposed DC-RFCL.. 62
Fig. 3.20 SPWM output sequence from the VSI and the measured DC link (i_{dc}) and the DC inductor (i_d) currents during the fault condition 66
Fig. 3.21 Equivalent circuits of operating intervals during the fault condition. (a) switching state:000 (b) switching state:100 (c)-(f) switching state:101 (g) switching state:111 (h)-(i) the DC inductor and the DC link current after the fault, (i) enlarged figure of (h) 70
Fig. 3.22 The simulated power system 73

Fig. 3.23 Simulation results for the LLLG fault at point F1 without the proposed DC-RFCL, (a) three-phase voltages at point F1, (b) three-phase output currents of the VSI, (c) A phase switch current of the inverter, (d) the DC link current 75
Fig. 3.24 Simulation results for the LLLG fault at point F1 when the proposed DC-RFCL is employed, (a) the DC inductor current, (b) three-phase output currents of the VSI, (c) A phase switch current of the inverter, (d) DC link current 75
Fig. 3.25 Simulation results for an LLG fault at point F1, three-phase output currents of VSI: (a) without the DC-RFCL, (b) with the DC-RFCL, A phase switches current of inverter: (c) without the DC-RFCL, (d) with the DC-RFCL. The DC link current and the DC inductor current: (e) without the DC-RFCL, (f) with the DC-RFCL 76
Fig. 3.26 Simulation results for an LG fault at point F1, three-phase output currents of VSI: (a) without the DC-RFCL, (b) with the DC-RFCL, A phase switches current of inverter: (c) without the DC-RFCL, (d) with the DC-RFCL, the DC link current and the DC inductor current: (e) without the DC-RFCL, (f) with the DC-RFCL 76
Fig. 3.27 Effectiveness of the proposed FRT scheme in suppressing the initial rate of current change in the SDs of the VSI 77
Fig. 3.28 Performance of the proposed FRT scheme during LG repeated transient fault at point F2. (a) three-phase output currents of VSI. (b) DC link current and DC inductor current.. 78
Fig. 4.1 The configuration of the DFIG-based wind turbine with (a) the crowbar protection (b) the modified DC chopper and (c) the general configuration of the DC chopper 86
Fig. 4.2 The switching states of the modified DC chopper in normal condition when $VDC < Vth$ 89
Fig. 4.3 The switching states of the modified DC chopper in normal condition when $VDC > Vth$ 89
Fig. 4.4 The switching states of the modified DC chopper in the fault condition when $iDC\ link > iDC\ th$... 89
Fig. 4.5 The control circuit of the modified DC chopper 90
Fig. 4.6 The power system with the DFIG-based wind turbine in the simulation.......... 93
Fig. 4.7 The simulations results for the three-phase fault for the general configuration of the DC chopper, incorporated with the crowbar and the modified DC chopper: (a)-(b) the terminal voltage, (c)-(d) the stator currents, (e)-(f) the rotor currents and (g)-(h) the DC link voltage... 95

Fig. 4.8 The simulations results for the line-to-line fault for the general configuration of the DC chopper, incorporated with the crowbar and the modified DC chopper: (a)-(b) the terminal voltage, (c)-(d) the stator currents, (e)-(f) the rotor currents and (g)-(h) the DC link voltage 96
Fig. 4.9 The proposed configuration of the non-controlled fault current limiter located in the rotor side of the DFIG 98
Fig. 4.10 The simulated power system 100
Fig. 4.11 The crowbar protection, (a) stator voltage, (b) stator current, (c) rotor current 101
Fig. 4.12 The proposed scheme, (a) non-superconducting inductance current, (b) stator current, (c) rotor current 101
Fig. 4.13 The crowbar protection, (a) DC link voltage, (b) rotor speed, (c) electrical torque 102
Fig. 4.14 The proposed scheme, (a) DC link voltage, (b) rotor speed, (c) electrical torque 102
Fig. 4.15 The crowbar protection, (a) stator current, (b) rotor current 103
Fig. 4.16 The proposed scheme, (a) stator current, (b) rotor current 103
Fig. 4.17 The proposed fault ride through configuration for the DFIG-based wind turbine during various power system faults 104
Fig. 4.18 The overall structure of the control circuits of the DFIG, (a): rotor side controller, (b): grid side controller 106
Fig. 4.19 Control circuit of the proposed DC-RFCL 106
Fig. 4.20 Schematic diagram of the simplified DFIG system for analytical analysis 111
Fig. 4.21 SPWM output sequence of the VSC with the measured DC link (i_{dc}) and the DC inductance (i_d) currents of the simplified DFIG system 116
Fig. 4.22 Equivalent circuits of the operating intervals. (a) switching state (000). (b) switching state (100). (c)-(d) switching state (101). (e) switching state (111). (f) single line diagram of the test system under study 117
Fig. 4.23 Simulation results for the LLLG fault at the PCC, the stator current: (a) with crowbar protection, (b) with the proposed FRT scheme, the rotor current: (c) with crowbar protection, (d) with the proposed FRT scheme, (e) the DC-link voltage, (f) the i_d, (g) the electrical torque, (h) the rotor speed, (i) the rotor current in-quadrature axis, q, i_{qr}, (j) the rotor current in the d-axis, i_{dr} 123

Fig. 4.24 Simulation results for the LLG fault at the PCC, the stator current: (a) with crowbar protection, (b) with the proposed FRT scheme, the stator current: (c) with crowbar protection, (d) the proposed FRT scheme, (e) the DC-link voltage, (f) the i_d, (g) the electrical torque, (h) the rotor speed, (i) the rotor current in-quadrature axis, q, i_{qr}, (j) the rotor current in the d-axis, i_{dr} 124
Fig. 4.25 Simulation results for the LG fault at the PCC, the stator current: (a) with crowbar protection, (b) with the proposed FRT scheme, the stator current: (c) with crowbar protection, (d) the proposed FRT scheme, (e) the DC-link voltage, (f) the i_d, (g) the electrical torque, (h) the rotor speed, (i) the rotor current in-quadrature axis, q, i_{qr}, (j) the rotor current in the d-axis, i_{dr} 126
Fig. 4.26 The super-synchronous speed of operation during the LLLG fault at the PCC, the stator current: (a) with crowbar protection, (b) with the proposed FRT scheme, the rotor current: (c) with crowbar protection, (d) with the proposed FRT scheme, (e) the DC-link voltage, (f) the i_d, (g) the electrical torque, (h) the rotor speed, (i) the rotor current in-quadrature axis, q, i_{qr}, (j) the rotor current in the d-axis, i_{dr}......... 127
Fig. 4.27 The sub-synchronous speed of operation and the LLLG fault at the PCC, the stator current: (a) with crowbar protection, (b) with the proposed FRT scheme, the rotor current: (c) with crowbar protection, (d) with the proposed FRT scheme, (e) the DC-link voltage, (f) the i_d, (g) the electrical torque, (h) the rotor speed, (i) the rotor current in-quadrature axis, q, i_{qr}, (j) the rotor current in the d-axis, i_{dr} 128
Fig. 4.28 Single line diagram of the experimental set-up 129
Fig. 4.29 Layout of experimental set-up 130
Fig. 4.30 Experimental results during the LLLG fault, (a) line-to-line voltage, B and C phases, without the DC-RFCL: (b) the AC output currents of the three-phase inverter, (c) the semi-conductor switch A phase current of the three-phase inverter, (d) the DC link current, with the DC-RFCL: (e) the DC inductor current, (f) the AC output currents of the three-phase inverter, (g) the semi-conductor switch A phase current of the three-phase inverter, (h) the DC link current 132
Fig. 4.31 Experimental results during the LLG fault, without the DC-RFCL: (a) the AC output currents of the three-phase inverter, (b) the semi-conductor switch A phase current of the three-phase inverter, (c) the DC link current, with the DC-RFCL, (d) the AC output currents of the three-phase inverter, (e) the semi-conductor switch A phase current of the three-phase inverter, (f) the DC link and DC inductor currents 133

Fig. 4.32 Experimental results during the LG fault, without the DC-RFCL: (a) the AC output currents of the three-phase inverter, (b) the semi-conductor switch A phase current of the three-phase inverter, (c) the DC link current, with the DC-RFCL: (d) the AC output currents of the three-phase inverter, (e) the semi-conductor switch A phase current of the three-phase inverter, (f) the DC link current and DC inductor current.. 134
Fig. 4.33 Experimental results about limiting the severe di/dt of the current in the initial moments of the fault in the semi-conductor switches of the three-phase inverter (a) without the DC-RFCL (b) with the DC-RFCL 135
Fig. 4.34 Experimental results during the LG repeated transient faults at the point F with the proposed FRT scheme. (a) three-phase output currents of the three-phase inverter. (b) the DC link current and the DC inductor current of the three-phase inverter 135

List of Tables

Table 2.1 Simulation parameters 24

Table 2.2 Simulation parameters 38

Table 3.1 Simulated power system parameters 51

Table 3.2 The simulation parameters 73

Table 4.1 The switching states of the semi-conductor switches in the modified DC chopper 91

Table 4.2 Simulated DFIG system specifications 121

List of Abbreviations and Acronyms

A list of major acronyms and abbreviations, used throughout the thesis, are presented in as follows:

FRT	Fault Ride Through
WECSs	Wind Energy Conversion Systems
VSWT	Variable Speed Wind Turbine
FSWTs	Fixed Speed Wind Turbines
SCIG	Squirrel Cage Induction Generator
DFIG	Doubly Fed Induction Generator
RSC	Rotor Side Converter
GSC	Grid Side Converter
FCLs	Fault Current Limiters
OR-FCL	Optimum Resistive Type Fault Current Limiter
CR-FCL	Controllable Resistive Type Fault Current Limiter
B-FCL	Bridge Type Fault Current Limiter
DC-RFCL	DC Link Resistive Type Fault Current Limiter
SDBR	Series Dynamic Braking Resistor
PCC	Point of Common Coupling
TSOs	Transmission System Operators
SDs	Semi-Conductor Devices
DGs	Distributed Generations
VSI	Voltage Source Inverter
CCS	Current Control Strategy
VCS	Voltage Control Strategy

Preface

Abstract

Due to increasing penetration levels of renewable energy in the power system, it is essential to keep renewable energy resources connected to the power grid during a fault considering the grid code requirements. In this thesis, the Fault Ride Through (FRT) capability of wind turbines is taken into account. All types of wind turbines are considered and for each one, the proposed methods will be discussed and studied.

In the first approach for Fixed Speed Wind Turbines (FSWTs), to achieve maximum FRT capability, this thesis proposes a single-phase Optimum Resistive Type Fault Current Limiter (OR-FCL) as an efficient solution during various grid faults. A dedicated control circuit is designed for the OR-FCL that enables it to insert an optimum value of resistance in the FSWT's fault current path for improving transient behaviour of the FSWT. The optimum resistance value depends on fault location and pre-fault active power. The control circuit of the proposed OR-FCL is capable of calculating the optimum resistance value for all the pre-fault conditions. By using the proposed control circuit, the FSWT can achieve its maximum FRT capability during symmetrical and asymmetrical faults, even at zero grid voltage. In the second approach for the FSWTs, to reduce the number of components, a three-phase Controllable Resistive Type Fault Current Limiter (CR-FCL), with the same operation of the OR-FCL, is investigated to improve the FRT capability of the FSWT.

Fully and partially rated converter wind turbines and solar power systems utilise an inverter to connect to the grid. The inverters are vulnerable due to their damaging effects of voltage sags in their terminals on semi-conductor self-turnoff switches. In this thesis, a Bridge Type Fault Current Limiter (B-FCL) is proposed with simple control system for

the FRT improvement of the inverters during different types of faults. The proposed B-FCL located, in Point of Common Coupling (PCC), is also capable of compensating for the voltage sag in the PCC and creates safe conditions not only for the inverter but also for any equipment which has been connected to the PCC in the power system. In the second approach, to analyse the FRT capability of inverter interfaced distributed generation, and to reduce the number of components, an FCL is placed in the DC link. This thesis proposes a DC Link Resistive Type Fault Current Limiter (DC-RFCL) based-voltage source inverter (VSI) for the FRT capability improvement, which is a new approach in the use of FCLs. Instead of using three-phase FCLs in the AC side of the VSI as in the first approach, just one single-phase proposed DC-RFCL is connected in series with the DC side of the VSI.

Doubly fed induction generator (DFIG)-based wind turbines employ small-scale voltage sourced converters with a limited over-current withstand capability, which makes the DFIG-based wind turbines very vulnerable to grid faults. Often, modern DFIG systems employ a crowbar protection at the rotor circuit to protect the rotor side converter (RSC) during the grid faults. This method converts the DFIG to a squirrel cage induction generator, which does not comply with the new grid codes. The recent grid codes require wind turbines to stay connected to the utility grid during and after the power system faults, especially under high penetration levels of wind power. Furthermore, the crowbar switch is expensive. Therefore, in this thesis, the FRT capabilities of DFIG-based wind turbines are studied. To improve the FRT capability of the DFIG-based wind turbines, three approaches are proposed: a modified DC chopper, a non-controlled FCL and a DC link resistive type fault current limiter. In the first approach, the modified DC-link chopper is proposed in order to maintain both the DC link voltage and the high current level in the stator and the rotor sides in a permissible level, without incorporating any extra fault current limiting strategies. In the second approach for the FRT improvement of the DFIG-based wind turbine, a non-controlled fault current limiter is proposed. Co-operative operation of the chopper circuit and the non-controlled FCL, which is located in the rotor side of the DFIG, are studied. It is demonstrated that locating the proposed topology on the rotor side is effective from the leakage coefficient point of view, limiting transient over-currents rather than on the stator side. Furthermore, it is shown that, by obtaining an optimum non-superconducting inductance value, the rate of the fault current change is limited to lower than the maximum rates of current change in the semi-conductor switches of the DFIG's converters during the fault. In the third approach for the FRT improvement of the DFIG-based wind turbine, this thesis proposes the application of the DC Link Resistive Type Fault Current Limiter (DC-RFCL) to improve the FRT capability of the DFIG. The proposed DC-RFCL is employed on the DC side of the RSC. The DC-RFCL solves crowbar protection activation problems and eliminates subsequent complications in the DFIG system. The proposed DC-RFCL does not have any significant impact on the overall performance of the DFIG during normal operation. The proposed approach is compared with the crowbar-based protection method. Simulation studies are carried out using PSCAD/EMTDC software. In addition, a prototype is provided to demonstrate the main concept of the proposed approach.

Thesis Outline

The thesis contains five chapters. Chapter 1 includes a concise and precise introduction to different types of wind energy conversion systems. Chapter 2 discusses the FRT capability improvement of the FSWT during any fault conditions. The single-phase and three-phase configurations of the proposed FCLs are investigated. Then, in Chapter 3, regarding fully and partially rated converters employed in wind turbines and solar power, the FRT capability enhancement of the inverter interfaced distributed generations will be investigated. Similarly, in Chapter 2, two approaches will be proposed. Lastly, in Chapter 4, the FRT capability of the DFIG-based wind turbine will be studied. Three approaches will be studied analytically and one of approaches will be experimentally discussed. Finally, a conclusion will be given, and future works will be discussed in Chapter 5.

Supporting Publications

This thesis includes the following referred journal and conference papers (the papers are arranged in the same order as the chapters.)

Referred journal publications:

1 **S.B. Naderi**, M. Negnevitsky, A. Jalilian, M. Tarafdar Hagh, K.M Muttaqi, "Optimum resistive type fault current limiter: An efficient solution to achieve maximum fault ride-through capability of fixed speed wind turbines during symmetrical and

asymmetrical grid faults," ***IEEE Trans. Ind. Appl.***, vol. 53, no. 1, pp. 538-548, Jan/Feb. 2017.

2. **S.B. Naderi**, M. Negnevitsky, A. Jalilian, M. Tarafdar Hagh, "Efficient fault ride-through scheme for three phase voltage source inverter-interfaced distributed generation using DC link adjustable resistive type fault current limiter," ***Elsevier Renewable Energy***, vol. 92, pp. 484-498 Jul. 2016.

3. A. Jalilian, **S.B. Naderi**, M. Negnevitsky, M. Tarafdar Hagh, "Controllable DC-link bridge-type FCL for low voltage ride-through enhancement of converter interfaced DG systems," ***Elsevier International Journal of Electrical Power and Energy Systems***, vol. 95, pp. 653-663, Feb. 2018.

4. A. Jalilian, **S.B. Naderi**, M. Negnevitsky, M. Tarafdar Hagh, K.M Muttaqi, "Controllable DC-link fault current limiter augmentation with DC chopper to improve fault ride-through of DFIG," ***IET Renewable Power Generation***, vol. 11, no. 2, pp. 313-324, Feb. 2017.

5. **S.B. Naderi**, M. Negnevitsky, A. Jalilian, M. Tarafdar Hagh, K.M Muttaqi, "Low voltage ride-through enhancement of DFIG-based wind turbine using DC link switchable resistive type fault current limiter," ***Elsevier International Journal of Electrical Power and Energy Systems***, vol. 86, pp. 104-119, Mar. 2017.

6. **S.B. Naderi**, P. Davari, D. Zhou, M. Negnevitsky, F. Blaabjerg, "A review on fault current limiting devices to enhance fault ride-through capability of doubly fed induction generator-based wind turbine," Submitted to ***Electric Power Components and Systems***, Under Review.

7. **S.B. Naderi**, M. Negnevitsky, K.M Muttaqi, "A Modified DC Chopper for Limiting the Fault Current and Controlling the DC Link Voltage to Enhance Fault Ride-Through Capability of Doubly-Fed Induction Generator Based Wind Turbine," Submitted to ***IEEE Trans. Ind. Appl.,*** Under Review.

Referred conference publications:

8. **S.B. Naderi**, M. Negnevitsky, A. Jalilian, M. Tarafdar Hagh, K.M Muttaqi, "Optimum resistive type fault current limiter: an efficient solution to achieve maximum fault ride-through capability of fixed speed wind turbines during symmetrical and

asymmetrical grid faults," in *Proc.* ***the 50th IEEE IAS Annual Meeting, Addison (Dallas area),*** Texas, USA, 2015, pp. 1-8.

9. **S.B. Naderi**, M. Negnevitsky, A. Jalilian, M. Tarafdar Hagh, "Fault ride through improvement of fixed speed wind turbine using CR-FCL with its modified control strategy," in *Proc.* ***Australasian Universities Power Engineering Conference (AUPEC),*** QLD, Australia, 2016, pp. 1-6.

10. M. Tarafdar Hagh, A. Jalilian, **S.B. Naderi**, M. Negnevitsky, K.M Muttaqi, "Improving fault ride-through of three-phase voltage source inverter during symmetrical fault using DC link fault current limiter," in *Proc.* ***Australasian Universities Power Engineering Conference (AUPEC),*** NSW, Australia, 2015, pp. 1-5.

11. **S.B. Naderi**, M. Negnevitsky, A. Jalilian, M. Tarafdar Hagh, K.M Muttaqi, "Voltage sag compensation of point of common coupling for low voltage ride-through enhancement of inverter interfaced DG using bridge type FCL," in *Proc.* ***Australasian Universities Power Engineering Conference (AUPEC),*** NSW, Australia, 2015, pp. 1-6.

12. **S.B. Naderi**, M. Negnevitsky, A. Jalilian, M. Tarafdar Hagh, "Non-controlled fault current limiter to improve fault ride through capability of DFIG-based wind turbine," in *Proc.* ***IEEE Power and Energy Society General Meeting,*** Boston, MA, USA, 2016, pp. 1-5.

13. **S.B. Naderi**, M. Negnevitsky, K.M Muttaqi, "A modified DC chopper for limiting the fault current and controlling the DC link voltage to enhance ride-through capability of doubly fed induction generator-based wind turbine," in *Proc.* ***the 52th IEEE IAS Annual Meeting,*** OH, USA, 2017, pp. 1-8.

14. **S.B. Naderi**, P. Davari, D. Zhou, M. Negnevitsky, F. Blaabjerg, "Study on application of new approach of fault current limiters in fault ride through capability improvement of DFIG-based wind turbine," Accepted for publication in ***IEEE Power and Energy Society General Meeting,*** Portland, OR, USA, 2018, pp. 1-5.

15. A. Rostami, A. Jalilian, **S.B. Naderi,** M. Negnevitsky, P. Davari and F. Blaabjerg, "A Novel Passive Islanding Detection Scheme for Distributed Generations Based on Rate of Change of Positive Sequence Component of Voltage and Current," in *Proc.* ***Australasian Universities Power Engineering Conference (AUPEC),*** Melbourne, Australia, 2017, pp. 1-5.

16. A. Rostami, M. Bagheri, **S.B. Naderi,** M. Negnevitsky, A. Jalilian and F. Blaabjerg, “A Novel Islanding Detection Scheme for Synchronous Distributed Generation Using Rate of Change of Exciter Voltage over Reactive Power at DG-Side,” in *Proc.* ***Australasian Universities Power Engineering Conference (AUPEC),*** Melbourne, Australia, 2017, pp. 1-5.

17. **S.B. Naderi,** M. Jafari, A. Zandnia, A. Jalilian, P. Davari, M. Negnevitsky and F. Blaabjerg, “Investigation on Capacitor Switching Transient Limiter with a Three Phase Variable Resistance”, in *Proc.* ***Australasian Universities Power Engineering Conference (AUPEC),*** Melbourne, Australia, 2017, pp. 1-6.

18. **S.B. Naderi** and M. Negnevitsky, “Soft and fast starting induction motors using controllable resistive type fault current limiter,” in *Proc.* ***IEEE Power and Energy Society General Meeting,*** Denver, CO, USA, 2015, pp. 1-5.

Chapter 1: Introduction

1.1 Wind Power

Because of environmental concerns and an increase in active power demands, the industries and the Transmission System Operators (TSOs) are becoming more interested in decreasing the dependency of the power system on the conventional generation units [1-3]. Consequently, the renewable energy-based generation units (solar, hydro and wind power and so on) include considerable portions of the generated active power in the overall power system and this will increase day by day. Of these renewable energy sources, wind power is the most important from economical and technical points of view, especially in places located in high altitudes or which have more coastlines; for example in Australia, the greatest potential is near coastal locations as in Tasmania [4] because the mean value of the wind speed would be higher than in places which are far from coastal areas [5]. In this case, when the penetration of the wind power increases in the power network, more attention should be given to the operation of wind turbines, especially when a fault occurs.

Any sudden off-grid of the wind power will damage the operation of the power system when the power system faults occur. Therefore, to maintain the stability of the power system during large disturbances, including symmetrical or asymmetrical grid faults, most of the TSOs require that wind turbines should be capable of staying connected to the utility grid, as do the conventional power plants during the fault because, in this way, the secure and reliable operation of the power networks is guaranteed. This operational behaviour is known as Fault Ride-Through (FRT) capability [6-8].

1.2 Different Types of Wind Energy Conversion Systems

The transient behaviour of Wind Energy Conversion Systems (WECSs) during a fault condition is one of the significant problems [9-13] for power systems, at the level of high penetration of wind power. With a high penetration level of WECS in the grid, the power system operators encounter new challenging issues, which could affect the stability of the power system. Until now, the wind energy conversion systems are categorised as being four to five generations. Basically, four generations are mostly employed in wind turbine investigated research [14]. But regarding the rotor speed variation, there are two type of wind turbine as follows:

1. Fixed speed: fixed speed wind Turbine and partial variable speed wind turbine with variable rotor resistance

2. Variable speed: variable speed wind turbine with partially scaled back-to-back converters and variable speed wind turbine with fully scaled back-to-back converters

In this thesis, the fault ride through capability of the fixed speed wind turbine and the variable speed wind turbine with partially scaled back-to-back converters will be taken into account in detail. Meanwhile, to consider the fault ride through capability of variable speed wind turbine with fully scaled back-to-back converters, a simplified model of fully scaled back-to-back converters which is suitable during the fault analysis will be discussed. In fact, the principle of the operation of a grid side converter as an inverter interfaced distributed generation unit will be discussed.

Comprehensive discussions will be presented in Chapter 2 for Fixed Speed Wind turbine (FSWT), in Chapter 3 for inverter interfaced distributed generations and in Chapter 4 for Variable Speed Wind Turbine with Partially Scaled Back-to-back Converters or Doubly Fed Induction Generator (DFIG) based wind turbine. As an introduction, the principles of operation and configuration of wind turbines are concisely outlined in the following subsections.

1.2.1 Fixed speed wind turbine

The Fixed Speed Wind turbine (FSWT) is directly connected to the grid via the Squirrel Cage Induction Generator (SCIG) as shown in Fig. 1.1. The rotor speed is close to the nominal value. The wind turbine is not able to track the maximum active power regarding the wind speed variation. Furthermore, it continuously absorbs reactive power from the grid, especially during the fault condition. This does not comply with the grid code requirement. Thus, to overcome this issue, the capacitor banks are utilised in the terminal of the FSWT. The FSWT is the first generation of wind turbine which is employed in the power system. They are still under operation in some wind farms due to their cheap, robust and low maintenance operation. Therefore, the FRT capability improvement of this type of wind turbine is still important as they could be made to survive longer, instead of replacing them with variable speed wind turbines.

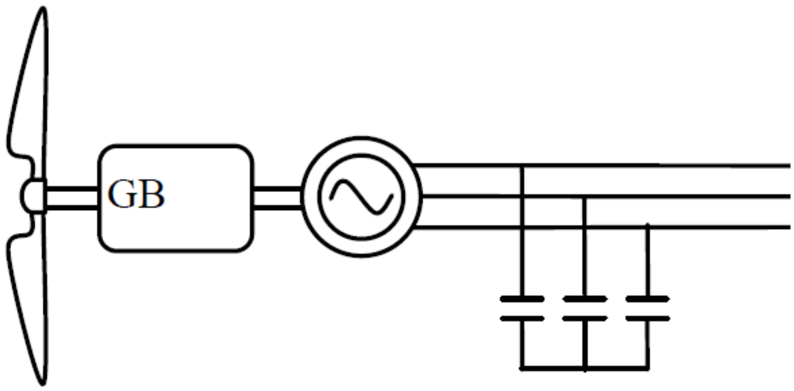

Fig. 1.1 Fixed Speed Wind Turbine (FSWT)

1.2.2 Variable speed wind turbine

As mentioned, there are two types of variable speed wind turbines which are categorised according to the rate of the back-to-back converters, including those which are partially rated and those which are fully rated. The Variable Speed Wind Turbine (VSWT) is the most interesting WECS due to the possibility of extracting more energy from a wind regime than from a Fixed Speed Wind Turbine (FSWT). Furthermore, enhanced power quality, low stress on the turbine and independent control of reactive and active powers are advantages of the VSWT [15, 16]. Currently, the large capacity of the VSWT is employed on the power network.

In this thesis, to consider the FRT capability of variable speed wind turbines with the fully rated back-to-back converters as shown in Fig. 1.2, only the operation of the grid side converter is taken into account; this could also be interesting for other types of renewable energy resources which are connected through a power electronic converter to the grid. This is due to the fact that, over the years, in addition to variable speed wind turbines, power electronic converters have found wide application in numerous grid interfaced systems, including distributed power generations like fuel cells [17], solar energy [18], adjustable speed drives [19] and active power filters [20]. Most of these systems employ three phase Voltage Source Inverters (VSIs) whose functionality is to exchange variable power with the utility grid.

Therefore, in Chapter 3, the FRT capability enhancement of the inverter interfaced distributed generation units is discussed. It will be explained that, for the proposed methods in the fault analysis, it can be assumed that the DC input voltage of the inverter is essentially fixed in the time frame 0-1.0 s, considering the grid side converter operation could be sufficient to generalise for the variable speed wind turbine with fully rated back-to-back converters. The full consideration of variable speed wind turbines with fully rated back-to-back converters could be taken into account for future works.

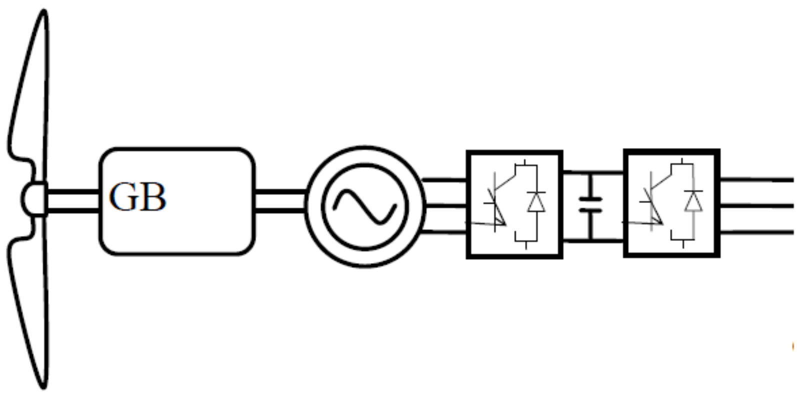

Fig. 1.2 Variable speed wind turbine with fully rated back-to-back converters

The Doubly Fed Induction Generator (DFIG)-based wind turbine, as a variable speed wind turbine with partially scaled back-to-back converters, is shown in Fig. 1.3. The stator of the DFIG is directly connected to the grid and the rotor is connected through back-to-back converters with the rate of 30% of nominal power of the wind turbine [21]. The main advantages of the DFIG is rotor speed controllability in the range of $\pm 30\%$, grid voltage support during voltage sag, maximum power tracking and cost effective from point of view of industry, compared with the fully rated converter employed in the WECS. However, it should be noted that, due to the limited capacity of the back-to-back converters, there is insufficient reactive power support, especially during grid faults. In fact, to ride through the fault and deep voltage sag, employing auxiliary circuits to limit the fault current level and to compensate for voltage sag are unavoidable. In this thesis, fault current limiters as an auxiliary circuit will be proposed, in order to enhance the FRT capability of the DFIG-based wind turbine.

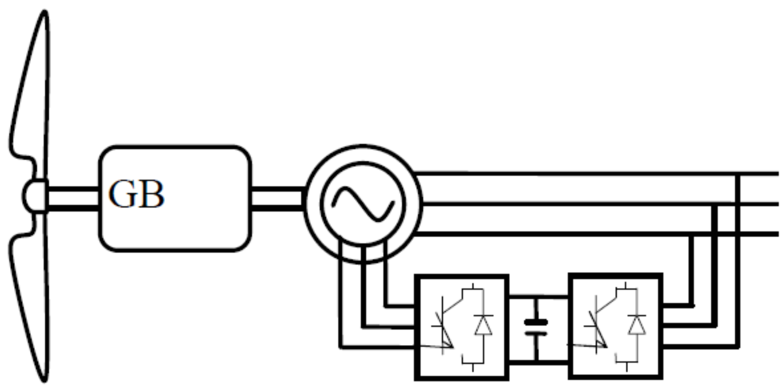

Fig. 1.3 Doubly Fed Induction Generator (DFIG)-based wind turbine as variable speed wind turbine with partially scaled back-to-back converters

1.3 Fault Ride Through Requirements

As discussed, the FRT means keeping the wind turbine connected to the power system during fault condition. It is obvious that, for secure power system operation, the wind turbines should meet the grid requirements. In fact, considering the grid codes, the wind turbines should not be disconnected from the network for a specific time after fault inception; this can maintain the stability of the grid voltage and frequency [22].

The FRT requirement varies from countries following characteristics of the power systems. Fig. 1.4 shows the grid code requirements of different countries for FRT capability of wind turbines. In the lower area of each curve, the wind turbine could be disconnected but, for any point in the upper area, the wind turbine should remain connected to the power system [6, 23].

Among the different grid codes, “E.ON” grid code has the strongest FRT requirements [6]. As shown in Fig. 1.5, according to the “E.ON”, when the voltage at the Point of Common Coupling (PCC) drops to a zero value for a timeframe of 0.15 seconds or fewer, the wind turbine must not be disconnected from the grid. If the fault lasts longer, then the Transmission System Operator (TSO) is allowed to disconnect the generation unit from the power system.

The grid code requirements for the fault ride through capability reveal that the wind turbines are supposed to provide more grid supports. In this condition, on the one hand, a high penetration level of wind power can be predicted and on the other hand, the wind turbines should be equipped with cutting-edge technologies to ride through the faults.

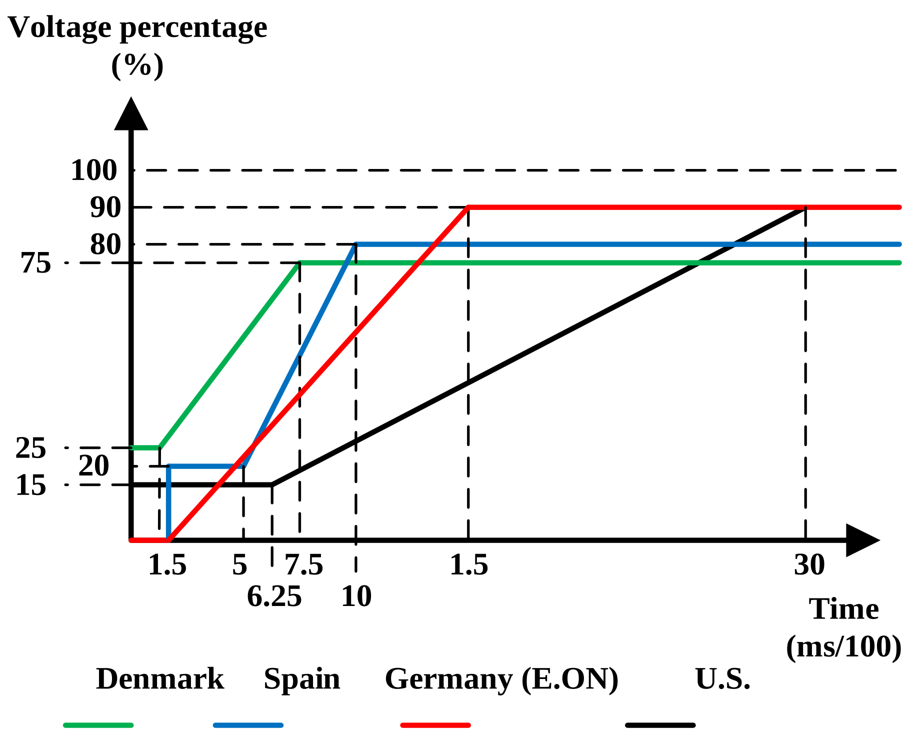

Fig. 1.4 The grid code requirement for the FRT of wind turbine in different countries [6, 23]

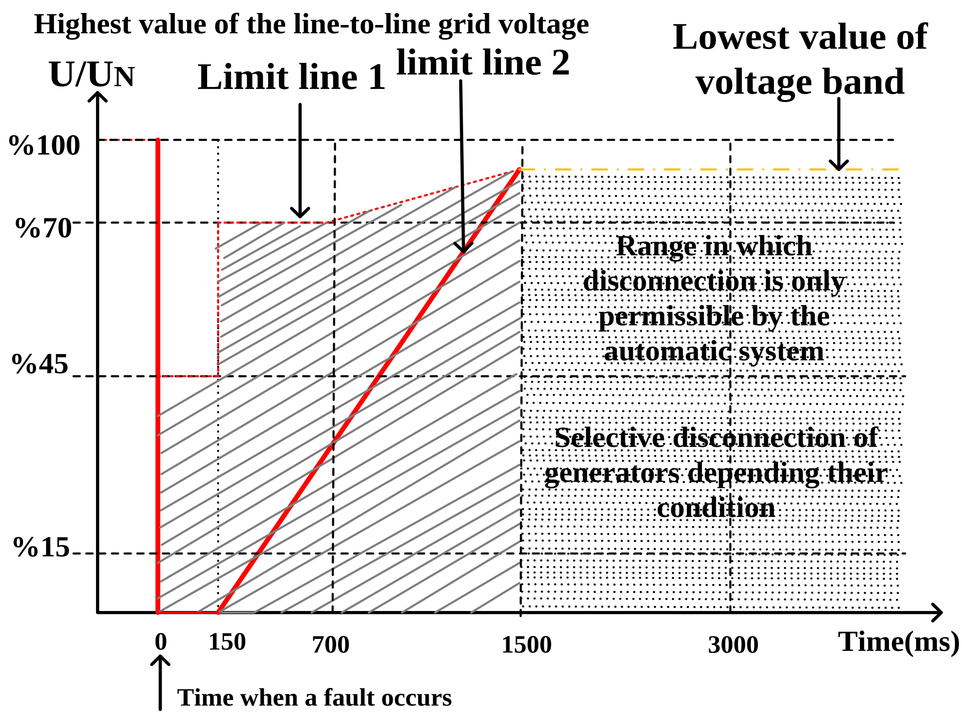

Fig. 1.5 Limits curve for the FRT requirement of the "E.ON" grid code

1.4 Project Objectives

In this thesis, new approaches, operations and applications of Fault Current Limiters (FCLs) are discussed in the improvement of the FRT capability of wind turbines. For each type of wind energy conversion systems, including fixed speed wind turbines, fully inverter interfaced units and doubly fed induction generator-based wind turbines as variable speed wind turbines with partially back-to-back converters, new approaches and applications of fault current limiters will be proposed as follows:

- In Chapter 1, a concise and precise introduction will be mentioned about different types of wind energy conversion systems.

- In Chapter 2, two configurations of the FCLs including a single phase optimum resistive type fault current limiter and a three-phase controllable resistive fault current limiter are proposed to investigate how a controllable resistance could affect the operation of fixed speed wind turbines during the fault condition with regard to pre-fault active power and fault location.

- In Chapter 3, a bridge type fault current limiter and a DC link resistive type fault current limiter are studied in the FRT improvement of inverter interfaced distributed generation units. It is shown that the latter, using a low number of components, has the same impact on limiting the fault current level.

- In Chapter 4, the FRT capability enhancement of doubly fed induction generator-based wind turbines is investigated, including three approaches. In the first approach, a modified DC chopper, which is not only able to adjust the DC link voltage level but which can also limit the DC link current level, is studied. Then, a non-controlled fault current limiter and the impact of impedance type and its location either in the stator side or in the rotor side are discussed. Finally, operation of the DC link resistive type fault current limiter is studied for different fault types in doubly fed induction generator-based wind turbines.

- In Chapter 5, a conclusion will be given, and future works will be discussed.

Meanwhile, in Chapters 2 to 4, the research background and the previous studied methods will be comprehensively presented.

Chapter 2-4 have been removed for copyright or proprietary reasons.

See pages vi-x for details of the referred journal and conference papers the removed chapters are made up of.

Chapter 5:

Conclusion and Future Works

5.1 Thesis Summary

In this thesis, the improvement of the fault ride through capability of wind energy conversion systems, including fixed speed wind turbine, voltage source inverter and doubly fed induction generator-based wind turbine by fault current limiting methods have been discussed. For each type of wind energy conversion system, a literature review has been presented in its own chapter.

In the fault ride through capability enhancement of the fixed speed wind turbine, two approaches have been discussed. In the first approach, an optimum resistive type FCL (OR-FCL) has been proposed to improve the fault ride-through capability of the FSWT during symmetrical and asymmetrical grid faults. A dedicated control circuit is also designed for the proposed OR-FCL. As shown, by means of this control circuit, the OR-FCL calculates an optimum resistance value ($R_{ac,opt.}$) with respect to all pre-fault operation conditions, including the fault location (k) and the pre-fault output active power (P_G) of the induction generator. The calculated value of $R_{ac,opt.}$ enters the fault current path through the use of the special switching pattern with the frequency of f_s and the duty cycle of $D_{opt.}$. In this way, the proposed OR-FCL limits the fault current efficiently and guarantees the maximum FRT capability of the FSWT during various grid faults. It has been also shown that the transient behaviour of the FSWT has been improved, especially during the worst cases of the fault condition, thanks to the proposed OR-FCL. Design consideration has been discussed to calculate the value of the DC inductance of the OR-FCL L_{dc} and the value of resistance R parallel with the self-turnoff switch. Therefore, the

OR-FCL guarantees that, for all wind speed variations, $R_{ac,opt.}$ is achieved by the special switching pattern and is ready to enter the fault phase.

In the second approach, a three-phase configuration of the OR-FCL has been proposed. The configuration of a controllable resistive type fault current limiter has been investigated during a symmetrical grid fault. The proposed CR-FCL guarantees the maximum FRT of the FSWT with a simple control circuit and a low number of components compared with the OR-FCL. As discussed, the FCLs with fixed impedance cannot be effective in reaching the maximum FRT capability for all the pre-fault conditions. The impact of the pre-fault conditions, including the fault location and the pre-fault output active power of the induction generator, has been considered on the maximum FRT of the FSWT during a three-phase fault. Therefore, the optimum resistance value has been calculated based on the pre-fault conditions. This optimum resistance value can be generated by the special frequency and the duty cycle of the proposed CR-FCL. Furthermore, the technical issues, which may arise in practical situations, have been discussed. The CR-FCL is not as effective as the OR-FCL during asymmetrical faults, including single phase faults and line-to-line faults because it affects healthy phases during faults.

As fully rated converters are employed in wind energy conversion systems, the enhancement of the fault ride through capability of inverter interfaced distributed generation units has been taken into account in this thesis. Two approaches have been proposed. In the first approach, the Bridge Type Fault Current Limiter (B-FCL) has been studied to improve the fault ride through capability of the inverter interfaced distribution generation. The single-phase B-FCL is placed in each individual phase. During the normal operation of the grid, the proposed structure does not affect the power system. When the fault occurs, the limiting resistance enters the faulty line and suppresses the fault current level. The effectiveness of the proposed B-FCL has been assessed through all grid fault types, including the three-phase fault, the line-to-line and to ground fault, as well as the single-phase fault. The B-FCL can mitigate the voltage sag at the point of common coupling during the fault and as a result, not only the inverter can stay connected to the utility but also the connected equipment to the PCC is not affected. Furthermore, with the proposed approach, the inverter is not required to change its operational condition in the fault condition and can continue to deliver as much active power as possible without any interruption. Simulation results have been provided by PSCAD/EMTDC software.

The second approach presented a novel DC-RFCL based FRT scheme to improve the FRT capability in the VSI. In comparison with the B-FCL, the proposed approach only uses one set of single-phase DC-RFCL, which is placed in the DC side of the VSI. Therefore, this approach reduces the number of the required FCLs, which are used in the AC side of the VSI as in the first approach, the B-FCL. In addition, in the proposed DC-RFCL, due to implementing the non-superconducting DC inductor, the initial cost also decreases. The VSC strategy is employed during normal operation as well as during the fault condition with the DC-RFCL. This characteristic is interesting for the industry, because in the other FRT methods, the control strategy of VSI is changed from the VSC to the CSC during the fault in order to restrict the fault current level. The proposed DC-RFCL can suppress severe *di/dt* at the first moments of the fault and protect the SDs of the VSI from damage even at zero grid voltage, as recommended by new grid codes, with a high degree of reliability. Simulation studies have been carried out. The proposed approach has reliable performance during both symmetrical and asymmetrical faults. To sum up, the proposed method can easily be implemented by commercial inverter manufacturing companies, with the least technical design of the inverter from the perspective of the practical.

To improve the fault ride through capability of the doubly fed induction generator-based wind turbine, three methods have been proposed in the thesis. In the first approach, the modified DC chopper has been proposed for controlling the DC link voltage and limiting the fault current to enhance fault ride-through capability of doubly fed induction generator-based wind turbines. The operation of the modified DC chopper has been discussed and compared with the general configuration of the DC chopper incorporated with the crowbar protection. The modified DC chopper is capable of limiting the high rotor and stator currents in addition to the DC link voltage control during the fault conditions. The modified DC chopper utilises three extra semi-conductor switches which enable it to insert the DC chopper resistance in series or parallel connections with the DC link, according to the DC link threshold current and the DC link threshold voltage, respectively. With the modified DC chopper, it is not necessary to stop the RSC switching and employ the anti-parallel diodes with a high current rating. Utilising the modified DC chopper can decrease the decaying time constant in the rotor side. The modes of operation of the proposed DC chopper have been carefully studied. A technique to determine the value of the DC chopper resistance has been presented that allows the proposed configuration to operate in both modes: the fault current limiting mode and the DC link voltage control mode. Extensive simulations have been carried out in PSCAD/EMTDC software to test the robustness and effectiveness of the proposed modified DC chopper for the symmetrical and the asymmetrical faults. The results prove that, by employing the modified DC chopper, the high rotor and stator currents can be restricted without employing any additional fault current limiting approaches.

In the second approach, a non-controlled fault current limiter has been proposed to improve the fault ride through capability of the DFIG-based wind turbine. It was shown that locating the non-controlled FCL in the rotor side is effective in restricting the rotor transient over-currents from the point of view of the leakage coefficient rather than the stator side. Operation of the proposed scheme was compared with the crowbar protection. Two case studies have been investigated: three phase fault and phase-to-phase fault. Meanwhile, the calculation of the optimum value of the non-superconducting inductance has been completed. With the optimum value of the inductance, it is guaranteed that the rate of fault current change is lower than di_{max}/dt of the semi-conductor switches of the rotor side converter. The proposed scheme does not require any measurement to limit the rotor fault current during the fault. Its configuration is simple and can be easily utilised by the industry. PSCAD/EMTDC software has been employed to evaluate the operation of the non-controlled FCL during all fault scenarios, including symmetrical and asymmetrical grid faults.

The last approach proposed a novel concept of the FCL application in the field of the FRT of the DFIG. The proposed DC-RFCL employs just one single set of the DC-RFCL in the DC side of the RSC to limit high rotor over-currents during various grid fault conditions. Therefore, it is more efficient than conventional approaches, which need three similar sets of the FCL at the AC side of the DFIG. In the proposed scheme, thanks to the DC-RFCL, the FRT capability is applied to a basic configuration of the RSC, which allows the proposed scheme to be implemented by industry easily. The DC-RFCL has a simple power circuit topology. The proposed approach is not affected by the depth of the voltage dip. With the present method, continuous operation can be achieved for the DFIG even at zero grid voltage during the fault condition. From the extensive simulation studies carried out in PSCAD/EMTDC software, it is proved that the proposed scheme can provide promising performance during the symmetrical and asymmetrical grid faults. Moreover, the main concept of the proposed method has been experimentally studied with a prototype set-up. The obtained results show that the proposed FRT configuration could eliminate the crowbar activation problems and subsequent complications in the DFIG-based wind turbines, thereby enabling the DFIG to remain connected to the utility grid during the power system faults.

5.2 Future Studies

As discussed within the thesis, the improvement of the FRT capability of fixed and variable speed wind turbines has been investigated and the proposed methods of and approaches by the FCLs have been studied for each type of wind turbine.

In future work, the application of the DC-RFCL should be employed and studied in a Permanent Magnet Synchronous Generator (PMSG)-based wind turbine. In fact, the operation of the DC-RFCL should be studied in the PMSG-based wind turbine to realise how the DC link current and the AC currents are limited during different types of grid faults.

From the point of view of the modified DC chopper, its application can be studied in any inverter interfaced generation units, including solar panels and the PMSG-based wind turbine. Regarding its application, it should be taken into account that the DC link current limitation or the DC link voltage control is the priority in the DC modified chopper. It can be found out by the level of DC link voltage and current during the operation of the modified DC chopper during different priorities.

In addition, the co-operation of the FCLs and voltage sag compensation devices are proposed for future works. As explained, due to their locations, the DC link fault current limiting devices are not capable of compensating for voltage sag at the point of common coupling or in the terminal of the generation units. Thus, not only can employing fault current limiting devices and voltage sag compensation devices compensate for the voltage sag in the AC side to some extent but this can also reduce the voltage and current rating of the fault current limiting device in the DC link of the inverter.

References

[1] J. C. Wu and Y. H. Wang, "Power conversion interface for small-capacity wind power generation system," *IET Gener. Transm. Dis.*, vol. 8, no. 4, pp. 689-696, Apr. 2014.

[2] R. Karki, H. Po, and R. Billinton, "A simplified wind power generation model for reliability evaluation," *IEEE Trans. Energy Convers.*, vol. 21, no. 2, pp. 533-540, Jun. 2006.

[3] M. E. Haque, Y. C. Saw, and M. M. Chowdhury, "Advanced control scheme for an IPM synchronous generator-based gearless variable speed wind turbine," *IEEE Trans. Sustain. Energy*, vol. 5, no. 2, pp. 354-362, Apr. 2014.

[4] D. Gautam, V. Vittal, and T. Harbour, "Impact of increased penetration of DFIG-based wind turbine generators on transient and small signal stability of power systems," *IEEE Trans. Power Syst.*, vol. 24, no. 3, pp. 1426-1434, Mar. 2009.

[5] W. Guo, L. Xiao, S. Dai, Y. Li, X. Xu, W. Zhou, *et al.*, "LVRT capability enhancement of DFIG with switch-type fault current limiter," *IEEE Trans. Ind. Electron.*, vol. 62, no. 1, pp. 332-342, Jan. 2015.

[6] M. Tsili and S. Papathanassiou, "A review of grid code technical requirements for wind farms," *IET Renew. Power Gen.*, vol. 3, no. 3, pp. 308-332, Mar. 2009.

[7] C. Chompoo-inwai, C. Yingvivatanapong, K. Methaprayoon, and L. Wei-Jen, "Reactive compensation techniques to improve the ride-through capability of wind turbine during disturbance," *IEEE Trans. Ind. Appl.*, vol. 41, no. 3, pp. 666-672, May/Jun. 2005.

[8] S. B. Naderi, M. Negnevitsky, A. Jalilian, M. T. Hagh, and K. M. Muttaqi, "Optimum resistive type fault current limiter: an efficient solution to achieve maximum fault ride-through capability of fixed-speed wind turbines during symmetrical and asymmetrical grid faults," *IEEE Trans. Ind. Appl.*, vol. 53, no. 1, pp. 538-548, Jan.-Feb. 2017.

[9] X. Wang, X. Wei, and Y. Meng, "Experiment on grid-connection process of wind turbines in fractional frequency wind power system," *IEEE Trans. Energy Convers.*, vol. 30, no. 3, pp. 22-31, Mar. 2015.

[10] M. H. Zamani, S. H. Fathi, G. Riahy, M. Abedi, and N. Abdolghani, "Improving transient stability of grid-connected squirrel-cage induction generators by plugging mode operation," *IEEE Trans. Energy Convers.*, vol. 27, no. 3, pp. 707-714, Mar. 2012.

[11] D. H. Nguyen and M. Negnevitsky, "A review of fault ride through strategies for different wind turbine systems," in *Proc. Australasian Uni. Power Eng. Conf. (AUPEC)*, 2010, pp. 1-5.

[12] M. Jafari, S. Naderi, M. Hagh, M. Abapour, and S. Hosseini, "Voltage sag compensation of point of common coupling (PCC) using fault current limiter," *IEEE Trans. Power Del.*, vol. 26, no. 4, pp. 2638-2646, Apr. 2011.

[13] C. E. Ugalde-Loo, J. B. Ekanayake, and N. Jenkins, "State-space modeling of wind turbine generators for power system studies," *IEEE Trans. Ind. Appl.*, vol. 49, no. 1, pp. 223-232, Jan./Feb. 2013.

[14] A. D. Hansen, F. Iov, F. Blaabjerg, and L. H. Hansen, "Review of contemporary wind turbine concepts and their market penetration," *Wind Engineering*, vol. 28, no. 3, pp. 247-263, May 2004.

[15] S. Alaraifi, A. Moawwad, M. S. El Moursi, and V. Khadkikar, "Voltage booster schemes for fault ride-through enhancement of variable speed wind turbines," *IEEE Trans. Sustain. Energy,* vol. 4, no. 4, pp. 1071-1081, Apr. 2013.

[16] N. K. S. Naidu and B. Singh, "Experimental implementation of doubly fed induction generator based standalone wind energy conversion system," *IEEE Trans. Ind. Appl.,* vol. 52, no. 4, pp. 3332-3339, Jul./Aug. 2016.

[17] X. Yu, M. R. Starke, L. M. Tolbert, and B. Ozpineci, "Fuel cell power conditioning for electric power applications: a summary," *IET Electr. Power Appl.*, vol. 1, no. 5, pp. 643-656, Sep. 2007.

[18] M. S. E. Moursi, W. Xiao, and J. L. Kirtley, "Fault ride through capability for grid interfacing large scale PV power plants," *IET Gener. Transm. Dis.,* vol. 7, no. 9, pp. 1027-1036, Sep. 2013.

[19] S. Bogarra, L. Monjo, J. Saura, F. Córcoles, and J. Pedra, "Comparison of simplified models for voltage-source-inverter-fed adjustable-speed drive during voltage sags when the during-event continue mode of operation is active," *IET Electr. Power Appl.,* vol. 8, no. 9, pp. 329–341, Nov. 2014.

[20] L. A. Moran, I. Pastorini, J. Dixon, and R. Wallace, "A fault protection scheme for series active power filters," *IEEE Trans. Power Electron.,* vol. 14, no. 5, pp. 928-938, Sep. 1999.

[21] S. Muller, M. Deicke, and R. W. D. Doncker, "Doubly fed induction generator systems for wind turbines," *IEEE Ind. Appl. Mag.,* vol. 8, no. 3, pp. 26-33, May/Jun. 2002.

[22] S. B. Naderi, M. Negnevitsky, A. Jalilian, and M. T. Hagh, "Non-controlled fault current limiter to improve fault ride through capability of DFIG-based wind turbine," in *Proc. IEEE Power & Energy Soc. General Meeting (PESGM),* Boston, MA, 2016, pp. 1-5.

[23] K. Ma, *Power electronics for the next generation wind turbine system* vol. 5: Springer, 2015.

[24] N. Jelani and M. Molinas, "Asymmetrical fault ride through as ancillary service by constant power loads in grid-connected wind farm," *IEEE Trans. Power Electron.*, vol. 30, no. 3, pp. 1704-1713, Mar. 2015.

[25] Y. Zou, M. E. Elbuluk, and Y. Sozer, "Simulation Comparisons and Implementation of Induction Generator Wind Power Systems," *IEEE Trans. Ind. Appl.,* vol. 49, no. 3, pp. 1119-1128, May/Jun. 2013.

[26] M. H. Ali and W. Bin, "Comparison of stabilization methods for fixed-speed wind generator systems," *IEEE Trans. Power Del.,* vol. 25, no. 1, pp. 323–331, Jan. 2010.

[27] C. Wessels, N. Hoffmann, M. Molinas, and F. W. Fuchs, "StatCom control at wind farms with fixed-speed induction generators under asymmetrical grid faults," *IEEE Trans. Ind. Electron.*, vol. 60, no. 7, pp. 2864-2873, Jul. 2013.

[28] T. Ahmed, O. Noro, E. Hiraki, and M. Nakaoka, "Terminal voltage regulation characteristics by static var compensator for a three-phase self-excited induction generator," *IEEE Trans. Ind. Appl.,* vol. 40, no. 4, pp. 978–988, Jul./Aug. 2004.

[29] A. P. Grilo, A. d. A. Mota, L. T. M. Mota, and W. Freitas, "An analytical method for analysis of large-disturbance stability of induction generators," *IEEE Trans. Power Syst.,* vol. 22, no. 4, pp. 1861-1869, Apr. 2007.

[30] M. A. Alam, A. H. M. A. Rahim, and M. A. Abido, "Supercapacitor based energy storage system for effective fault ride through of wind generation system," in *Proc. IEEE Int. Symp. Ind. Electron. (ISIE),* 2010, pp. 2481–2486.

[31] M. M. A. Mahfouz and M. A. H. El-Sayed, "Static synchronous compensator sizing for enhancement of fault ride-through capability and voltage stabilisation of fixed speed wind farms," *IET Renew. Power Gen.*, vol. 8, no. 1, pp. 1-9, Jan. 2014.

[32] S. M. Muyeen, R. Takahashi, T. Murata, J. Tamura, and M. H. Ali, "Stabilization of wind farms connected with multi-machine power system by using STATCOM/BESS," in *Proc. Int. Conf. Electrical Mach. Syst. (ICEMS)*, 2007, pp. 232-237.

[33] M. S. E. Moursi, K. Goweily, J. L. Kirtley, and M. Abdel-rahman, "Application of series voltage boosting schemes for enhanced fault ride through performance of fixed speed wind turbines," *IEEE Trans. Power Del.*, vol. 29, no. 1, pp. 61-71, Jan. 2014.

[34] A. A. Hussein and M. H. Ali, "Comparison between DVR and SFCL for fault ride through capability improvement of fixed-speed wind generator," in *Proc. IEEE PES T&D Conf. Exposition*, 2014, pp. 1-5.

[35] A. Causebrook, D. J. Atkinson, and A. G. Jack, "Fault ride-through of large wind farms using series dynamic braking resistors (March 2007)," *IEEE Trans. Power Syst.*, vol. 22, no. 3, pp. 966-975, Mar. 2007.

[36] N. G. Jayanti, M. Basu, M. F. Conlon, and K. Gaughan, "STATCOM and UPQC: Options to enhance fault-ride-through capability of a fixed speed wind generator," in *Proc. IET Int. Conf. Power Electron., Mach. Drives (PEMD)*, 2012, pp. 1-6.

[37] A. Moghadasi and A. Islam, "Enhancing LVRT capability of FSIG wind turbine using current source UPQC based on resistive SFCL," in *Proc. IEEE PES T&D Conf. Exposition*, 2014, pp. 1-5.

[38] Y. Hu and Z. Chen, "Effects of capacitor bank on fault ride through capability of induction generator based wind turbines," in *Proc. Asia-Pacific Power Energy Eng. Conf. (APPEEC)*, 2010, pp. 1-4.

[39] R. T. Vinakaya, R. M. Shereef, and S. A. Khaparde, "Comparison of SVCs And D-STATCOMs to control voltage violations of fixed speed induction generators," in *Proc. IEEE Power India Conf.*, 2012, pp. 1-6.

[40] M. Ferdosian, H. Abdi, and A. Bazaei, "Improved dynamic performance of wind energy conversion system by UPFC," in *Proc. IEEE Int. Conf. Ind. Technology (ICIT)*, 2013, pp. 545-550.

[41] M. Firouzi and G. B. Gharehpetian, "Improving fault ride-through capability of fixed-speed wind turbine by using bridge-type fault current limiter," *IEEE Trans. Energy Convers.*, vol. 28, no. 2, pp. 361-369, Feb. 2013.

[42] G. Rashid and M. H. Ali, "A modified bridge-type fault current limiter for fault ride-through capacity enhancement of fixed speed wind generator," *IEEE Trans. Energy Convers.*, vol. 29, no. 2, pp. 527-534, Feb. 2014.

[43] S. B. Naderi, M. Negnevitsky, A. Jalilian, M. T. Hagh, and K. M. Muttaqi, "Optimum resistive type fault current limiter: an efficient solution to achieve maximum fault ride-through capability of fixed speed wind turbines during symmetrical and asymmetrical grid faults," in *Proc. IEEE Ind. Appl. Soc. Annual Meeting*, TX, USA, 2015, pp. 1-8.

[44] S. B. Naderi, M. Negnevitsky, A. Jalilian, and M. T. Hagh, "Fault ride through improvement of fixed speed wind turbine using CR-FCL with its modified control strategy," in *Proc. Australasian Uni. Power Eng. Conf. (AUPEC)*, 2016, pp. 1-6.

[45] M. Singh and S. Santoso, *Dynamic models for wind turbines and wind power plants*: National Renew. Energy Lab., 2011.

[46] A. K. Theraja, *A.T.B. of electrical technology*: S. Chand Limited, 2007.

[47] L. Holdsworth, J. B. Ekanayake, and N. Jenkins, "Power system frequency response from fixed speed and doubly fed induction generator-based wind turbines," *Wind Energy,* vol. 7, no. 1, pp. 21-35, Jan. 2004.

[48] B. Abdi, A. H. Ranjbar, G. B. Gharehpetian, and J. Milimonfared, "Reliability considerations for parallel performance of semiconductor switches in high-power switching power supplies," *IEEE Trans. Ind. Electron.,* vol. 56, no. 6, pp. 2133-2139, Jun. 2009.

[49] B. Ju Won, Y. Dong-Wook, and K. Heung-Geun, "High-voltage switch using series-connected IGBTs with simple auxiliary circuit," *IEEE Trans. Ind. Appl.,* vol. 37, no. 6, pp. 1832-1839, Nov./Dec. 2001.

[50] M. E. Baran and I. El-Markaby, "Fault analysis on distribution feeders with distributed generators," *IEEE Trans. Power Syst.,* vol. 20, no. 4, pp. 1757–1764, Nov. 2005.

[51] A. D. Hansen and G. Michalke, "Fault ride-through capability of DFIG wind turbines," *Renewable Energy,* vol. 32, no. 9, pp. 1594-1610, Jul. 2007.

[52] N. H. Saad, A. A. Sattar, and A. E.-A. M. Mansour, "Low voltage ride through of doubly-fed induction generator connected to the grid using sliding mode control strategy," *Renewable Energy,* vol. 80, no. 8, pp. 583-594, Aug. 2015.

[53] A. Yazdani and R. Iravani, *Voltage-sourced converters in power systems: modeling, control, and applications*: John Wiley & Sons, 2010.

[54] A. H. Etemadi and R. Iravani, "Overcurrent and overload protection of directly voltage-controlled distributed resources in a microgrid," *IEEE Trans. Ind. Electron.,* vol. 60, no. 12, pp. 5629-5638, Dec. 2013.

[55] J. M. Bloemink and M. R. Iravani, "Control of a multiple source microgrid with built-in islanding detection and current limiting," *IEEE Trans. Power Del.,* vol. 27, no. 4, pp. 2122–2132, Oct. 2012.

[56] F. Gao and M. R. Iravani, "A control strategy for a distributed generation unit in grid-connected and autonomous modes of operation," *IEEE Trans. Power Del.,* vol. 23, no. 2, pp. 850-859, Apr. 2008.

[57] J. Keller and B. Kroposki, "Understanding fault characteristics of inverter-based distributed energy resources," National Renewable Energy Laboratory (NREL), Golden, CO.2010.

[58] "IEEE standard for interconnecting distributed resources with electric power systems," in *IEEE Std 1547-2003,* ed, 2003, pp. 1–28.

[59] E. Netz, "Grid code; high and extra high voltage," in *E-One Netz GmbH, Bayreuth* vol. 4, ed, 2006.

[60] W. Bartels, F. Ehlers, K. Heidenreich, R. Huttner, H. Kuhn, T. Meyer, *et al.,* "Generating plants connected to the medium-voltage network," 2008.

[61] J. Kwon, S. Yoon, H. Kim, and S. Choi, "Fault ride through control with voltage compensation capability for utility interactive inverter with critical load," in *Proc. 8th Int. Conf. Power Electron. - ECCE Asia*, 2011, pp. 3041-3047.

[62] G. M. S. Islam, A. Al-Durra, S. M. Muyeen, and J. Tamura, "Low voltage ride through capability enhancement of grid connected large scale photovoltaic system," in *Proc. 37th Ann. Conf. of the IEEE Ind. Electron. Soc. - IECON 2011,* 2011, pp. 884-889.

[63] T. Loix, T. Wijnhoven, and G. Deconinck, "Protection of microgrids with a high penetration of inverter-coupled energy sources," in *Proc. 2009 CIGRE/IEEE PES Joint Symp. Integration of Wide-Scale Renewable Resources Into the Power Del. Syst.*, 2009, pp. 1-6.

[64] C. A. Plet, M. Graovac, T. C. Green, and R. Iravani, "Fault response of grid-connected inverter dominated networks," in *Proc. IEEE Power & Energy Soc. General Meeting (PESGM)*, 2010, pp. 1-8.

[65] C. A. Plet, M. Brucoli, J. D. F. McDonald, and T. C. Green, "Fault models of inverter-interfaced distributed generators: Experimental verification and application to fault analysis," in *Proc. IEEE Power & Energy Soc. General Meeting (PESGM)*, 2011, pp. 1-8.

[66] A. Camacho, M. Castilla, J. Miret, A. Borrell, and L. G. d. Vicuña, "Active and reactive power strategies with peak current limitation for distributed generation inverters during unbalanced grid faults," *IEEE Trans. Ind. Electron.*, vol. 62, no. 3, pp. 1515-1525, Mar. 2015.

[67] A. Camacho, M. Castilla, J. Miret, J. C. Vasquez, and E. Alarcon-Gallo, "Flexible voltage support control for three-phase distributed generation inverters under grid fault," *IEEE Trans. Ind. Electron.*, vol. 60, no. 4, pp. 1429-1441, Apr. 2013.

[68] X. Pei and Y. Kang, "Short-circuit fault protection strategy for high-power three-phase three-wire inverter," *IEEE Trans. Ind. Informat.*, vol. 8, no. 3, pp. 545-553, Aug. 2012.

[69] J. Miret, M. Castilla, A. Camacho, L. G. d. Vicuña, and J. Matas, "Control scheme for photovoltaic three-phase inverters to minimize peak currents during unbalanced grid-voltage sags," *IEEE Trans. Power Electron.*, vol. 27, no. 10, pp. 4262-4271, Oct. 2012.

[70] M. T. Hagh and M. Abapour, "Nonsuperconducting fault current limiter with controlling the magnitudes of fault currents," *IEEE Trans. Power Electron.*, vol. 24, no. 3, pp. 613-619, Mar. 2009.

[71] G. G. Karady, "Concept of a combined short circuit limiter and series compensator [power lines]," *IEEE Trans. Power Del.*, vol. 6, no. 3, pp. 1031-1037, Jul. 1991.

[72] S. B. Naderi, M. Jafari, and M. Tarafdar Hagh, "Controllable resistive type fault current limiter (CR-FCL) with frequency and pulse duty-cycle," *Int. J. Elect. Power & Energy Syst.*, vol. 61, no. 10, pp. 11-19, Oct. 2014.

[73] S. B. Naderi, M. Negnevitsky, A. Jalilian, M. T. Hagh, and K. M. Muttaqi, "Voltage sag compensation of point of common coupling for low voltage ride-through enhancment of inverter interfaced DG using bridge type FCL," in *Proc. Australasian Uni. Power Eng. Conf. (AUPEC)*, 2015, pp. 1-6.

[74] S. B. Naderi, M. Negnevitsky, A. Jalilian, and M. T. Hagh, "Efficient fault ride-through scheme for three phase voltage source inverter-interfaced distributed generation using DC link adjustable resistive type fault current limiter," *Renewable Energy*, vol. 92, no. 7, pp. 484-498, Jul. 2016.

[75] A. Jalilian, S. B. Naderi, M. Negnevitsky, and M. T. Hagh, "Controllable DC-link bridge-type FCL for low voltage ride-through enhancement of converter interfaced DG systems," *Int. J. Elect. Power & Energy Syst.*, vol. 95, no. 2, pp. 653-663, Feb 2018.

[76] M. T. Hagh, A. Jalilian, S. B. Naderi, M. Negnevitsky, and K. M. Muttaqi, "Improving fault ride-through of three phase voltage source inverter during symmetrical fault using DC link fault current limiter," in *Proc. Australasian Uni. Power Eng. Conf. (AUPEC)*, 2015, pp. 1-5.

[77] S. Chen, "A non-superconducting fault current limiter (NSFCL)," Citeseer, 2013.

[78] N. Bottrell and T. C. Green, "Comparison of current-limiting strategies during fault ride-through of inverters to prevent latch-up and wind-up," *IEEE Trans. Power Electron.*, vol. 29, no. 7, pp. 3786-3797, Jul. 2014.

[79] ABB, "High-power semiconductors," ed, 2015, p. 71.

[80] N. Nimpitiwan, G. T. Heydt, R. Ayyanar, and S. Suryanarayanan, "fault current contribution from synchronous machine and inverter based distributed generators," *IEEE Trans. Power Del.*, vol. 22, no. 1, pp. 634-641, Jan. 2007.

[81] A. Keyhani and M. Marwali, *Smart power grids 2011*: Springer, 2012.

[82] A. F. Zobaa and R. C. Bansal, *Handbook of renewable energy technology*: World Scientific, 2011.

[83] A. Jalilian, M. T. Hagh, M. Abapour, and K. M. Muttaqi, "DC-link fault current limiter-based fault ride-through scheme for inverter-based distributed generation," *IET Renew. Power Gen.*, vol. 9, no. 6, pp. 690-699, Aug. 2015.

[84] Z. Miao, A. Domijan, and L. Fan, "Investigation of microgrids with both inverter interfaced and direct AC-connected distributed energy resources," *IEEE Trans. Power Del.*, vol. 26, no. 3, pp. 1634-1642, July. 2011.

[85] B. Lu and S. K. Sharma, "A literature review of IGBT fault diagnostic and protection methods for power inverters," *IEEE Trans. Ind. Appl.*, vol. 45, no. 5, pp. 1770-1777, Sep./Oct. 2009.

[86] J. Quintero, V. Vittal, G. Heydt, and Z. Hui, "The impact of increased penetration of converter control-based generators on power system modes of oscillation," in *Proc. IEEE Power & Energy Soc. General Meeting (PESGM)*, Denver, CO, 2015, pp. 1-1.

[87] A. Tohidi, H. Hajieghrary, and M. A. Hsieh, "Adaptive disturbance rejection control scheme for DFIG-based wind turbine: theory and experiments," *IEEE Trans. Ind. Appl.*, vol. 52, no. 3, pp. 2006-2015, May-June 2016.

[88] G. Wen, Y. Chen, Z. Zhong, and Y. Kang, "Dynamic voltage and current assignment strategies of nine-switch-converter-based DFIG wind power system for low-voltage ride-through (LVRT) under symmetrical grid voltage dip," *IEEE Trans. Ind. Appl.*, vol. 52, no. 4, pp. 3422-3434, July-Aug. 2016.

[89] X. Yan, G. Venkataramanan, Y. Wang, Q. Dong, and B. Zhang, "Grid-fault tolerant operation of a DFIG wind turbine generator using a passive resistance network," *IEEE Trans. Power Electron.*, vol. 26, no. 10, pp. 2896-2905, Oct. 2011.

[90] S. Wang, N. Chen, D. Yu, A. Foley, L. Zhu, K. Li, *et al.*, "Flexible fault ride through strategy for wind farm clusters in power systems with high wind power penetration," *Energy Conver. and Management*, vol. 93, pp. 239-248, Mar. 2015.

[91] I. Erlich, H. Wrede, and C. Feltes, "Dynamic behavior of DFIG-based wind turbines during grid faults," in *Proc. Power Conv. Conf.*, Nagoya, Japan, 2007, pp. 1195-1200.

[92] S. Hu, X. Lin, Y. Kang, and X. Zou, "An improved low-voltage ride-through control strategy of doubly fed induction generator during grid faults," *IEEE Trans. Power Electron.*, vol. 26, no. 12, pp. 3653-3665, Dec. 2011.

[93] G. Pannell, B. Zahawi, D. J. Atkinson, and P. Missailidis, "Evaluation of the performance of a DC-link brake chopper as a DFIG low-voltage fault-ride-through device," *IEEE Trans. Energy Convers.*, vol. 28, no. 3, pp. 535-542, Mar. 2013.

[94] K. E. Okedu, S. M. Muyeen, R. Takahashi, and J. Tamura, "Wind farms fault ride through using DFIG with new protection scheme," *IEEE Trans. Sustain. Energy,* vol. 3, no. 2, pp. 242-254, Feb. 2012.

[95] P. Kanjiya, B. B. Ambati, and V. Khadkikar, "A novel fault-tolerant DFIG-based wind energy conversion system for seamless operation during grid faults," *IEEE Trans. Power Syst.*, vol. 29, no. 3, pp. 1296-1305, May 2014.

[96] B. B. Ambati, P. Kanjiya, and V. Khadkikar, "A low component count series voltage compensation scheme for DFIG WTs to enhance fault ride-through capability," *IEEE Trans. Energy Convers.,* vol. 30, no. 1, pp. 208–217, Mar. 2015.

[97] P. S. Flannery and G. Venkataramanan, "A fault tolerant doubly fed induction generator wind turbine using a parallel grid side rectifier and series grid side converter," *IEEE Trans. Power Electron.,* vol. 23, no. 3, pp. 1126-1135, May 2008.

[98] P. S. Flannery and G. Venkataramanan, "Unbalanced voltage sag ride-through of a doubly fed induction generator wind turbine with series grid-side converter," *IEEE Trans. Ind. Appl.,* vol. 45, no. 5, pp. 1879-1887, Sep./Oct. 2009.

[99] J. Mohammadi, S. Afsharnia, and S. Vaez-Zadeh, "Efficient fault-ride-through control strategy of DFIG-based wind turbines during the grid faults," *Energy Conver. and Management,* vol. 78, no. 2, pp. 88-95, Feb. 2014.

[100] S. Xiao, H. Geng, H. Zhou, and G. Yang, "Analysis of the control limit for rotor-side converter of doubly fed induction generator-based wind energy conversion system under various voltage dips," *IET Renew. Power Gen.,* vol. 7, no. 1, pp. 71-81, Feb. 2013.

[101] D. Xie, Z. Xu, L. Yang, J. Østergaard, Y. Xue, and K. P. Wong, "A comprehensive LVRT control strategy for DFIG wind turbines with enhanced reactive power support," *IEEE Trans. Power Syst.,* vol. 28, no. 3, pp. 3302-3310, Aug. 2013.

[102] H. Fathabadi, "Control of a DFIG-based wind energy conversion system operating under harmonically distorted unbalanced grid voltage along with nonsinusoidal rotor injection conditions," *Energy Conver. and Management,* vol. 84, no. 8, pp. 60-72, Aug. 2014.

[103] R. Zhu, Z. Chen, X. Wu, and F. Deng, "Virtual damping flux-based LVRT control for DFIG-based wind turbine," *IEEE Trans. Energy Convers.,* vol. 30, no. 2, pp. 714-725, Jun. 2015.

[104] S. Xiao, G. Yang, H. Zhou, and H. Geng, "An LVRT control strategy based on flux linkage tracking for DFIG-based WECS," *IEEE Trans. Ind. Electron.,* vol. 60, no. 7, pp. 2820-2832, Jul. 2013.

[105] M. Rahimi and M. Parniani, "Efficient control scheme of wind turbines with doubly fed induction generators for low-voltage ride-through capability enhancement," *IET Renew. Power Gen.,* vol. 4, no. 3, pp. 242-252, May 2010.

[106] W. Qiao, R. Harley, and G. Venayagamoorthy, "Coordinated reactive power control of a large wind farm and a STATCOM using heuristic dynamic programming," in *Proc. IEEE Power & Energy Soc. General Meeting (PESGM),* Calgary, Alberta Canada, 2009, pp. 1-1.

[107] A. O. Ibrahim, T. H. Nguyen, D. C. Lee, and S. C. Kim, "A fault ride-through technique of DFIG wind turbine systems using dynamic voltage restorers," *IEEE Trans. Energy Convers.,* vol. 26, no. 3, pp. 871-882, Mar. 2011.

[108] A. Jalilian, S. B. Naderi, M. Negnevitsky, M. T. Hagh, and K. M. Muttaqi, "Controllable DC-link fault current limiter augmentation with DC chopper to improve fault ride-through of DFIG," *IET Renew. Power Gen.,* vol. 11, no. 2, pp. 313-324, Feb. 2017.

[109] W. Guo, L. Xiao, and S. Dai, "Enhancing low-voltage ride-through capability and smoothing output power of DFIG with a superconducting fault-current limiter–magnetic energy storage system," *IEEE Trans. Energy Convers.,* vol. 27, no. 2, pp. 277-295, Feb. 2012.

[110] W. Guo, L. Xiao, and S. Dai, "Fault current limiter-battery energy storage system for the doubly-fed induction generator: analysis and experimental verification," *IET Gener. Transm. Dis.*, vol. 10, no. 3, pp. 653-660, Feb. 2016.

[111] M. K. Hossain and M. H. Ali, "Transient stability augmentation of PV/DFIG/SG-based hybrid power system by nonlinear control-based variable resistive FCL," *IEEE Trans. Sustain. Energy*, vol. 6, no. 4, pp. 1638-1649, Apr. 2015.

[112] S. B. Naderi, M. Negnevitsky, A. Jalilian, M. Tarafdar Hagh, and K. M. Muttaqi, "Low voltage ride-through enhancement of DFIG-based wind turbine using DC link switchable resistive type fault current limiter," *Int. J. Elect. Power & Energy Syst.*, vol. 86, no. 3, pp. 104-119, Mar. 2017.

[113] J. Yang, J. E. Fletcher, and J. O'Reilly, "A series-dynamic-resistor-based converter protection scheme for doubly-fed induction generator during various fault conditions," *IEEE Trans. Energy Convers.*, vol. 25, no. 2, pp. 422-432, Feb. 2010.

[114] K. E. Okedu, "Enhancing DFIG wind turbine during three-phase fault using parallel interleaved converters and dynamic resistor," *IET Renew. Power Gen.*, vol. 10, no. 8, pp. 1211-1219, Sep. 2016.

[115] S. B. Naderi, P. Davari, D. Zhou, M. Negnevitsky, and F. Blaabjerg, "Study on opplication of new approach of fault current limiters in fault ride through capability improvement of DFIG based wind turbine," in *Proc. IEEE Power & Energy Soc. General Meeting (PESGM)*, OR, USA, 2018, pp. 1-5.

[116] S. B. Naderi, M. Negnevitsky, and K. M. Muttaqi, "A modified DC chopper for limiting the fault current and controlling the DC link voltage to enhance ride-through capability of doubly-fed induction generator based wind turbine," in *Proc. IEEE Ind. Appl. Soc. Annual Meeting*, 2017, pp. 1-8.

[117] J. Lopez, P. Sanchis, X. Roboam, and L. Marroyo, "Dynamic behavior of the doubly fed induction generator during three-phase voltage dips," *IEEE Trans. Energy Convers.*, vol. 22, no. 3, pp. 709-717, Mar. 2007.

[118] G. Abad, J. Lopez, M. Rodríguez, L. Marroyo, and G. Iwanski, *Doubly fed induction machine: modeling and control for wind energy generation* vol. 85: John Wiley & Sons, 2011.

[119] S. B. Naderi, M. Jafari, and M. T. Hagh, "Parallel-resonance-type fault current limiter," *IEEE Trans. Ind. Electron.*, vol. 60, no. 7, pp. 2538-2546, Jul. 2013.

[120] G. Hua, L. Cong, and Y. Geng, "LVRT capability of DFIG-based WECS under asymmetrical grid fault condition," *IEEE Trans. Ind. Electron.*, vol. 60, no. 6, pp. 2495-2509, Jun. 2013.

[121] W. Guo, L. Xiao, S. Dai, X. Xu, Y. Li, and Y. Wang, "Evaluation of the performance of BTFCLs for enhancing LVRT capability of DFIG," *IEEE Trans. Power Electron.*, vol. 30, no. 7, pp. 3623-3637, Jul. 2015.

[122] G. Rashid and M. H. Ali, "Transient stability enhancement of doubly fed induction machine-based wind generator by bridge-type fault current limiter," *IEEE Trans. Energy Convers.*, vol. 30, no. 3, pp. 939-947, Feb. 2015.

[123] M. E. Elshiekh, D. E. A. Mansour, and A. M. Azmy, "Improving fault ride-through capability of DFIG-based wnd turbine using superconducting fault current limiter," *IEEE Trans. Appl. Supercond.*, vol. 23, no. 3, pp. 5601204-5601204, Jun. 2013.

[124] W. Fei, Y. Zhang, and Z. Lu, "Novel bridge-type FCL based on self-turnoff devices for three-phase power systems," *IEEE Trans. Power Del.*, vol. 23, no. 4, pp. 2068-2078, Oct. 2008.

[125] M. T. Hagh and M. Abapour, "DC reactor type transformer inrush current limiter," *IET Electr. Power Appl.*, vol. 1, no. 5, pp. 808-814, Sep. 2007.

[126] J. LÓpez, E. GubÍa, P. Sanchis, X. Roboam, and L. Marroyo, "Wind turbines based on doubly fed induction generator under asymmetrical voltage dips," *IEEE Trans. Energy Convers.*, vol. 23, no. 1, pp. 321-330, Mar. 2008.

[127] F. Sulla, J. Svensson, and O. Samuelsson, "Short-circuit analysis of a doubly fed induction generator wind turbine with direct current chopper protection," *Wind Energy*, vol. 16, no. 1, pp. 37-49, Dec. 2013.

[128] R. Pena, J. C. Clare, and G. M. Asher, "Doubly fed induction generator using back-to-back PWM converters and its application to variable-speed wind-energy generation," *IEE Proceedings - Electr. Power Appl.*, vol. 143, no. 3, pp. 231-241, May 1996.

[129] A. H. Kasem, E. F. El-Saadany, H. H. El-Tamaly, and M. A. A. Wahab, "An improved fault ride-through strategy for doubly fed induction generator-based wind turbines," *IET Renew. Power Gen.*, vol. 2, no. 4, pp. 201-214, Dec. 2008.