WOUND ROTOR INDUCTION MACHINE FOR MEDIUM VOLTAGE APPLICATIONS FED FROM SERIES-CONNECTED INVERTER MODULES

APURVA VERMA

DEPARTMENT OF ELECTRICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY DELHI

JULY 2025

Wound Rotor Induction Machine for Medium Voltage Applications fed From Series-Connected Inverter Modules

by

APURVA VERMA

Department of Electrical Engineering

Submitted

in partial fulfillment of the requirements of the degree of Doctor of Philosophy

to the

INDIAN INSTITUTE OF TECHNOLOGY DELHI

JULY 2025

Dedicated to ... Mummy Papa and Bhai

Certificate

This is to certify that the thesis entitled **"Wound Rotor Induction Machine for Medium Voltage Applications fed From Series-Connected Inverter Modules"**, submitted by **Apurva Verma** to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy** in the Department of Electrical Engineering, is a record of the original, bona fide research work carried out by her under my supervision and guidance. The thesis has reached the standards fulfilling the requirements of the regulations related to the award of the degree.

The results contained in this thesis have not been submitted in part or in full to any other University or Institute for the award of any degree or diploma to the best of our knowledge.

Date:

Place:

Prof. Amit Kumar Jain
Department of Electrical Engineering,
Indian Institute of Technology Delhi.

Acknowledgements

First and foremost, I would like to express my heartfelt gratitude to my thesis supervisor, Prof. Amit Kumar Jain, for giving me the opportunity to pursue my Ph.D. under his guidance. I am deeply thankful for his unwavering support, insightful feedback, and continuous encouragement throughout the research journey. His expertise and thoughtful suggestions played a pivotal role in shaping the direction and quality of this work. His guidance in academic as well as non-academic matters, motivated me and provided me strength during challenging times. It has been a privilege to work and learn under his mentorship.

I would also like to thank my SRC members, Prof. M. Veerachary and Prof. Sumit Pramanick, for their time, constructive criticism, and encouragement, which greatly enhanced the quality of this thesis work.

I would like to express my sincere gratitude to my seniors, especially Dr. Nikhil Krishna Bajjuri, Dr. Navneet Vaishnav and Dr. Cheshta Jain, for their generous help in clarifying concepts, troubleshooting technical issues, and providing insights that strengthened my research. I wish to express my appreciation for my colleagues and juniors Mr. Shayak Choudhary, Mr. Ruttala Sanakar Rao, Mr. Subhasis Nayak and Mr. Vaibhav Bhardwaj, for time to time technical discussions, which gave me different perspective to look into things. The enlightening conversations with Mr. Himanshu Swami and Dr. Durgesh Banchhor will always be memorable. I owe a special thanks to Ms. Keerthi R. Gopan and Mr. Sumit Singh for their cooperation and support. I also express my appreciation to my former research colleagues and seniors Dr. Prasun Mishra, Dr. Kapil Sharma, Dr. Khushboo Kumari, Dr. Rahul Sharma, Dr. Nidhi Bisht, Dr. Martin Cheerangal Joy, and Dr. Amir Rafiq. I am thankful to my juniors Mrs. Saumya Tripathi, Mr. Shashank Pannikar, Mr. Pranav Narkhede, Mr. Indrasis Roy, Mr. Surajit Saha, Mr. Abhishek, Mr. Arjun, and other labmates for their assistance and for contributing to a lively and productive work environment.

I am especially grateful to my friend Ms. Shipra Sinha for her unwavering emotional support throughout this journey. She has been a pillar of strength during times of stress and doubt, always offering encouragement and comfort when I needed it most. I also thank Mr. Manas Mishra, Dr. Nidhi Gupta, and my senior and dear friend Dr. Cheshta Jain for their friendship and presence through both the highs and lows. Their belief in me even when I couldn't see the finish line, kept me going.

Last but not the least, I am grateful to my parents, Mr. Akhil Kishore Verma and Mrs. Usha Verma, for having their trust in me and giving me the freedom to follow my passion. Their efforts, prayers and sacrifices made it possible to successfully complete this endeavour. I am indebted to my brother Mr. Kshitij Verma for his constant support and encouragement. Despite being the younger sibling, he shouldered all family responsibilities with patience and dedication during the course of my research. His selflessness has been a cornerstone of this achievement. I extend my gratitude to all other family members for their cooperation and understanding throughout this journey.

Thank you all for being an integral part of this experience and for your invaluable contributions to my academic and personal growth.

Abstract

This thesis presents a novel Wound Rotor Induction Machine (WRIM)-based topology designed for medium-voltage (MV) motoring and generating applications. Unlike the conventional approach where the WRIM is supplied by Parallel-Connected Inverter Modules (P.C.I.M.), the proposed topology employs Series-Connected Inverter Modules (S.C.I.M.). This series connection at the inverter dc-links results in a high-voltage dc-link, making the topology well-suited for high-voltage dc (HVDC) transmission applications.

A comprehensive control scheme is developed for deploying the proposed topology in Doubly-Fed Induction Generator (DFIG)-dc applications, operating it either as a voltage generation system or when interfaced with a constant-voltage dc grid. In both scenarios, the mid-point of the series-connected dc-link remains floating. To address this, the proposed control strategy incorporates a unique feature of mid-point voltage regulation to ensure stable and efficient power generation. The control methodology is validated through experimental results, demonstrating its effectiveness for DFIG-dc applications.

Additionally, the thesis proposes a control approach for using the topology in motor drive applications, covering both configurations — where the dc-link mid-point is either connected to the neutral point of a three-level Neutral Point Clamped (3L-NPC) Front-End Converter (FEC), or left floating. In the latter case, a thorough analysis of mid-point voltage imbalance during four-quadrant operation (forward motoring, forward braking, reverse motoring, and reverse braking) is carried out. A key contribution of this work is the formulation of a unified control approach that actively regulates the mid-point voltage across all the four operating modes ensuring reliable and stable drive operation.

Further, the thesis introduces a novel dual-Direct Current Control (DCC) technique, based on three-level hysteresis controllers applied to the stator and rotor current components. This approach eliminates the need for PI-controllers, thereby reducing the dependency on machine parameters. The method delivers fast dynamic performance comparable to Direct Torque Control (DTC), without requiring torque estimation — overcoming challenges related to torque estimation under specific operating conditions, as discussed in the later part of the thesis.

Two variants of the DCC strategy are explored. In the first, three-level hysteresis control is applied to the $\alpha\beta$ components of the current, and this method is experimentally

validated on the proposed WRIM drive topology fed from S.C.I.M. In the second variant, the hysteresis controller operates on the flux-oriented dq components of current, and this scheme is experimentally validated (in the later part of the thesis) for the conventional WRIM drive topology fed from P.C.I.M.

In addition to this, the thesis explores an optimized and fault-tolerant operation of the conventional drive topology based on WRIM fed from P.C.I.M. The optimized mode of operation offers lesser system losses leading to better efficiency, thermal performance and reliability. The proposed solutions of optimized and fault-tolerant operation are supported by detailed comparative analysis, thermal simulations using PLECS, and experimental validations, establishing their effectiveness and efficiency for industrial drive applications.

सारांश

यह अनुसंधान कार्य एक नवीन वाउंड रोटर इंडक्शन मशीन (WRIM) आधारित टोपोलॉजी प्रस्तावित करता है, जिसे मध्य-वोल्टेज (MV) स्तर के मोटर चालित (motoring) एवं विद्युत उत्पादन (generating) अनुप्रयोगों के लिए अभिकल्पित किया गया है। पारंपरिक विन्यास, जिसमें WRIM को पैरेलल-कनेक्टेड इन्वर्टर मॉड्यूल्स (P.C.I.M.) से आपूर्ति की जाती है, के विपरीत यह प्रस्तावित संरचना सीरीज-कनेक्टेड इन्वर्टर मॉड्यूल्स (S.C.I.M.) का समावेश करती है। इन्वर्टर डीसी-लिंक्स का श्रेणीबद्ध संयोजन एक उच्च-वोल्टेज डीसी लिंक को जन्म देता है, जिससे यह टोपोलॉजी उच्च-वोल्टेज डीसी (HVDC) पारेषण प्रणालियों हेतु अत्यंत उपयुक्त सिद्ध होती है।

इस संरचना के डबली-फेड इंडक्शन जनरेटर (DFIG)-डीसी अनुप्रयोगों में कार्यान्वयन के लिए एक समन्वित नियंत्रण पद्धति विकसित की गई है, जो इसे या तो एक स्वतंत्र डीसी वोल्टेज जनरेशन प्रणाली के रूप में अथवा एक नियत-वोल्टेज डीसी ग्रिड से योजित अवस्था में क्रियान्वित करने की क्षमता प्रदान करती है। दोनों ही स्थितियों में, सीरीज-कनेक्टेड डीसी लिंक का मध्य बिंदु 'फ्लोटिंग' अवस्था में रहता है। इस मध्य बिंदु वोल्टेज में संभावित अस्थिरता को दूर करने हेतु, प्रस्तावित नियंत्रण पद्धति में एक समर्पित मध्य-बिंदु वोल्टेज नियमन तंत्र सम्मिलित किया गया है, जो प्रणाली की स्थिरता और शक्ति रूपांतरण की दक्षता सुनिश्चित करता है। प्रस्तुत विधि को प्रयोगात्मक रूप से सत्यापित किया गया है, जिससे इसकी प्रभावकारिता DFIG-डीसी अनुप्रयोगों हेतु प्रमाणित होती है।

इस अनुसंधान कार्य में प्रस्तावित टोपोलॉजी के मोटर ड्राइव अनुप्रयोगों में उपयोग के लिए भी एक नियंत्रण रणनीति प्रस्तुत की गई है, जो दो प्रकार के डीसी लिंक मध्य-बिंदु विन्यासों को संबोधित करती है — (i) जहाँ मध्य बिंदु को एक तीन-स्तरीय न्यूट्रल-पॉइंट क्लैम्प्ड (3L-NPC) फ्रंट-एंड कन्वर्टर (FEC) के न्यूट्रल पॉइंट से संयोजित किया गया है तथा (ii) जहाँ इसे फ्लोटिंग रखा गया है। फ्लोटिंग विन्यास की स्थिति में, चार-चतुर्थांश संचालन (अग्रगामी मोटरिंग, अग्रगामी ब्रेकिंग, प्रत्यागामी मोटरिंग तथा प्रत्यागामी ब्रेकिंग) के दौरान मध्य-बिंदु वोल्टेज असंतुलन का विश्लेषण प्रस्तुत किया गया है। इस कार्य का एक महत्त्वपूर्ण योगदान एक समेकित नियंत्रण ढांचे का प्रस्ताव है, जो समस्त परिचालन चतुर्थांशों में मध्य-बिंदु वोल्टेज का सक्रिय नियमन करता है, जिससे विश्वसनीय एवं स्थिर ड्राइव प्रदर्शन सुनिश्चित होता है।

अग्रतर, इस अनुसंधान कार्य में एक नवीन द्वैध-डायरेक्ट करंट कंट्रोल (Dual-DCC) तकनीक प्रस्तावित की गई है, जो स्टेटर तथा रोटर करंट के घटकों पर तीन-स्तरीय हिस्टेरेसिस नियंत्रकों का उपयोग करती है। यह तकनीक पारंपरिक PI नियंत्रकों की आवश्यकता को समाप्त करती है, जिससे मशीन पैरामीटर्स पर निर्भरता में कमी आती है। यह पद्धति डायरेक्ट टॉर्क कंट्रोल (DTC) के तुल्य गतिशील प्रदर्शन प्रदान करती है, किन्तु टॉर्क आकलन की आवश्यकता के बिना — जो विशेष परिचालन स्थितियों में टॉर्क आकलन से संबंधित जटिलताओं को निष्क्रिय करती है, जैसा कि अनुसंधान कार्य के उत्तरार्ध में विवेचित है।

DCC पद्धति के दो प्रकार इस अनुसंधान कार्य में विवेचनार्थ प्रस्तुत किए गए हैं। प्रथम संस्करण में, करंट के $\alpha\beta$ घटकों पर तीन-स्तरीय हिस्टेरेसिस नियंत्रण लागू किया गया है, जिसका प्रयोगात्मक सत्यापन प्रस्तावित WRIM ड्राइव टोपोलॉजी (S.C.I.M. से पोषित) पर किया गया है। द्वितीय संस्करण में, नियंत्रक करंट के फ्लक्स-उन्मुख dq घटकों पर कार्य करता है, जिसे पारंपरिक WRIM ड्राइव टोपोलॉजी (P.C.I.M. से पोषित) पर प्रयोगात्मक रूप से सत्यापित किया गया है।

अंततः, यह अनुसंधान कार्य WRIM पर आधारित पारंपरिक ड्राइव टोपोलॉजी (P.C.I.M. संचालित) के श्रेष्ठीकृत एवं फॉल्ट-टोलरेंट संचालन हेतु नवीन रणनीतियाँ प्रस्तुत करता है। श्रेष्ठीकृत संचालन विधि के माध्यम से प्रणालीगत हानियाँ न्यूनतम की जाती हैं, जिसके परिणामस्वरूप बेहतर ऊर्जा दक्षता, उन्नत थर्मल व्यवहार, तथा प्रणाली की दीर्घकालिक विश्वसनीयता प्राप्त होती है। प्रस्तावित रणनीतियों की प्रभावशीलता को तुलनात्मक विश्लेषण, PLECS आधारित थर्मल सिमुलेशन, एवं प्रयोगात्मक परीक्षणों द्वारा सत्यापित किया गया है, जिससे इनके औद्योगिक ड्राइव अनुप्रयोगों में उपयुक्तता की पुष्टि होती है।

Contents

Certificate i

Acknowledgements ii

Abstract iv

Contents ix

List of Figures xv

List of Tables xxi

Abbreviations xxiii

Symbols xxvii

1 Introduction 1
- 1.1 General Background of WRIM . . . 1
- 1.2 Literature Survey . . . 2
  - 1.2.1 Conventional WRIM Topologies for Generating and Motoring Applications . . . 2
  - 1.2.2 Control of WRIM Based DFIG-dc Topologies for Generating Applications . . . 5
  - 1.2.3 Control of WRIM Based Drive Topology for Motoring Applications . . . 6
  - 1.2.4 Performance Optimization and Fault-Tolerant Operation . . . 8
- 1.3 Research gap . . . 10
- 1.4 Scope and Contribution . . . 12
  - 1.4.1 Proposal of a Medium Voltage WRIM fed From Series-Connected Inverter Modules for Motoring and Generating Applications . . . 12

1.4.2 Control of the WRIM fed From Series-Connected Inverter Modules for Medium Voltage Generating Applications 13
1.4.3 Control of the WRIM fed From Series-Connected Inverter Modules for Medium Voltage Motoring Applications 14
1.4.4 Optimized and Fault-Tolerant Operation of the Conventional WRIM Drive fed From Parallel-Connected Inverter Modules 15
1.5 Thesis Organisation 16

2 A WRIM fed From Series-Connected Inverter Modules for Connection to Medium Voltage AC/DC Grids 19
2.1 Conventional WRIM Based DFIG-dc Topologies for WECS 20
2.2 Proposed WRIM fed From Series-Connected Inverter Modules for WECS and its Comparison With Conventional Topologies 23
2.3 Conventional WRIM Based Industrial Drive Topologies 28
2.4 Proposed WRIM fed From Series-Connected Inverter Modules for Industrial Drive Systems and its Comparison With Conventional Topologies 30
2.4.1 Loss-Analysis of the Proposed and the Conventional WRIM-Based Drive Topologies 32
2.5 Conclusion 36

3 Control of the WRIM fed From Series-Connected Inverter Modules for Medium Voltage DFIG-DC Applications 39
3.1 Modelling and Phasor Analysis of WRIM in Generating Mode 40
3.1.1 Modelling of WRIM in Magnetizing Current Oriented Reference Frame 40
3.1.2 Modelling of WRIM in Stator and Rotor Current Oriented Reference Frames 43
3.2 Control Scheme for the Proposed DFIG-dc Based Voltage Generation System 45
3.2.1 DC-Link Voltage Regulation (V_{dc}) 46
3.2.2 DC-Link Current Supply (i_{dc}) 48
3.2.3 Generation of Current References for Current-Oriented-Control (COC) 48
3.2.4 DC-Link Voltage and Current Controller Design 50
3.2.4.1 Design of Current Controller (G_{ci}) 52
3.2.4.2 Design of Voltage Controller (G_{cv}) 53
3.2.5 DC-Link Voltage Balancing ($\Delta V_{dc} \rightarrow 0$) 54
3.2.5.1 Voltage Equalizer-I (ΔK_m) 55
3.2.5.2 Voltage Equalizer-II ($\Delta \omega_s$) 55
3.2.5.3 Sequence of operation of VE-I and VE-II 56
3.2.6 Experimental Results 56
3.2.6.1 DC-Link Voltage Build-up During Starting 57
3.2.6.2 Step Change in DC-Link Power Demand 58
3.2.6.3 Step Change in DC Voltage Reference $\boldsymbol{V_{dc}^*}$ 58
3.2.6.4 Variation in Input Speed $\boldsymbol{\omega_m}$ 59

3.2.6.5 Voltage Balancing Using Voltage Equalizers (VEs) 60
3.3 Control Scheme for the Proposed DFIG-dc System Connected to Constant Voltage DC-Grid 61
3.3.1 Experimental Results 64
3.3.1.1 Step Change in Torque Reference 64
3.3.1.2 Input Speed Variation 65
3.4 Conclusion 66

4 Control of the WRIM fed From Series-Connected Inverter Modules for Medium Voltage Motor Drive Applications **69**
4.1 Phasor Analysis of WRIM in Motoring Mode 70
4.2 Control of the Proposed WRIM Drive System With Mid-point Connection . 71
4.2.1 Dual-Direct Current Control (Dual-DCC) 72
4.2.2 Generation of Current Vector References 73
4.2.3 Estimation of Rotor Position 74
4.2.4 Stator and Rotor Frequency Profile 76
4.2.5 Hysteresis Control 76
4.2.6 Comparison of the Proposed Control Technique With the Existing Techniques 80
4.2.7 Grid Side Control 82
4.2.7.1 Calculation of Grid Voltage Angle θ_g 83
4.2.7.2 Voltage Balancing Algorithm 84
4.2.8 Experimental Results 86
4.2.8.1 Drive Performance During Speed Transients 87
4.2.8.2 Drive Performance With Step Change in Load 89
4.2.8.3 Steady State Drive Performance and its Comparison With Parallel Connected DC-Link Drive Topology 89
4.2.8.4 DC-Link Currents During Speed and Load Transients 91
4.2.8.5 Harmonic Spectra of Stator, Rotor and Grid Currents . . . 92
4.3 Control of the Proposed WRIM Drive System Without Mid-point Connection 93
4.3.1 Control Scheme 94
4.3.2 Voltage Balancing in Four-quadrant Operation 95
4.3.2.1 First Quadrant: Forward Motoring 96
4.3.2.2 Fourth Quadrant: Forward Braking 97
4.3.2.3 Third Quadrant: Reverse Motoring 98
4.3.2.4 Second Quadrant: Reverse Braking 98
4.3.3 Comparison of Control Schemes 100
4.3.4 Experimental Results 100
4.3.4.1 Four-quadrant Operation at No-Load 100
4.3.4.2 Step Change in Mechanical Load 101
4.3.4.3 DC-link Currents During Speed and Load Transients 102
4.4 Conclusion 103

5 Optimized and Fault-Tolerant Operation of the WRIM Drive fed From Parallel-Connected Inverter Modules 105
5.1 Control Philosophy . . . 106
5.1.1 Optimized Operation . . . 106
5.1.2 Fault-Tolerant Operation . . . 107
5.2 Control Strategy . . . 109
5.3 Results and Discussion . . . 111
5.3.1 Operation with Optimized Frequency Profile . . . 111
5.3.2 Power Loss Variation in the SQIM and WRIM Modes . . . 112
5.3.3 Fault-tolerant operation . . . 113
5.4 Conclusion . . . 117

6 Conclusions and Scope of Future Work 119
6.1 General . . . 119
6.2 Summary of the Present Work . . . 120
6.3 Scope of Future Work . . . 121

References 123

A System Parameters and Experimental Setup 135
A.1 System Parameters . . . 135
A.2 Detailed Discussion of Experimental Setup . . . 135
A.2.1 Motoring Application . . . 136
A.2.2 Generating Application . . . 138

B Investigation on Torque Estimation Techniques in Wound Rotor Induction Machine 143
B.1 System Description . . . 144
B.1.1 WRIM Description . . . 144
B.1.1.1 Voltage Expressions: . . . 144
B.1.1.2 Flux Expressions: . . . 144
B.1.1.3 Frequency Expressions: . . . 145
B.1.2 WRIM Operations . . . 145
B.2 Electromagnetic Torque Estimations . . . 146
B.3 Analysis on Torque Estimations and Simulation Results . . . 149
B.3.1 Zero Speed Full Torque Operation . . . 149
B.3.1.1 With Torque Control . . . 149
B.3.1.2 With Current Control . . . 151
B.3.2 Assessing Low Frequency Oscillations . . . 153
B.3.2.1 With Current Control . . . 153
B.3.2.2 With Torque Control . . . 153

B.4 Experimental Results 155
B.4.1 Results on ZSFT in current Control 155
B.5 Conclusion 157

C Flux-oriented *dq*-based Direct Current Control of the WRIM Drive fed From Parallel-Connected Inverter Modules 159
C.1 Machine Model in Rotor Flux Oriented Reference Frame 160
C.2 Proposed Control Technique 161
C.3 Simulation Results 164
C.4 Experimental Results 166
C.5 Conclusion 167

List of Patent and Publications 169

Biography 171

List of Figures

1.1 Conventional (a) Dual-VSI DFIG-dc topology for generating applications and (b) DI-WRIM topology for motoring applications. 3
1.2 Proposed WRIM fed from series-connected inverter modules for (a) generating applications and (b) motoring applications. 12

2.1 Various topologies for DFIG-dc systems 20
2.2 Detailed diagram of the proposed dual-VSI DFIG-dc topology having WRIM fed from S.C.I.M. 23
2.3 Experimental results showing (a) power, (b) dc-link voltages, (c) dc-link currents and (d) machine currents in the (i) proposed and (ii) conventional topology. Time scale=2s/div. 27
2.4 Single line diagram representing the evolution of the proposed industrial drive topology. 28
2.5 Detailed diagram of the proposed WRIM drive topology fed from S.C.I.M. . 30
2.6 (a) 2L FEC in the conventional drive. (b) 3L-NPC FEC in the proposed drive. 33

3.1 (a) Per-phase equivalent circuit and phasor diagram in magnetizing current *dq*-reference frame of WRIM for (b) sub-synchronous and (c) super-synchronous generation mode. 41
3.2 Phasor diagram of WRIM in magnetizing current *dq*-reference frame, representing the stator and rotor current oriented reference frames. 43
3.3 WRIM based DFIG-dc system, fed from S.C.I.M., working as voltage generation system. 45
3.4 Control scheme for the proposed WRIM based DFIG-dc system when working as a voltage generation system. 50
3.5 Block diagram for the dc-link voltage and current control system 51
3.6 Flow chart illustrating the sequence of operation for Voltage Equalizers. . . . 56
3.7 Experimental results showing system performance during voltage build-up at starting. Scale: V_{dc}^{*},V_{dc},V_{dcs},V_{dcr} = 80V/div, i_{m}^{*} = 1.9A/div, M_{d} = 10Nm/div, i_{sd1}^{*}, i_{sd1}, i_{rd2}^{*}, i_{rd2}, i_{sq1}, i_{rq2} = 2.97A/div, $\sin\delta$, $\cos\delta$ = 0.6 p.u./div, V_{sd1}^{*}, V_{sq1}^{*}, V_{rd2}^{*}, V_{rq2}^{*} = 92V/div, V_{s1}, V_{r1} = 142V/div, i_{s1}, i_{r1} = 5A/div, Time = 2s/div. 57

3.8 Experimental results showing system performance with step change in dc-link power demand. Scale: V_{dc} = 80V/div, V_{dcs},V_{dcr} = 40V/div, i_{dc} = 1.28A/div, i_m^* = 1.9A/div, M_d = 10Nm/div, i_{sd1}^*, i_{sd1}, i_{rd2}^*, i_{rd2}, i_{sq1}, i_{rq2} = 2.97A/-div, $\sin\delta$, $\cos\delta$ = 0.24 p.u./div, i_{s1}, i_{s2}, i_{r1}, i_{r2} = 5A/div, Time = 2s/div (a),(b),(c),(d),(e), 100ms/div e(i),e(ii). 58

3.9 Experimental results illustrating controller performance for step change in V_{dc} and variation in input speed ω_m. Scale: V_{dc}^*,V_{dc},V_{dcs},V_{dcr} = 80V/div, i_{dc} = 1.28A/div, i_m^* = 1.9A/div, i_{sd1}^*, i_{sd1}, i_{rd2}^*, i_{rd2}, i_{sq1}, i_{rq2} = 2.97A/div, $\sin\delta$, $\cos\delta$ = 0.24 p.u./div, i_{s1}, i_{r1} = 5A/div, ω_m = 39.26 rad/s/div, Time = 2s/div (a),(b),(c),(d),(e),(f),(g),(h), 500ms/div c(i),c(ii),g(i),g(ii). 59

3.10 Experimental results showing voltage balancing when $V_{dcs} < V_{dcr}$. Scale: V_{dcs}, V_{dcr}, V_{dc} = 80V/div, ΔK_m = 0.35 unit/div, $\Delta\omega_s$ = 12 elec. rad/s/div, i_{sd1}, i_{rd2} = 2.97A/div, ω_s, ω_r = 39.26 elec. rad/s/div, P_{dc} = 192W/div, i_{s1}, i_{r1} = 5A/div, Time = 2s/div a(i), b(i), c(i), d(i), e(i), 200ms/div a(ii), 500ms/div b(ii), c(ii), d(ii), 50ms/div e(ii), e(iii). 60

3.11 WRIM based DFIG-dc system, fed from S.C.I.M., connected to constant voltage dc-grid. 61

3.12 Control scheme for the proposed WRIM based DFIG-dc system when connected to constant voltage dc-grid. 62

3.13 Experimental results validating the control scheme for proposed WRIM based DFIG-dc system when connected to constant voltage dc-grid. Scale: i_{s1}, i_{s2}, i_{r1}, i_{r2} = 5 A/div, ω_m = 35.68 mech. rad/s, i_{arm} = 4.5 A/div, V_{dcs}, V_{dcr} = 68 V/div, ΔK_m = 0.6 unit/div, $\Delta\omega_s$ = 10.6 elec. rad/s, ω_s, ω_r = 71.5 elec. rad/s, i_{sd1q1}^*, i_{sd1q1}, i_{rd2q2}^*, i_{rd2q2} = 3.96 A/div, M_d^*, M_d = 5 Nm/div, $\sin\delta$, $\cos\delta$ = 1.11 units/div, i_{Load}, i_{grid}, i_{DFIG} = 1A/div and Time = 5s/div (a)-(h), 50ms/div (f1). 65

3.14 Experimental results validating the control scheme for proposed WRIM based DFIG-dc system when connected to constant voltage dc-grid. Scale: i_{s1}, i_{s2}, i_{r1}, i_{r2} = 5 A/div, ω_m = 35.68 mech. rad/s, i_{arm} = 4.5 A/div, V_{dcs}, V_{dcr} = 68 V/div, ΔK_m = 0.6 unit/div, $\Delta\omega_s$ = 10.6 elec. rad/s, ω_s, ω_r = 71.5 elec. rad/s, i_{sd1q1}^*, i_{sd1q1}, i_{rd2q2}^*, i_{rd2q2} = 3.96 A/div, M_d^*, M_d = 5 Nm/div, $\sin\delta$, $\cos\delta$ = 1.11 units/div, i_{Load}, i_{grid}, i_{DFIG} = 1A/div and Time = 5s/div (a)-(h), 50ms/div (f1),(f2). 66

4.1 (a) Per-phase equivalent circuit and phasor diagram in magnetizing current dq-reference frame of WRIM for (b) sub-synchronous and (c) super-synchronous motoring mode. 70

4.2 WRIM fed from S.C.I.M. for motor drive application with mid-point at dc-link connected to the neutral point of the 3L-FEC 71

4.3 Position-sensorless Dual-Direct Current Control (Dual-DCC) scheme for WRIM drive fed from S.C.I.M. with dc-link mid-point connected to the neutral point of 3L-NPC FEC. 72

4.4 Phasor diagram in stator reference frame. 73

4.5 (a) Error vector $\vec{i_{s,err}} = \vec{i_s^*} - \vec{i_s}$. (b) Three-phase and $\alpha\beta$-Components of $\vec{i_{s,err}}$. 77

4.6 Active and zero voltage vectors in $\alpha\beta$-reference frame. 77
4.7 (a) Implementation of 3L Hysteresis controller. (b) Virtual voltage vectors in $\alpha\beta$-reference frame. 78
4.8 Grid Side control of 3L-FEC [92]. 82
4.9 PLL: Generation of grid voltage angle θ_g [92]. 83
4.10 Voltage balancing Algorithm [93]. 84
4.11 Results illustrating (a) the response of speed controller and variation of ω_s, ω_r, (b) response of grid side voltage controller, current controller and VBA, in the proposed drive, when speed changes from 0 to 2p.u., 2p.u. to -2p.u. and then -2p.u. to 2p.u. (c) Transient response of stator and (d) rotor hysteresis current controllers at time instants $t = t1$ and (e), (f) $t = t2$ respectively. . . 87
4.12 Results illustrating (a) the response of speed controller, (b) grid side voltage and current controllers, (c) variation of measured stator, rotor A-phase currents and (d) measured grid side line currents, in the proposed drive, when 0.5p.u. load is applied at $t = t1$ and removed at $t = t2$. 88
4.13 Steady state results at 2p.u. speed and 0.5p.u. load showing (a) stator, rotor currents (b) grid currents (c) grid voltage and currents in the proposed drive topology; and (d) stator, rotor currents (e) grid currents (f) grid voltage and currents in the conventional drive topology. 90
4.14 DC-link currents in (a) proposed drive and (b) conventional drive when speed changes from 0 to 2p.u., 2p.u. to -2p.u.; and DC-link currents in (c) proposed drive and (d) conventional drive when 0.5 p.u. load is applied at t=0s. . . . 91
4.15 Measured waveforms and harmonic spectra of (a) stator current, (b) rotor current and (c) grid current in the proposed series-connected and (d), (e), (f) the conventional parallel-connected dc-link drive topology respectively, when the WRIM is operating at 2 p.u. speed and 0.5 p.u. mechanical load. 92
4.16 WRIM fed from S.C.I.M. with floating dc-link mid-point for motor drive application. 93
4.17 Control block-diagram for WRIM based drive system fed from S.C.I.M. with floating mid-point. 95
4.18 Operation of voltage equalizers in all the four operating modes. 96
4.19 Detailed operation of Voltage Equalizers 99
4.20 Experimental results showing system performance during four-quadrant operation of the drive with floating mid-point. Scale: V_{dcs},V_{dcr} = 36 V/div, ω_m^*, ω_m = 78.5 mech. rad/s/div, K_m = 0.6 p.u./div, $\Delta\omega_s$ = 18.5 elec. rad/s, M_d = 10Nm/div, $\sin\delta$, $\cos\delta$ = 1.2 p.u./div, $i^*_{s\alpha\beta}$, $i_{s\alpha\beta}$, $i^*_{r\alpha_r\beta_r}$, $i_{r\alpha_r\beta_r}$ = 5.94A/div, ω_s, ω_r = 78.5 elec. rad/s, Time = 10s/div (a)-(f), 1s/div (d2)-(d3), (f1)-(f3). 101
4.21 Experimental results showing system performance during four-quadrant operation of the drive with floating mid-point. Scale: V_{dcs},V_{dcr} = 36 V/div, ω_m = 39.25 mech. rad/s, K_m = 0.6 p.u./div, $\Delta\omega_s$ = 18.5 elec. rad/s, M_d = 12.3 Nm/div, $\sin\delta$, $\cos\delta$ = 0.6 p.u./div, $i^*_{s\alpha\beta}$, $i_{s\alpha\beta}$, $i^*_{r\alpha_r\beta_r}$, $i_{r\alpha_r\beta_r}$ = 5.94A/div, ω_s, ω_r = 39.25 elec. rad/s, Time = 5s/div (a)-(f), 200 ms/div (d1)-(d2), (f1)-(f2). 102

4.22 Variation of dc-link currents in the system during speed and load transients. Scale: V_{dcs},V_{dcr}= 36 V/div, ω_m^*, ω_m= 78.5 mech. rad/s/div (a), 39.25 mech. rad/s (b), M_d= 12.3 Nm/div, i_{dcs}, i_{dcr}, i_{dc}= 2 A/div, Time=10s/div (a) and 5s/div (b). 103

5.1 Conventional WRIM drive fed from P.C.I.M. 106
5.2 Frequency profile in (a) the conventional super-SMM and (b) the proposed optimized operation of WRIM drive fed from P.C.I.M. 107
5.3 Speed-torque characteristics representing Constant Torque (CT) region and Field Weakening (FW) region of SQIM drive and WRIM (fed from P.C.I.M.) drives. 108
5.4 Control scheme with optimized frequency profile and fault-tolerant feature for the WRIM drive fed from P.C.I.M. 109
5.5 Phasor diagram in magnetizing current reference frame. 110
5.6 Experimental results illustrating optimized operation of WRIM drive fed from P.C.I.M. in all four-quadrants. Scale: MODE = 1.25 units/div, ω_m = 46.2 mech. rad/s, ω_s, ω_r = 87.3 elec. rad/s, i_m = 6.58 A/div, M_d = 4.975 Nm/div, $\sin\delta$, $\cos\delta$ = 1.25 p.u./div, i_{sd1q1}, i_{rd2q2} = 3.96 A/div, i_{s12}, i_{r12} = 2 A/div, Time = 10 s/div. 112
5.7 Results illustrating power loss variation with respect to switching frequency F_{sw} and Load Torque M_{Load} 113
5.8 Simulation result illustrating the drive performance in the event of fault in stator-VSC at operating point A. 114
5.9 Simulation result illustrating the drive performance in the event of fault in stator-VSC at operating point B. 115
5.10 Simulation result illustrating the drive performance in the event of fault in stator-VSC at operating point D. 116

A.1 Block diagram of the complete setup for motoring application. 137
A.2 Block diagram of the complete setup for generating application. 139
A.3 Photograph of experimental setup for motoring application. 141
A.4 Photograph of experimental setup for generating application. 142

B.1 A Double-Inverter-fed WRIM drive. 144
B.2 Power flow and phasor diagram in stationary $\alpha\beta$-reference frame for (a) sub-synchronous motoring and (b) super-synchronous motoring modes. 146
B.3 Block diagram of employed control schemes while estimating EM torque. (a) From [40]. (b) From [41]. 148
B.4 Simulation results for ZSFT operation with control technique of Fig. B.3(b) and four EM torque estimations, M_{d1}, M_{d2}, M_{d3} and M_{d4}. (a) Speed controller responses . (b) Variation of ω_s, ω_r with ω_e i.e. given frequency profile. [(c), (e), (g), and (i)] Actual variation of ω_s, ω_r. [(d), (f), (h) and (j)] EM torque estimation profiles. 150

B.5 Simulation result comparing M_{d1}, M_{d2}, M_{d3}, and M_{d4} together for ZSFT operation with control technique of Fig. B.3(b). 151
B.6 Simulation results showing stator and rotor currents for similar operations as in Fig. B.4 for torque estimations using (a) M_{d1}, (b) M_{d2} (c) M_{d3}, and (d) M_{d4} technique. 151
B.7 Simulation results for ZSFT operation with control technique of Fig. B.3(a). (a) Speed controller response. (b) Variation of ω_s, ω_r with ω_e. Torque estimations using: (c) M_{d1}, (d) M_{d2} (e) M_{d3}, and (f) M_{d4} technique. 152
B.8 Simulation results showing (a) i_s, (b) i_r and torque estimation using [(c), (d), (e), (f)] M_{d1}, M_{d2}, M_{d3} and M_{d4} techniques with control of Fig. B.3(a), when LFH of 0.01 p.u. 5Hz, 0.1 p.u. 5Hz and 0.1 p.u. 10Hz is injected at t=3s, t=4s and t=5s respectively [ω_m=1.5 p.u., M_L=0.75 p.u.]. 154
B.9 Simulation results showing the reference torque and estimated torque employing [(a), (b), (c), (d)] M_{d1}, M_{d2}, M_{d3} and M_{d4} techniques with control of Fig B.3(b), when LFH of 0.01 p.u. 5Hz, 0.1 p.u. 5Hz and 0.1 p.u. 10Hz is injected at t=3s, t=4s and t=5s respectively. [ω_m=1.5 p.u., M_L=0.75 p.u.] . 154
B.10 Experimental results with employed control technique of Fig. B.3(a), showing (a), (b) ω_m controller response, (c) estimated torques M_{d1}, M_{d2}, (d) M_{d3}, M_{d4} and (e), (f) corresponding i_s and i_r, when ω_m changes from (I.) zero to 70 mech. rad/s and (II.) 70 mech. rad/s to zero respectively with load. 156

C.1 WRIM drive fed from parallel connected inverter modules. 159
C.2 Phasor diagram in stator reference frame 160
C.3 (a) Proposed Control Algorithm for WRIM drive fed from P.C.I.M. (b) Voltage vectors in $\alpha\beta$-plane divided in 24 sectors 161
C.4 Implementation of 3L-hysteresis comparator 162
C.5 Simulation results illustrating (a) speed controller performance (b) variation of ω_s, ω_r (c) i_{mr} controller performance (d) i_{sD2} and (e) i_{sQ2} controller performance and (f) i_{rD2} and i_{rQ2} waveform for the proposed control algorithm when the speed reference is changes from 0 to 1.3 p.u. to -1.3 p.u. 164
C.6 Simulation results illustrating (a) speed controller performance (b) variation of ω_s, ω_r (c) i_{mr} controller performance (d) i_{sD2} and (e) i_{sQ2} controller performance and (f) i_{rD2} and i_{rQ2} waveform for the proposed control algorithm when 0.9 p.u. load is applied at 1.3 p.u. speed. 165
C.7 Simulation results showing i_{sQ2} waveform while switching with (a) TABLE-C.1 and (b) TABLE-C.2. 166
C.8 Simulation results showing i_{mr} waveform while switching with TABLE-C.1 (green colour) and TABLE-C.2 (blue colour). 166
C.9 Experimental results illustrating (a) the performance of stator current controllers during flux build-up (b) the performance of speed controller and variation of ω_s, ω_r when speed changes from 0 to 70 elec. rad/s to -70 elec. rad/sec (c) the measured steady state stator and rotor currents at ω_e=70 elec. rad/sec 167

List of Tables

2.1 Comparative Analysis of DFIG-DC Topologies 24
2.2 Comparison of Proposed Topology With Existing Topology . . 31
2.3 System Data for Loss Calculation 34
2.4 Losses in the Conventional and Proposed Topology 36

3.1 Illustration of operation of Voltage Equalizers 55

4.1 ST for 2L-Hysteresis Comparator on $i_{s,err_{\alpha\beta}}$ 77
4.2 ST for 3L-Hysteresis Comparator on $i_{s,err_{\alpha\beta}}$ 79
4.3 ST for 3L-Hysteresis Comparator on $i_{s,err_{\alpha\beta}}$ Including Virtual Voltage Vectors (VVs) 80
4.4 Comparison of Proposed Technique With Existing Technique . . 81
4.5 Comparison of control schemes 100

5.1 System operation in pre-fault and post-fault conditions 108
5.2 High Power Machine Rating 112

A.1 System Ratings 135
A.2 System Electrical and Mechanical Parameters 136
A.3 System Rating for Drive Topologies 137
A.4 System Rating for DFIG-DC Topologies 139

C.1 Switching Table using Active Voltage Vectors 163
C.2 Modified Switching Table using Active and Virtual Voltage Vectors 163

Abbreviations

IM	**I**nduction **M**achine
SQIM	**S**quirrel **C**age **I**nduction **M**achine
WRIM	**W**ound **R**otor **I**nduction **M**achine
DI-WRIM	**D**ouble **I**nverter fed **W**ound **R**otor **I**nduction **M**achine
DFIM	**D**oubly **F**ed **I**nduction **M**achine
DFIG	**D**oubly **F**ed **I**nduction **G**enerator
OE-DFIG	**O**pen **E**nded **D**oubly **F**ed **I**nduction **G**enerator
WECS	**W**ind **E**nergy **C**onversion **S**ystem
FOC	**F**lux **O**riented **C**ontrol
COC	**C**urrent **O**riented **C**ontrol
DCC	**D**irect **C**urrent **C**ontrol
DDCC	**D**ual **D**irect **C**urrent **C**ontrol
DTC	**D**irect **T**orque **C**ontrol
DDTC	**D**ual **D**irect **T**orque **C**ontrol
MPC	**M**odel **P**redictive **C**ontrol
MTPA	**M**aximum **T**orque **P**er **A**mpere
PI	**P**roportional **I**ntegral
PI-R	**P**roportional **I**ntegral **R**esonant
sub-SMM	sub - **S**ynchronous **M**otoring **M**ode
super-SMM	super - **S**ynchronous **M**otoring **M**ode
LFH	**L**ow **F**requency **H**armonics
ZSFT	**Z**ero **S**peed **F**ull **T**orque
S-VSI	**S**tator-**V**oltage **S**ource **I**nverter
R-VSI	**R**otor-**V**oltage **S**ource **I**nverter
VSC	**V**oltage **S**ource **C**onverter
NP	**N**eutral **P**oint

NPC	**N**eutral **P**oint **C**lamped
FEC	**F**ront **E**nd **C**onverter
PWM	**P**ulse **W**idth **M**odulated
THD	**T**otal **H**armonic **D**istortion
MV	**M**edium **V**oltage
AC/ac	**A**lternating **C**urrent
DC/dc	**D**irect **C**urrent
HVDC	**H**igh **V**oltage **D**irect **C**urrent
P.C.I.M.	**P**arallel **C**onnected **I**nverter **M**odules
S.C.I.M.	**S**eries **C**onnected **I**nverter **M**odules
VV	**V**oltage **V**ector
ST	**S**witching **T**able
LPF	**L**ow **P**ass **F**ilter
PLL	**P**hase **L**ocked **L**oop
UPF	**U**nity **P**ower **F**actor
VBA	**V**oltage **B**alancing **A**lgorithm
VE	**V**oltage **E**qualizer
FM	**F**orward **M**otoring
FB	**F**orward **B**raking
RM	**R**everse **M**otoring
RB	**R**everse **B**raking
CT	**C**onstant **T**orque
FW	**F**ield **W**eakening
FT	**F**ault **T**olerant
EM	**E**lectro- **M**agnetic
EMF	**E**lectro- **M**otive **F**orce
EV	**E**lectric **V**ehicle
CW	**C**lock **W**ise
CCW	**C**ounter **C**lock **W**ise
WT	**W**ind **T**urbine
UC	**U**ncontrolled **C**onverter
CC	**C**ontrolled **C**onverter
HCC	**H**alf **C**ontrolled **C**onverter
OEW	**O**pen **E**nded **W**inding
IGBT	**I**nsulated **G**ate **B**ipolar **T**ransistor

RMS	**R**oot **M**ean **S**quare

Symbols

Symbol	Definition	Unit
System parameters and the associated variables		
R_s, R_r	Stator and rotor resistance per phase	Ω
L_s, L_r	Stator and rotor self inductance per phase	H
L_{ls}, L_{lr}	Stator and rotor leakage inductance per phase	H
L_m	Magnetising inductance	H
σ_s, σ_r	Stator and rotor leakage factor	
σ	Total leakage factor	
P	Number of poles	
J	Moment of inertia	$Kg - m^2$
B	Coefficient of friction	$Nm/(rad/sec)$
M_d	Electromagnetic torque of the motor	Nm
R_a	Armature winding resistance of DC-machine	Ω
L_a	Armature winding inductance of DC-machine	H
L_g	Grid interfacing inductance per phase	H
Voltage, Current and Flux variables		
V_s	Stator terminal voltage	V
V_r	Rotor terminal voltage	V
V_g	Grid voltage	V
V_i	Grid-VSI/FEC ac-output voltage	V
e_s	Stator back-EMF	V
e_r	Rotor back-EMF	V
i_s	Stator current	A
i_r	Rotor current	A

i_g	Grid current	A
ψ_s	Stator flux	Wb
ψ_r	Rotor flux	Wb
ψ_m	Air-gap flux	Wb
i_{mr}	Rotor-flux magnetizing current	A
i_m	Air-gap flux magnetizing current	A

DC-link variables

V_{dc}	Total dc-link voltage	V
V_{dcs}	dc-link voltage of stator-VSC/VSI	V
V_{dcr}	dc-link voltage of rotor-VSC/VSI	V
i_{dc}	Total dc-link current	A
i_{dcs}	dc-link current of stator-VSC/VSI	A
i_{dcr}	dc-link current of rotor-VSC/VSI	A
i_{dcFEC}	dc-link current of FEC	A

Power variables

P_{con}	Conduction Loss	W
P_{sw}	Switching Loss	W
P_{ag}	Total air-gap power	W
P_{ag_s}	Part of air-gap power, associated with stator-circuit	W
P_{ag_r}	Part of air-gap power, associated with rotor- circuit	W
P_{loss_s}	Power loss in the stator-circuit	W
P_{loss_r}	Power loss in the rotor-circuit	W
P_{dcs}	Power available at the dc-link of stator-VSI/VSC	W
P_{dcr}	Power available at the dc-link of rotor-VSI/VSC	W
P_{dc}	Power available at the final dc-link	W
P_{in}	Input Power	W
P_{out}	Output Power	W
P_{mech}	Mechanical Power at the shaft	W

Constants

K_t	Torque constant	

K_m	Fraction of magnetizing current shared from stator side	

Mathematical operators

p	d/dt operator	

Reference frames

$\alpha - \beta$	Stator reference frame with α-axis along stator A-phase axis	
$\alpha_r - \beta_r$	Rotor reference frame with α_r-axis along rotor A-phase axis	
$d - q$	Magnetizing current reference frame with d-axis along magnetizing current phasor $\vec{i_m}$	
$d1 - q1$	Stator current reference frame with $d1$-axis along stator current phasor $\vec{i_s}$	
$d2 - q2$	Rotor current reference frame with $d2$-axis along rotor current phasor $\vec{i_r}$	
$d' - q'$	Grid-voltage reference frame with q'-axis along grid voltage phasor $\vec{v_g}$	
$D2 - Q2$	Rotor flux reference frame with $D2$-axis along rotor flux phasor $\vec{\psi_r}$	

Angles

ϵ	Angle between stator and rotor A-phase axis	*elec.rad*
θ_m	Angle of $\bar{\psi_m}$ or $\bar{i_m}$ with respect to stator A-phase axis	*elec.rad*
θ_s	Angle of $\bar{i_s}$ with respect to stator A-phase axis	*elec.rad*
θ_r	Angle of $\bar{i_r}$ with respect to rotor A-phase axis	*elec.rad*
θ_{rs}	Angle of $\bar{i_{rs}}$ with respect to stator A-phase axis	*elec.rad*
δ	Angle between stator $\bar{i_s}$ and rotor $\bar{i_r}$ current phasor	*elec.rad*
δ_r	Angle between rotor current $\bar{i_r}$ and air-gap flux magnetizing current $\bar{i_m}$ phasor	*elec.rad*
ρ	Angle of $\bar{\psi_r}$ with respect to stator A-phase axis	*elec.rad*
θ_g	Angle of d'-axis with respect to stator A-phase axis	*elec.rad*

ϕ_s	Angle between stator voltage and stator current phasors	$elec.rad$
ϕ_r	Angle between rotor voltage and rotor current phasors	$elec.rad$

Angular frequencies

ω_g	AC-grid supply frequency	$elec.rad/sec$
ω_s	Stator supply frequency w.r.t. stator reference frame	$elec.rad/sec$
ω_r	Rotor supply frequency w.r.t. rotor reference frame	$elec.rad/sec$
ω_e	Rotor angular velocity	$elec.rad/sec$
ω_m	Rotor angular velocity	$mech.rad/sec$

Subscripts

"rs"	Rotor variable referred to $(\alpha - \beta)$ frame
"sr"	Stator variable referred to $(\alpha_r - \beta_r)$ frame
"x_{max}"	represents maximum value of a quantity 'x'
"x_{min}"	represents minimum value of a quantity 'x'
"x_{rated}"	represents rated value of a quantity 'x'
"x_{ref}"	represents reference value of a quantity 'x'
"x_{err}"	represents error between reference and actual value of a quantity 'x'
"x_y"	represents y-axis component of the quantity 'x'
"x_{abc}"/"x_{123}"	represents three-phase components of the quantity 'x'

Superscripts

"x^*"	represents reference value of quantity 'x'
"$\bar{x}$"	represents space phasor of quantity 'x'

Inverter parameters

F_{sw}	Switching frequency	Hz
T_{sw}	Switching time period	$sec.$

S_{135}	Switching signals of three upper switches of the staor-VSC/VSI
R_{135}	Switching signals of three upper switches of the rotor-VSC/VSI

Controller parameters

K_{pc}, K_{ic}	Proportional and integral gain of current PI-controller
K_{pv}, K_{iv}	Proportional and integral gain of V_{dc} PI-controller
G_{inv}	Inverter transfer function
G_{vf}	Feedback path gain of V_{dc} feedback
G_{ci}	Transfer function of current PI-controller
G_{cv}	Transfer function of V_{dc} PI-controller
G_{OL-i}	Open-loop transfer function of inner current loop
G_{CL-i}	Closed-loop transfer function of inner current loop
G_{OL-v}	Open-loop transfer function of outer voltage loop
ω_{gc-i}, PM_i	Gain cross-over frequency and phase margin of inner current loop
ω_{gc-v}	Gain cross-over frequency of outer V_{dc} loop