

Fault Tolerant Topologies for Cascaded H-Bridge Converter

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submitted

in fulfillment of the requirement of the degree of Doctor of Philosophy

to the



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To my teachers, family, and friends...

CERTIFICATE

This is to certify that the thesis entitled, “**Fault Tolerant Topologies for Cascaded H-Bridge Converter**” being submitted by **Mrs. Nidhi Bisht (Entry No. : 2017EEZ8156)** to the Department of Electrical Engineering, Indian Institute of Technology Delhi, for the award of the degree of Doctor of Philosophy, is a record of bonafide research work carried out by her under my guidance and supervision.

Mrs. Nidhi Bisht has fulfilled the requirements for the submission of this thesis, which to my knowledge has reached the requisite standard. The results obtained herein have not been submitted in part or in full to any other University or Institute for the award of any degree.

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ABSTRACT

Cascaded H-bridge converter is one of the most widely accepted multilevel converter topologies in the medium-voltage and high-power applications due to its modular structure, easy scalability, and fault tolerant ability. It is already used in various applications such as solar photo voltaic (PV) systems, wind energy conversion, railway traction, motor drives, battery energy storage system, static synchronous compensators (STATCOM), etc.

CHB converter is a prevalent topology for medium-voltage high-power STATCOM applications where only reactive power is exchanged with the grid. However, due to the large number of power devices in CHB converter, the possibility of a devices failure in the converter is high. Hence, fault-tolerant operation of the CHB converter is essential in STATCOM application where continuous reactive power support is necessary for maintaining the voltage stability of the grid. Several works have been done to operate the CHB STATCOM with a fault condition inside the converter. However, a suitable fault tolerant technique to sustain multiple number of faulty devices or cells inside the CHB STATCOM is not explored much. Additionally, the CHB STATCOM converter poses a challenge of cell capacitor voltage balancing during post-fault conditions. In this work, a multiple-fault-tolerant topology for CHB STATCOM is proposed which uses a redundant module in the event of a fault inside the converter. A novel geometrical approach is proposed which helps to maintain the pre-fault angle between output voltages of the remaining healthy cells and the line currents, so that zero average active power flow is ensured. Maintaining zero average active power guarantees the balanced capacitor voltages of the remaining healthy CHB cells. In addition to this geometrical technique maintains the capacitor voltage of the redundant cell. The post-fault voltage and reactive power capability of the CHB STATCOM is maintained same as pre-fault conditions.

Further, a fundamental zero-sequence voltage based new approach is proposed to operate the remaining healthy cells and the redundant cell during post-fault conditions. This approach is based on the reactive power distributions during post-fault conditions of the CHB STATCOM. In addition to this, the output voltages of the CHB STATCOM are maximized by adding the harmonic voltages to the fundamental output voltages of the CHB cells. It helps in optimally utilizing the DC-link voltages of the cell capacitors. During post-fault conditions, natural cancellation of harmonic voltages does not happen due to unequal number of operating cells. Hence, a harmonic compensation method is reported in this thesis where the redundant cell generates compensatory harmonic voltages for restricting the flow of the harmonics into the grid currents.

One important aspect of CHB STATCOM is to continuously operate it even with a single or multiple number of faulty cells until the next schedule maintenance is done for the converter. During this time interval, the faulty CHB STATCOM must sustain the grid disturbances and support the grid with the reactive power injection and at the same maintain its cell capacitor balanced. The grid disturbances may be caused due to a variety of reasons such as grid voltage sag due to grid faults or unbalanced loading etc. During such unbalanced grid conditions, due to cross interaction of the positive and negative sequence voltages and currents, per phase average active powers are not always zero. This non-zero average active power diverges the capacitor voltages of phases of CHB STATCOM and may lead to disconnection of the converter due to overvoltage trip. The operation of the CHB STATCOM becomes more challenging when there is a fault inside the converter. To operate the faulty CHB STATCOM stably during grid unbalanced conditions, a coordinated control is proposed in this thesis. By virtue

of the proposed control, the faulty CHB STATCOM supports the unbalanced grid with positive as well as negative sequence currents and maintains its cell capacitor voltages balanced.

Similar to CHB STATCOM, the fault tolerant feature of the CHB converter is highly attractive for medium voltage (MV) drives where continuity of service is essential. With the available fault tolerant techniques, although the CHB converter can offer continuity of operation at reduced voltage, the performance of the motor is degraded due to its power and speed limitations. Hence, in this work, a fault tolerant topology of CHB converter is reported where redundant cells are used to maintain the rated voltage of the CHB converter even with multiple number of faulty cells. The redundant cells are inserted to the power circuit of the converter during post-fault conditions and fed power from the existing pre-charge windings which remain dormant after starting up process of the drive. Hence, by utilizing these pre-charge windings along with the redundant cells, a multiple-fault-tolerant topology of CHB converter is developed for MV drive applications.

सारांश

कैस्केड एच-ब्रिज कनवर्टर अपनी मॉड्यूलर संरचना, आसान स्केलेबिलिटी और दोष सहन करने की क्षमता के कारण मध्यम-वोल्टेज और उच्च-शक्ति अनुप्रयोगों में सबसे व्यापक रूप से स्वीकृत मल्टीलेवल कनवर्टर टोपोलॉजी में से एक है। इसका उपयोग पहले से ही विभिन्न अनुप्रयोगों में किया जाता है जैसे कि सौर फोटो वोल्टिक (पीवी) सिस्टम, पवन ऊर्जा रूपांतरण, रेलवे ट्रेक्शन, मोटर ड्राइव, बैटरी ऊर्जा भंडारण प्रणाली, स्टेटिक सिंक्रोनस कम्पेसाटर (स्टेटकॉम), आदि।

सीएचबी कनवर्टर मध्यम-वोल्टेज उच्च-शक्ति स्टेटकॉम अनुप्रयोगों के लिए एक प्रचलित टोपोलॉजी है जहां ग्रिड के साथ केवल प्रतिक्रियाशील शक्ति का आदान-प्रदान किया जाता है। हालाँकि, सीएचबी कनवर्टर में बड़ी संख्या में पावर डिवाइस होने के कारण, कनवर्टर में डिवाइस के विफल होने की संभावना अधिक होती है। इसलिए, स्टेटकॉम एप्लिकेशन में सीएचबी कनवर्टर का दोष-सहिष्णु संचालन आवश्यक है जहां ग्रिड की वोल्टेज स्थिरता बनाए रखने के लिए निरंतर प्रतिक्रियाशील बिजली समर्थन आवश्यक है। कनवर्टर के अंदर खराबी की स्थिति में सीएचबी स्टेटकॉम को संचालित करने के लिए कई कार्य किए गए हैं। हालाँकि, सीएचबी स्टेटकॉम के अंदर कई दोषपूर्ण उपकरणों या कोशिकाओं को बनाए रखने के लिए एक उपयुक्त दोष सहिष्णु तकनीक की ज्यादा खोज नहीं की गई है। इसके अतिरिक्त, सीएचबी स्टेटकॉम कनवर्टर पोस्ट-फॉल्ट स्थितियों के दौरान सेल कैपेसिटर वोल्टेज संतुलन की चुनौती पेश करता है। इस कार्य में, सीएचबी स्टेटकॉम के लिए एक बहु-दोष-सहिष्णु टोपोलॉजी प्रस्तावित है जो कनवर्टर के अंदर गलती की स्थिति में एक अतिरिक्त मॉड्यूल का उपयोग करती है। एक नवीन ज्यामितीय दृष्टिकोण प्रस्तावित है जो शेष स्वस्थ सेल के आउटपुट वोल्टेज और लाइन धाराओं के बीच प्री-फॉल्ट कोण को बनाए रखने में मदद करता है, ताकि शून्य औसत सक्रिय बिजली प्रवाह सुनिश्चित हो सके। शून्य औसत सक्रिय शक्ति बनाए रखने से शेष स्वस्थ सीएचबी कोशिकाओं के संतुलित संधारित्र वोल्टेज की गारंटी मिलती है। इसके अलावा ज्यामितीय तकनीक निरर्थक सेल के कैपेसिटर वोल्टेज को बनाए रखती है। सीएचबी स्टेटकॉम की पोस्ट-फॉल्ट वोल्टेज और प्रतिक्रियाशील बिजली क्षमता को प्री-फॉल्ट स्थितियों के समान बनाए रखा जाता है।

इसके अलावा, शेष स्वस्थ सेल और निरर्थक सेल को पोस्ट-फॉल्ट स्थितियों के दौरान संचालित करने के लिए एक मौलिक शून्य-अनुक्रम वोल्टेज आधारित नया दृष्टिकोण प्रस्तावित है। यह दृष्टिकोण सीएचबी स्टेटकॉम की पोस्ट-फॉल्ट स्थितियों के दौरान प्रतिक्रियाशील बिजली वितरण पर आधारित है। इसके अलावा, सीएचबी स्टेटकॉम के आउटपुट वोल्टेज को सीएचबी सेल के मौलिक आउटपुट वोल्टेज में हार्मोनिक वोल्टेज जोड़कर अधिकतम किया जाता है। यह सेल कैपेसिटर के डीसी-लिंक वोल्टेज का इष्टतम उपयोग करने में मदद करता है। खराबी के बाद की स्थितियों के दौरान, ऑपरेटिंग सेल की असमान संख्या के कारण हार्मोनिक वोल्टेज का प्राकृतिक रद्दीकरण नहीं होता है। इसलिए, इस थीसिस में एक हार्मोनिक क्षतिपूर्ति विधि की सूचना दी गई है जहां अतिरिक्त सेल ग्रिड धाराओं में हार्मोनिक्स के प्रवाह को प्रतिबंधित करने के लिए प्रतिपूरक हार्मोनिक वोल्टेज उत्पन्न करता है।

सीएचबी स्टेटकॉम का एक महत्वपूर्ण पहलू एक या एकाधिक संख्या में दोषपूर्ण कोशिकाओं के साथ भी इसे लगातार संचालित करना है जब तक कि कनवर्टर के लिए अगला शेड्यूल रखरखाव नहीं हो जाता। इस समय अंतराल के दौरान, दोषपूर्ण सीएचबी स्टेटकॉम को ग्रिड से कनेक्शन रखना होगा और प्रतिक्रियाशील पावर इंजेक्शन के साथ ग्रिड का समर्थन करना होगा और साथ ही इसके सेल कैपेसिटर को संतुलित बनाए रखना होगा। ग्रिड में गड़बड़ी कई कारणों से हो सकती है जैसे ग्रिड दोष या असंतुलित लोडिंग आदि के कारण ग्रिड वोल्टेज में कमी। ऐसी असंतुलित ग्रिड स्थितियों के दौरान, सकारात्मक और नकारात्मक अनुक्रम वोल्टेज और धाराओं के क्रॉस इंटरैक्शन के कारण, प्रति चरण औसत सक्रिय होता है।

शक्तियाँ सदैव शून्य नहीं होतीं। यह गैर-शून्य औसत सक्रिय शक्ति सीएचबी स्टेटकॉम के चरणों के संधारित्र वोल्टेज को अलग कर देती है और ओवरवॉल्टेज ट्रिप के कारण कनवर्टर के वियोग का कारण बन सकती है। कनवर्टर के अंदर कोई खराबी होने पर सीएचबी स्टेटकॉम का संचालन अधिक चुनौतीपूर्ण हो जाता है। ग्रिड असंतुलित स्थितियों के दौरान दोषपूर्ण सीएचबी स्टेटकॉम को स्थिर रूप से संचालित करने के लिए, इस थीसिस में एक समन्वित नियंत्रण प्रस्तावित है। प्रस्तावित नियंत्रण के आधार पर, दोषपूर्ण सीएचबी स्टेटकॉम सकारात्मक और नकारात्मक अनुक्रम धाराओं के साथ असंतुलित ग्रिड का समर्थन करता है और इसके सेल कैपेसिटर वोल्टेज को संतुलित रखता है।

सीएचबी स्टेटकॉम के समान, सीएचबी कनवर्टर की दोष सहनशील सुविधा मध्यम वोल्टेज (एमवी) ड्राइव के लिए अत्यधिक आकर्षक है जहां सेवा की निरंतरता आवश्यक है। उपलब्ध दोष सहिष्णु तकनीकों के साथ, हालांकि सीएचबी कनवर्टर कम वोल्टेज पर संचालन की निरंतरता प्रदान कर सकता है, इसकी शक्ति और गति सीमाओं के कारण मोटर का प्रदर्शन खराब हो जाता है। इसलिए, इस कार्य में, सीएचबी कनवर्टर की एक दोष सहिष्णु टोपोलॉजी की सूचना दी गई है जहां एकाधिक संख्या में दोषपूर्ण कोशिकाओं के साथ भी सीएचबी कनवर्टर के रेटेड वोल्टेज को बनाए रखने के लिए अतिरिक्त कोशिकाओं का उपयोग किया जाता है। दोष के बाद की स्थितियों के दौरान अतिरिक्त कोशिकाओं को कनवर्टर के पावर सर्किट में डाला जाता है और मौजूदा प्री-चार्ज वाइंडिंग्स से बिजली आपूर्ति की जाती है जो ड्राइव की प्रक्रिया शुरू करने के बाद निष्क्रिय रहती हैं।

TABLE OF CONTENTS

Certificate.....	i
Acknowledgements	iii
Abstract	v
Table of Contents	ix
List of Figures	xv
List of Tables	xxi
Chapter 1 Introduction	1
1.1 Background and Motivation	1
1.2 Research Gap Identification	2
1.3 Objectives of the Work	3
1.4 Outline of the Thesis.....	4
Chapter 2 Literature Review.....	7
2.1 Introduction	7
2.2 Multilevel Converter Topologies	7
2.2.1 Neutral Point Clamped (NPC) Converter	8
2.2.2 Flying Capacitor (FC) Converter	9
2.2.3 Cascaded H-bridge (CHB) Converter	9
2.2.4 Modular Multilevel Converter (MMC)	10
2.3 Carrier-based PWM Technique for CHB Converter	11
2.3.1 Phase-shifted PWM Technique	11
2.3.2 Level-shifted PWM Technique	13
2.4 Applications of CHB Converter	15
2.5 Fault-Tolerant Operation of CHB Converter	17
2.5.1 Bypassing of faulty cell	18
2.5.2 Fault-Tolerant Techniques and Their Limitations for CHB based Drives.....	19
2.5.3 Fault-Tolerant Techniques and Their Limitations for Grid connected CHB STATCOM.....	22
2.6 Operation of Grid-connected CHB Converter with Unbalanced Grid	23
2.7 Summary	26
Chapter 3 A Multiple-Fault-Tolerant Topology of Cascaded H-Bridge STATCOM	27
3.1 Introduction	27
3.2 System Configuration	28
3.2.1 Operation of Proposed Topology during Normal or Pre-fault Condition	29

3.2.2	Transition from Pre-fault to Post-fault Condition	30
3.2.3	Operation of Proposed Topology during Post-fault Condition	30
3.3	Active and Reactive Power Distribution during Post-fault Conditions	36
3.3.1	Active Power Calculation	38
3.3.2	Reactive Power Calculation	39
3.4	Designing of Redundant Cell Capacitor	40
3.5	Closed-loop Control of the CHB STATCOM Topology.....	42
3.5.1	Overall Voltage and Reactive Power Control	47
3.5.2	Inter-cluster Controller	48
3.5.3	Intra-cluster Controller	48
3.5.4	Redundant Cell Voltage Control	50
3.6	Comparison with Other Fault-Tolerant Topologies.....	51
3.7	Simulation Results	52
3.7.1	Case 1: Single faulty bypassed cell, (4,4,3) condition	52
3.7.2	Case 2: Multiple faulty bypassed cells, (4,3,2) condition	53
3.8	Experimental Results	55
3.8.1	Case 1: Single faulty bypassed cell, (4,4,3) condition	56
3.8.2	Case 2: Multiple faulty bypassed cells, (4,3,2) condition	59
3.8.3	Transition from Pre-fault to Post-fault Condition.....	60
3.9	Summary	61
Chapter 4 Maximizing the Post-fault Output Voltages of the CHB STATCOM using Harmonic Compensation Technique		63
4.1	Introduction.....	63
4.2	Expression of Reactive Powers during Pre-fault Condition.....	64
4.3	Injection of FZSV during Post-fault Conditions.....	65
4.3.1	Expression of FZSV during Post-fault Conditions.....	66
4.3.2	Operation of the Redundant cell during Post-fault Conditions	67
4.4	Maximizing the Post-fault Output Voltages from CHB Phases and the Redundant Cell.....	69
4.4.1	Optimizing the DC-link Voltage Requirement from the Redundant Cell	69
4.4.2	Addition of Harmonic Voltages during Pre-fault Condition	71
4.4.3	Addition of Harmonic Voltages during Post-fault Conditions	71
4.4.4	Comparison of Line Voltages with Sine-PWM and the Proposed Harmonic Compensation Technique.....	75
4.5	Closed-loop Control of the Proposed Technique	75
4.6	Simulation Results	77
4.6.1	Pre-fault Healthy Condition	77
4.6.2	Single Faulty Cell Condition	78
4.6.3	Multiple Faulty Cells Condition	78
4.6.4	Transient Results during Grid Voltage Dip and Phase Change	79

4.7	Experimental Results	81
4.7.1	Single Faulty Cell Condition	82
4.7.2	Multiple Faulty Cells Condition	83
4.7.3	Comparison of the Line Voltages with Sine-PWM and the Proposed Harmonic Compensation Technique.....	84
4.8	Summary	85
Chapter 5	Positive Sequence Current Injection from Faulty CHB STATCOM during Grid Voltage Sag	87
5.1	Introduction	87
5.2	Power Flow Analysis for a CHB STATCOM.....	88
5.2.1	Expression of Powers with Balanced Grid Voltages.....	88
5.2.2	Expression of Powers during Asymmetrical Grid Voltage Sag.....	89
5.2.3	Addition of Zero Sequence Voltage to the CHB STATCOM during Asymmetrical Grid Voltage Sag	92
5.3	Working of a Faulty CHB STATCOM with Grid Voltage Sag	93
5.3.1	With Balanced Grid Voltages	93
5.3.2	With Grid Voltage Sag	95
5.4	Closed-loop Control with Grid Voltage Sag.....	99
5.4.1	Overall Voltage and Sequence Component Current Controllers	99
5.4.2	Inter-cluster and Intra-cluster Controller with Grid Voltage Sag	100
5.4.3	Post-fault Controller for CHB Cells and Redundant Cell	101
5.5	Simulation Results	102
5.5.1	50% Voltage Sag in V_{ga} with (4,4,3) Fault Condition	102
5.5.2	50% Voltage Sag in V_{ga} with (4,3,2) Fault Condition	103
5.6	Experimental Results	104
5.6.1	50% Voltage Sag in V_{ga} with (4,4,3) Fault Condition	105
5.6.2	50% Voltage Sag in V_{ga} with (4,3,2) Fault Condition	107
5.6.3	Transient Results from Grid Voltage Sag Condition	108
5.7	Summary.....	109
Chapter 6	Injection of Positive and Negative Sequence Currents to the Unbalanced Grid from Faulty CHB STATCOM	111
6.1	Introduction	111
6.2	Operation of Healthy CHB STATCOM with Unbalanced Grid Conditions	112
6.2.1	Addition of Zero-sequence Voltage with Injection of Both Sequence Currents	113
6.2.2	Limitation of Injecting the Negative Sequence Currents from CHB STATCOM	115
6.3	Operation of Faulty CHB STATCOM with Unbalanced Grid Conditions	117
6.3.1	Post-fault Control of Faulty CHB STATCOM with Unbalanced Grid	117
6.3.2	Post-fault Control of Faulty CHB STATCOM with Balanced Grid	120
6.4	Capacitor Voltage Balancing of the CHB Cells and Redundant Cell	121

6.5	Closed-loop Control for Unbalanced Grid Conditions.....	123
6.5.1	Sequence Voltages and Currents Extraction	123
6.5.2	Overall Voltage and Decoupled Current Controllers	123
6.5.3	Inter-cluster and Intra-cluster Controller	124
6.5.4	Redundant Cell Controller	124
6.6	Simulation Results	125
6.6.1	With Single Faulty Cell in One Phase	125
6.6.2	With Multiple Faulty Cells in Two Phases	126
6.7	Experimental Results	127
6.7.1	With Single Faulty Cell in One Phase	127
6.7.2	With Multiple Faulty Cells in Two Phases	129
6.8	Summary	130
 Chapter 7 A Multiple-Fault-Tolerant Topology of CHB Converter for Motor Drives using Existing Pre-charge Windings		131
7.1	Introduction	131
7.2	Conventional CHB Converter with Pre-charge Winding	132
7.3	Circuit Configuration of the Proposed Topology of CHB Converter	133
7.3.1	DC-link Voltage of the Redundant Cells.....	134
7.3.2	Sequence of Operation	134
7.4	Analysis during Pre-fault and Post-fault Conditions	135
7.4.1	Pre-fault or Normal Operation of the Converter	136
7.4.2	Post-fault Operation of the Converter	136
7.5	Clamping Technique and Extended Power Factor Angle of Operation during Post-fault Conditions	139
7.6	Simulation Results	142
7.6.1	Multiple Fault Conditions	143
7.6.2	Whole Leg Bypass Condition	144
7.7	Experimental Results	145
7.7.1	Single Fault Condition	146
7.7.2	Multiple Faults Condition	146
7.7.3	Whole Leg Bypass Condition	148
7.8	Summary	148
 Chapter 8 Development of the Downscaled Experimental Setup in the Laboratory		151
8.1	Intelligent Power Module (IPM) based H-bridge Cells	151
8.1.1	Signal side Components	152
8.1.2	Power side Components	153
8.1.3	Protection Circuit Components.....	154
8.2	DC-link Capacitor Board	155

8.3	Voltage and Current Sensor Boards	156
8.4	Control Architecture and Realization	157
8.5	Experimental Test Setup for CHB STATCOM Topology.....	159
8.6	Experimental Test Setup for CHB Converter for Drive Applications	160
8.7	Summary	161
Chapter 9	Conclusions and Future Scopes of the Work	163
9.1	Conclusion	163
9.2	Future Scope	165
	Bibliography	167
	List of Publications	177

LIST OF FIGURES

2.1	Circuit diagram of (a) neutral point clamped (NPC) converter, (b) flying capacitor (FC) converter, (c) cascaded H-bridge (CHB) converter.....	8
2.2	Circuit diagram of a three-phase cascaded H-bridge converter.....	10
2.3	Circuit diagram of a three-phase modular multilevel converter (MMC).....	11
2.4	Phase-shifted PWM for two cells of CHB converter.....	12
2.5	Generating PWM signals for two cells of CHB converter using Phase-shifted PWM technique.....	12
2.6	Cell and pole voltage outputs for CHB converter with phase-shifted PWM their corresponding harmonic spectrum.....	13
2.7	Level-shifted PWM for two cells of CHB converter.....	14
2.8	Generating PWM signals for two cells of CHB converter using Level-shifted PWM technique.....	14
2.9	Cell and pole voltage outputs for CHB converter with level-shifted PWM their corresponding harmonic spectrum.....	15
2.10	CHB converter based MV drive with multi-winding transformer.....	16
2.11	CHB converter based grid connected PV systems.....	16
2.12	CHB converter for STATCOM applications.....	17
2.13	An H-bridge cell with bypass switch arrangement.....	18
2.14	Circuit diagram of a CHB converter with bypass mechanism for drive applications.....	19
2.15	(a) An example of multiple faulty bypassed cells inside the CHB converter, (b) unbalanced line voltage triangle formation with faulty cells, (c) balanced line voltage triangle formation with FPS method.....	20
2.16	Voltage versus fault duration LVRT curves for grid-connected converters connected to high-voltage grids in various grid codes.....	24
3.1	The proposed circuit topology of Cascaded H-bridge STATCOM, (a) during normal healthy condition, (b) during post-fault condition.....	28
3.2	Bypass switch mechanism for SW ₁ and SW ₂	28
3.3	(a) Phasor diagram during pre-fault balanced operation of the proposed CHB STATCOM, (b) phasor diagram for phase 'a' supplying lagging current, (c) phasor diagram for phase 'a' supplying leading current to the grid.....	30
3.4	Fault categories, (a) single fault condition, (b) multiple faults conditions.....	31
3.5	Post-fault operation of the proposed CHB STATCOM with (4,4,3) single fault condition....	32
3.6	Post-fault operation of the proposed CHB STATCOM with (4,3,2) multiple faults condition..	33
3.7	Post-fault phasor diagram for active and reactive power distribution of proposed CHB STATCOM.....	35
3.8	Block diagram for <i>dq</i> -current controller.....	43
3.9	Block diagram for average voltage controller.....	44
3.10	Block diagram for inter-cluster controller.....	45
3.11	Block diagram for redundant cell voltage controller.....	45

3.12	Overall block diagram of closed-loop control system of the proposed fault tolerant topology during pre-fault and post-fault conditions.....	46
3.13	Operation of different devices in a cell during charging and discharging periods.....	49
3.14	Status of the cells within LS-PWM technique.....	50
3.15	Individual cell voltage balancing for three cells in a phase by sorting algorithm and PWM (for $n_x = 3$ and $N = 4$).....	50
3.16	Simulation results: (a) reactive power to the grid, (b) reference signals for CHB, (c) reference signals for redundant cell, (d) capacitor voltages of CHB cells (e) capacitor voltage of redundant cell and voltage across bypass switch (SW_2), (f) output voltages of three phases of CHB, (g) output voltages across whole phase of the converter, (h) line currents to the grid.....	53
3.17	Simulation results for transition from lagging reactive powers to leading reactive power with (4,4,3) single fault and (4,3,2) multiple faults condition.....	54
3.18	Experimental setup and results for pre-fault (4,4,4) condition, (a) a picture of experimental setup, (b). average capacitor voltages of CHB phases, (50 V/div), (c). output voltages across three phases of CHB (200 V/div), (d). balanced line currents to the grid (5 A/div), (x-axis: 10msec/div).....	56
3.19	Experimental results with single fault: (4,4,3) (a). reference and actual values of active and reactive components of current (5 A/div), (b). reference signals for CHB (1 pu/div), (c). reference signals for redundant cell (1 pu/div), (x-axis: 10msec/div). (d). average capacitor voltages of CHB phases and redundant cell (50 V/div), (e). output voltages across three phases of CHB (200 V/div), (f). output voltages across the three phases of the redundant cell (100 V/div), (g). balanced line currents to the grid (5 A/div), (x-axis: 10msec/div).....	57
3.20	Voltage and current phasors from experimental setup for (4,4,3) single fault condition (a). for converter, (b). across the CHB phases, (c). for redundant cell, (d). for grid.....	58
3.21	Experimental results for transition from lagging reactive powers to leading reactive power with (4,4,3) single fault condition: (a). reactive powers, (b). reference and actual values of active and reactive components of current (5 A/div), (c). reference signals for CHB (1 pu/div), (d). reference signals for redundant cell (1 pu/div), (x-axis: 10msec/div). (e). average capacitor voltages of CHB phases and redundant cell (50 V/div), (f). output voltages across 'a' phase of CHB and redundant cell and line current (200 V/div), (50 V/div) and (10 A/div), (g). output voltages across 'a' phase of CHB and redundant cell and line current (200 V/div), (50 V/div) and (10 A/div), (h). output voltages across 'a' phase of CHB and redundant cell and line current (200 V/div), (50 V/div) and (10 A/div), (x-axis: 10msec/div).....	58
3.22	Experimental results with multiple faults (4,3,2), (a). reference and actual values of active and reactive components of current (5 A/div), (b). reference signals for CHB (1 pu/div), (c). reference signals for redundant cell (1 pu/div), (x-axis: 10msec/div), (d). average capacitor voltages of CHB phases and redundant cell (50 V/div), (e). output voltages across three phases of CHB (200 V/div), (f). output voltages across the three phases of the redundant cell (200 V/div), (g). balanced line currents to the grid (5 A/div), (x-axis: 10msec/div).....	59
3.23	Voltage and current phasors diagram from experimental setup for (4,3,2) single fault condition (a). for converter, (b). across the CHB phases, (c). for redundant cell, (d). for grid....	60
3.24	Transition from normal healthy (4,4,4) condition to single fault (4,4,3) condition: (a). output voltage across phase 'c' of CHB (200V/div), (b). redundant cell capacitor voltage (100V/div), (c). voltage across bypass switch (SW_2) (100V/div), (d) phase 'c' line current to the grid (5A/div).....	61
4.1	(a) Equivalent circuit diagram and (b) phasor diagram of grid connected CHB STATCOM during pre-fault condition.....	55
4.2	(a) Equivalent circuit diagram and (b) phasor diagram of grid connected CHB STATCOM during post-fault condition.....	56
4.3	Circuit diagram of proposed converter with redundant cell.....	58

4.4	Phasor diagram of the CHB STATCOM during post-fault conditions after insertion of the redundant cell.....	58
4.5	Relationship graph between DC-link voltage of the redundant cell, i.e., V_{dc}^r and modulation index (m) of CHB STATCOM.....	60
4.6	(a) An example for obtaining the output voltages ($V_a^{rr}, V_b^{rr}, V_c^{rr}$) for the redundant cell with lower DC-link voltage, (b) graph between V_{dc}^r and m before and after reducing the required DC-link voltage of the redundant cell.....	60
4.7	Block diagram for generating three phase reference signals for producing maximum output voltages across the CHB phases.....	62
4.8	Obtaining balanced maximum line voltages with (4,3,2) fault condition: (a) without and (b) with adding the proposed compensating harmonic voltages ($v_{x(h)}^r$) to the redundant cell.....	63
4.9	Block diagram for generating three phase reference signals for redundant cell with addition of compensatory harmonic voltages ($v_{a(h)}^{r*}, v_{b(h)}^{r*}, v_{c(h)}^{r*}$).....	63
4.10	Comparison of the proposed harmonic compensation technique with the sine-PWM method for (4,4,3) single fault condition.....	64
4.11	Block diagram for closed-loop control of CHB STATCOM (including redundant cell) with harmonic compensation technique.....	65
4.12	Simulation results for (4,4,4) healthy to (4,4,3) single fault condition (a) reactive power, (b) FZSV and modulating signals for CHB phases, (c) modulating signals for redundant cell, (d) capacitor voltages of H-bridge cells and (e) redundant cell, (f) output voltages across CHB phases, (g) 'a' phase output voltage of redundant cell, (h) reactive grid line currents.....	67
4.13	Simulation results (4,3,2) multiple faulty cells condition (a) reactive power, (b) FZSV and modulating signals for CHB phases, (c) modulating signals for redundant cell, (d) capacitor voltages of H-bridge cells and I redundant cell, (f) output voltages across CHB phases, (g) 'a' phase output voltage of redundant cell, (h) reactive grid line currents.....	68
4.14	Transient results for (4,4,3) fault condition under grid voltage variation: (a) grid voltages, (b) references for the CHB phases, (c) references for the redundant cell, (d) CHB and redundant cell capacitor voltages, (e) output voltages across the CHB phases, (f) grid line currents.....	69
4.15	Transient results for (4,4,3) fault under grid voltage phase change of $-\pi/6$: (a) grid voltages, (b) references for the CHB phases, (c) references for the reserved cell, (d) CHB and reserved cell capacitor voltages, (e) output voltages across the CHB phases, (f) grid line currents.....	70
4.16	Experimental results during (4,4,3) single fault condition, (a) dq -axis reference and actual currents (5A/div) (b) modulating reference signals for CHB phases (1 pu/div), (c) modulating reference signals for redundant cell (1 pu/div) (d), (e), (f) (i) output pole voltage of CHB phases (200 V/div), (ii) output voltage of the redundant cell (100 V/div), (iii) line current (10 A/div), (g) faulty phase 'c' output voltages (200 V/div) and grid line currents (10 A/div), (h) cell capacitor voltages (50 V/div), (x-axis scale: 10msec/div).....	71
4.17	Experimental results during (4,3,2) multiple faults condition, (a) dq -axis reference and actual currents (5A/div) (b) modulating reference signals for CHB phases (1 pu/div), (c) modulating reference signals for redundant cell (1 pu/div) (d), (e), (f) (i) output pole voltage of CHB phases (200 V/div), (ii) output voltage of the redundant cell (200 V/div), (iii) line current (10 A/div), (g) faulty phase 'c' output voltages (200 V/div) and grid line currents (10 A/div), (h) cell capacitor voltages (50 V/div), (x-axis scale: 10msec/div).....	72
4.18	Comparison of the proposed harmonic compensation technique with the sine-PWM method performed in the experimental setup for (4,4,3) single fault condition.....	73
5.1	Circuit diagram of a grid connected converter with balanced grid.....	77
5.2	Circuit diagram of grid connected CHB STATCOM with unbalanced grid, (a) positive-sequence network, (b) negative sequence network.....	78

5.3	Circuit diagram of the proposed CHB STATCOM with the redundant cell.....	82
5.4	Phasor diagram of the faulty CHB STATCOM with balanced grid voltages and single faulty cell in 'c' phase.....	82
5.5	Phasor diagrams of the faulty CHB STATCOM during grid voltage sag and single faulty cell in 'c' phase (a) positive sequence phasors, (b) negative sequence phasors, (c) zero sequence phasors, (d) total pole voltage phasors obtained by adding (a), (b) and (c).....	84
5.6	Phasor diagrams of the faulty CHB STATCOM during grid voltage sag and faulty cells in 'b' and 'c' phases (a) positive sequence phasors, (b) negative sequence phasors, (c) zero sequence phasors, (a) total pole voltage phasors obtained by adding (a), (b) and (c).....	86
5.7	Overall voltage and sequence component current controller.....	88
5.8	Inter-cluster and intra-cluster controller for CHB STATCOM.....	88
5.9	Post-fault controller for the CHB cells and the redundant cell.....	89
5.10	Simulation results with (4,4,3) fault condition: (a) grid phase voltages the grid, (b) reference signals for CHB, (c) reference signals for redundant cell, (d) capacitor voltages of CHB cells (e) capacitor voltage of redundant cell, (f) output pole voltages of three phases of CHB, (g) line currents to the grid.....	90
5.11	Simulation results with (4,3,2) fault condition: (a) grid phase voltages the grid, (b) reference signals for CHB, (c) reference signals for redundant cell, (d) capacitor voltages of CHB cells (e) capacitor voltage of redundant cell, (f) output pole voltages of three phases of CHB, (g) line currents to the grid.....	91
5.12	Experimental results for (4,4,3) fault condition with 50% voltage sag in V_{ga} : (a) reference signals and zero-sequence reference for the CHB cells (1 pu/div), (b) reference signals for the redundant cell (1 pu/div), (x-axis: 10msec/div).....	93
5.13	Experimental results for (4,4,3) fault condition with 50% voltage sag in V_{ga} : (a) average capacitor voltages (50 V/div), (b) pole voltages and redundant cell voltage (200 V/div and 100 V/div), (c) line currents (10 A/div), (x-axis: 10 msec/div).....	93
5.14	Experimental results for (4,3,2) fault condition with 50% voltage sag in V_{ga} : (a) reference signals and zero-sequence reference for the CHB cells (1 pu/div), (b) reference signals for the reserve cell (1 pu/div), (x-axis: 10msec/div).....	94
5.15	Experimental results for (4,3,2) fault condition with 50% voltage sag in V_{ga} : (a) average capacitor voltages (150 V/div), (b) pole voltages and reserve cell voltage (200 V/div), (c) line currents (10 A/div), (x-axis: 10 msec/div).....	95
5.16	Transient results with 50% voltage sag in V_{ga} : (a) before voltage sag, (b) during voltage sag, (c) after voltage sag, (x-axis: 1 sec/div, y-axis: (a) 200 V/div, (b) 50 V/div, (c) 10 A/div)....	95
5.17	Transient results with 50% voltage sag in V_{ga} : (a) before voltage sag, (b) during voltage sag, (c) after voltage sag, (x-axis: 1 sec/div, y-axis: (a) 200 V/div, (b) 50 V/div, (c) 10 A/div).....	96
6.1	Positive and negative sequence networks of grid connected CHB STATCOM converter.....	98
6.2	Phasor diagram for CHB STATCOM during unbalanced grid condition with addition of zero-sequence voltage.....	101
6.3	Variation in pole voltages with respect to I^n , other parameters are: $V_{ga}=0.5$ pu, $I^p = -0.8$ pu and $m_x=0.85$	102
6.4	Variations in three phase pole voltages of the CHB STATCOM with variation in V_{ga} and I^n keeping $I^p = -0.8$ pu & $m_x=0.85$	102
6.5	Post-fault phasor diagram of voltages across the CHB phases and redundant cell with faulty cells in all three phases.....	104
6.6	Post-fault phasor diagram of voltages across the CHB phases and redundant cell with faulty cells in: (a) two phases, (b) single phase.....	105

6.7	Post-fault phasor diagram of voltages across the CHB phases and redundant cell with balanced grid condition and faulty cells in 'c' phase.....	106
6.8	Overall control block diagram of the proposed post-fault control technique for CHB STATCOM with unbalanced grid conditions.....	109
6.9	Simulation results with single fault i.e. {4,4,3} condition: (a) grid phase voltages the grid, (b) positive and negative sequence reactive currents, (c) reference signals for CHB, (d) reference signals for reserve module, (e) capacitor voltages of CHB cells (f) capacitor voltage of reserve module, (g) output pole voltages of three phases of CHB, (h) line currents to the grid.....	111
6.10	Simulation results with multiple faults i.e. {4,3,2} condition: (a) grid phase voltages the grid, (b) positive and negative sequence reactive currents, (c) reference signals for CHB, (d) reference signals for reserve module, (e) capacitor voltages of CHB cells (f) capacitor voltage of reserve module, (g) output pole voltages of three phases of CHB, (h) line currents to the grid.....	112
6.11	Experimental results for {4,4,3} fault condition: (a) grid voltages (y-axis: 200 V/div), (b) reference and actual d and q axis positive and negative sequence reactive, (c) reference signals for the CHB phases, (d) reference signals for redundant cell (y-axis: 1 pu/div), (x-axis: 10msec/div).....	114
6.12	Experimental results for {4,4,3} fault condition: (a) capacitor voltages from a, b, c phase of CHB (20 V/div) and redundant cell (20 V/div), (b) output voltages across the CHB phases and redundant cell, (c) line currents (10 A/div), (x-axis: 10 msec/div).....	114
6.13	Experimental results for {4,3,2} fault condition: (a) grid voltages (y-axis: 200 V/div), (b) reference and actual d and q axis positive and negative sequence reactive, (c) reference signals for the CHB phases, (d) reference signals for redundant cell (y-axis: 1 pu/div), (x-axis: 10msec/div).....	115
6.14	Experimental results for {4,3,2} fault condition: (a) capacitor voltages from a, b, c phase of CHB (20 V/div) and redundant cell (30 V/div), (b) output voltages across the CHB phases and redundant cell, (c) line currents (10 A/div), (x-axis: 10 msec/div).....	115
7.1	Circuit diagram of a Cascaded H-bridge (CHB) converter with pre-charge winding.....	118
7.2	Proposed fault tolerant topology of CHB converter with pre-charge windings and gradually increasing low voltage auxiliary supply.....	119
7.3	Power circuit of the proposed converter during: (a) starting condition, (b) pre-fault or normal condition, (c) post-fault condition.....	121
7.4	Fault categories, (a) single, (b) multiple, (redundant cells are not shown).....	123
7.5	Waveforms for clamping technique during (5,5,3) post-fault condition.....	126
7.6	Block diagram of the clamping technique.....	126
7.7	Phasor diagram for the converter with fundamental zero-sequence voltage addition.....	127
7.8	Waveform of the proposed converter from starting to normal operation (with $k=2$) (a) capacitor voltages, (b) state of the main contactor, (c) pole voltages, (d) line voltages, (e) line currents.....	129
7.9	Simulation results of proposed topology: (a) reference voltage signals, (b) output voltages across healthy cells, (c) output voltages of redundant cells, (d) pole voltages across phases of converter, (e) zero-sequence voltage, (f) line voltages, (g) line current.....	131
7.10	Experimental setup and results: (a) pole voltages of three phases and load current during transition from normal healthy condition to $(n_a, n_b, n_c) = (4,4,3)$ i.e. single fault condition, (b) pole voltage of faulty phase 'c', DC- link voltages of normal and redundant cell and speed characteristic during transition from normal to single fault condition (c) pole voltages during $(n_a, n_b, n_c) = (4,4,3)$ fault (200 V/div), (d) line voltages during $(n_a, n_b, n_c) = (4,4,3)$ (500 V/div), (e) line currents during $(n_a, n_b, n_c) = (4,4,3)$ (2 A/div).....	133

7.11	Experimental results from proposed topology with $(n_a, n_b, n_c) = (4,3,2)$ balanced condition: (a) pole voltages (200 V/div), (b) line voltages (500 V/div), (c) line currents to the load (2 A/div).....	133
7.12	Experimental results from proposed topology with $(n_a, n_b, n_c) = (4,4,0)$ condition showing a full phase bypass: (a) pole voltages (200 V/div), (b) line voltages (500 V/div), (c) line currents to the load (2 A/div).....	134
8.1	Labelled picture of IPM PCB.....	138
8.2	Pin diagram of 6N135 optocoupler.....	139
8.3	Block diagram of IPM PCB.....	140
8.4	Circuit connection for over-temperature protection.....	141
8.5	DC-link capacitor's PCB.....	141
8.6	Voltage sensor circuit.....	142
8.7	Single carrier implementation for operating four cells in a phase of the CHB converter.....	144
8.8	Control block diagram of the experimental test setup for CHB STATCOM.....	144
8.9	Testing of the experimental setup as CHB converter-based grid connected STATCOM.....	145
8.10	Testing the complete experimental setup for CHB converter with drive application.....	147

LIST OF TABLES

2.1	Multilevel converters with commercial ratings for medium voltage applications.....	8
2.2	Application of CHB converter with their voltage and power ratings.....	17
3.1	Various fault conditions and output voltages for the proposed topology.....	34
3.2	Active and reactive powers during different fault conditions.....	37
3.3	Comparison of proposed topology with other existing fault-tolerant topologies of CHB converters.....	51
3.4	Parameters used in simulation results.....	52
3.5	Parameters used in experimental results.....	55
4.1	Different fault conditions and power distribution for the proposed fault-tolerant technique..	59
4.2	Maximum line voltage during different fault conditions.....	64
4.3	Parameters used in simulation results.....	66
4.4	Parameters used in experimental results.....	70
5.1	Various fault conditions and voltages for the CHB STATCOM with voltage sag in V_{ga}	85
5.2	Parameters used in simulation results.....	89
5.3	Parameters used in experimental results.....	92
6.1	Magnitude and angles of post-fault voltages across CHB phases and redundant cell.....	107
6.2	Parameters used in simulation results.....	111
6.3	Parameters used in experimental results.....	113
7.1	Maximum line voltage during different post-fault conditions (with $N=4$).....	124
7.2	Fundamental and 3 rd harmonic components in zero-sequence voltage and power factor angle range for different post-fault conditions.....	128
7.3	Parameters used in simulation results.....	128
7.4	Parameters used in experimental results.....	132
8.1	Parameters used in experimental test setup of CHB STATCOM.....	146
8.2	Parameters used in experimental test setup of CHB converter for drive application.....	146