

**NEW CIRCUIT TOPOLOGIES OF MODULAR
MULTILEVEL CONVERTERS WITH PASSIVE FILTERS:
MODELING, DESIGN AND OPERATION**

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**DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI**

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**NEW CIRCUIT TOPOLOGIES OF MODULAR MULTILEVEL
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DESIGN AND OPERATION**

by

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Department of Electrical Engineering

Submitted

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CERTIFICATE

This is to certify that the thesis titled, “**New Circuit Topologies of Modular Multilevel Converters with Passive Filters: Modeling, Design and Operation**” being submitted by **Ms. Nibedita Parida** 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.

Ms. Nibedita Parida 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

Modular Multilevel Converter (MMC) is an established multilevel converter technology and is gaining wide acceptance in high power, medium or high voltage applications. Some of the interesting features of the converter are high degree of modularity, easy scalability in terms of voltage and current, excellent quality of output waveforms, transformer-less operation, and a common dc bus operation. These features have attracted commercial applications as well as academia to explore the implementation of the converter in emerging as well as traditional medium/high voltage applications. MMC has been commercially implemented in the range of hundreds of kV and power ratings in hundreds of MW by many industries. Active research is being pursued to develop many circuit topologies, converter models, modulation techniques, and control strategies for grid connected and HVDC applications.

The thesis investigates new circuit topologies of MMC derived from conventional MMC and explores their suitability in HVDC, grid connected as well as motor drives applications. In particular, this research work is focused on the development of novel circuit topologies of MMC with lesser number of cells or submodules as compared to conventional MMC, by introducing passive filters in the circuit. The idea is to reduce the number of power devices and replacing them with cheaper passive filters without compromising on the performance of the converter. This results in the reduction of overall investment cost and complexity of the system. In this work, new circuit topologies of MMC with passive filters for applications such as High Voltage DC (HVDC) interface, grid-connected systems, and medium voltage drives are proposed.

A new modular multilevel DC-AC-DC converter is proposed for the HVDC application. The proposed converter operates with two stages of power conversion i.e., HVDC to AC and AC to Medium Voltage DC (MVDC) using an intermediate medium frequency transformer. In HVDC side, MMC has only two arms along with passive LC filters at the primary side of the intermediate transformer. Operation at medium frequency AC ensures the reduction in the size of the transformer and other passive elements. A high voltage transformation ratio can be achieved by the proposed converter. The proposed converter can be used to extract some power from the existing HVDC line to feed some local medium voltage AC or DC grid.

A new circuit topology of MMC is proposed for grid-connected applications. Unlike the conventional MMC, the proposed MMC topology has passive tuned LC filters in the lower arms in place of many cells. The upper arms of the proposed converter are having cells similar to

conventional MMC. The presence of passive *LC* filters helps to generate an equal magnitude of output AC voltage as conventional MMC with half of the input DC bus voltage magnitude. The passive *LC* filters absorb the higher order switching harmonics generated from the upper arm voltage. Thus, the AC voltage available at the output of the converter is close to a pure sine wave. The investment cost of the converter which includes the cost of semiconductor devices, gate drive circuits, and cell capacitors is also reduced. Measurement and communication circuit requirements such as voltage and current sensors are also reduced.

An MMC with a filter capacitor at the output terminal is proposed for long cable fed medium voltage drive application to mitigate the overvoltage phenomena. Arm inductors which are inherent components in each phase of MMC are tuned with the filter capacitor to behave like a low pass *LC* filter at the MMC output terminal. As a result, the output voltage of the converter is highly sinusoidal with negligible switching frequency harmonics. The overvoltage phenomenon that occurs at the motor terminal due to cable resonance and voltage reflection is almost eliminated and hence with the proposed concept, the motor can be installed at very long distances from the converter.

In this work, MMC converter circuits with different configurations of passive filters are proposed for HVDC, long cable fed medium voltage drive, and grid connected applications. The overall investment cost and complexity of the proposed MMC circuit topologies are reduced as compared to the conventional MMC topology. The proposed circuit topologies of MMC are simulated using MATLAB/Simulink and the same are verified experimentally by designing experimental prototypes.

सार

मॉड्यूलर मल्टीलेवल कन्वर्टर (MMC) एक स्थापित मल्टीलेवल कन्वर्टर तकनीक है और उच्च शक्ति, मध्यम या उच्च वोल्टेज अनुप्रयोगों में व्यापक स्वीकृति प्राप्त कर रहा है। कनवर्टर की कुछ दिलचस्प विशेषताएं उच्च स्तर की प्रतिरूपकता, वोल्टेज और करंट के मामले में आसान मापनीयता, आउटपुट तरंगों की उत्कृष्ट गुणवत्ता, ट्रांसफार्मर-कम संचालन और एक डीसी बस संचालन हैं। इन विशेषताओं ने उभरते और साथ ही पारंपरिक माध्यम/उच्च वोल्टेज अनुप्रयोगों में कनवर्टर के कार्यान्वयन का पता लगाने के लिए व्यावसायिक अनुप्रयोगों के साथ-साथ शिक्षाविदों को भी आकर्षित किया है। एमएमसी को कई उद्योगों द्वारा सैकड़ों केवी की सीमा में और सैकड़ों मेगावाट में बिजली रेटिंग में व्यावसायिक रूप से लागू किया गया है। ग्रिड से जुड़े और एचवीडीसी अनुप्रयोगों के लिए कई सर्किट टोपोलॉजी, कनवर्टर मॉडल, मॉड्यूलेशन तकनीक और नियंत्रण रणनीति विकसित करने के लिए सक्रिय अनुसंधान का अनुसरण किया जा रहा है।

थीसिस पारंपरिक एमएमसी से प्राप्त एमएमसी के नए सर्किट टोपोलॉजी की जांच करती है और एचवीडीसी, ग्रिड से जुड़े और साथ ही मोटर ड्राइव अनुप्रयोगों में उनकी उपयुक्तता की पड़ताल करती है। विशेष रूप से, यह शोध कार्य पारंपरिक एमएमसी की तुलना में कम संख्या में सबमॉड्यूल के साथ एमएमसी के उपन्यास सर्किट टोपोलॉजी के विकास पर केंद्रित है, सर्किट में फिल्टर पेश करके। यह विचार बिजली उपकरणों की संख्या को कम करने और कनवर्टर के प्रदर्शन से समझौता किए बिना उन्हें सस्ते फिल्टर के साथ बदलने का है। इसके परिणामस्वरूप समग्र निवेश लागत और प्रणाली की जटिलता में कमी आती है। इस काम में, हाई वोल्टेज डीसी (एचवीडीसी) इंटरफेस, ग्रिड-कनेक्टेड सिस्टम और मध्यम वोल्टेज ड्राइव जैसे अनुप्रयोगों के लिए फिल्टर के साथ एमएमसी के नए सर्किट टोपोलॉजी प्रस्तावित हैं।

एचवीडीसी एप्लिकेशन के लिए एक नया मॉड्यूलर मल्टीलेवल डीसी-एसी-डीसी कनवर्टर प्रस्तावित है। प्रस्तावित कनवर्टर एक मध्यवर्ती मध्यम आवृत्ति ट्रांसफार्मर का उपयोग करके बिजली रूपांतरण के दो चरणों यानी एचवीडीसी से एसी और एसी से मध्यम वोल्टेज डीसी (एमवीडीसी) के साथ संचालित होता है। एचवीडीसी साइड में, एमएमसी के पास मध्यवर्ती ट्रांसफार्मर के प्राथमिक पक्ष में एलसी फिल्टर के साथ केवल दो भुजाएं हैं। मध्यम आवृत्ति एसी पर संचालन ट्रांसफार्मर और अन्य तत्वों के आकार में कमी सुनिश्चित करता है। प्रस्तावित कनवर्टर द्वारा एक उच्च वोल्टेज परिवर्तन अनुपात प्राप्त किया जा सकता है। प्रस्तावित कनवर्टर का उपयोग कुछ स्थानीय मध्यम वोल्टेज एसी या डीसी ग्रिड को खिलाने के लिए मौजूदा एचवीडीसी लाइन से कुछ बिजली निकालने के लिए किया जा सकता है।

ग्रिड से जुड़े अनुप्रयोगों के लिए एमएमसी का एक नया सर्किट टोपोलॉजी प्रस्तावित है। पारंपरिक एमएमसी के विपरीत, प्रस्तावित एमएमसी टोपोलॉजी में कई कोशिकाओं के स्थान पर निचली भुजाओं में ट्यून्ड एलसी फिल्टर होते हैं। प्रस्तावित कनवर्टर की ऊपरी भुजाओं में पारंपरिक एमएमसी के समान सेल हैं। एलसी फिल्टर की उपस्थिति इनपुट डीसी बस वोल्टेज परिमाण के आधे के साथ पारंपरिक एमएमसी के रूप में आउटपुट एसी वोल्टेज के बराबर परिमाण उत्पन्न करने में मदद करती है। एलसी फिल्टर ऊपरी बांह वोल्टेज से उत्पन्न उच्च क्रम स्विचिंग हार्मोनिक्स को अवशोषित करते हैं। इस प्रकार, कनवर्टर के आउटपुट पर उपलब्ध एसी वोल्टेज शुद्ध साइन वेव के करीब है। कनवर्टर की निवेश लागत जिसमें सेमीकंडक्टर उपकरणों, गेट ड्राइव सर्किट और सेल कैपेसिटर की लागत भी शामिल है, भी कम हो जाती है। वोल्टेज और करंट सेंसर जैसे मापन और संचार सर्किट की आवश्यकताएं भी कम हो जाती हैं।

ओवरवोल्टेज घटना को कम करने के लिए लंबे केबल फेड मध्यम वोल्टेज ड्राइव एप्लिकेशन के लिए आउटपुट टर्मिनल पर एक फिल्टर कैपेसिटर के साथ एक एमएमसी प्रस्तावित है। आर्म इंडक्टर्स जो एमएमसी के प्रत्येक चरण में निहित घटक हैं, एमएमसी आउटपुट टर्मिनल पर कम पास एलसी फिल्टर की तरह व्यवहार करने के लिए फिल्टर कैपेसिटर के साथ ट्यून किए जाते हैं। नतीजतन, कनवर्टर का आउटपुट वोल्टेज नगण्य स्विचिंग आवृत्ति हार्मोनिक्स के साथ अत्यधिक साइनसॉइडल है। केबल अनुनाद और वोल्टेज प्रतिबिंब के कारण मोटर टर्मिनल पर होने वाली ओवरवोल्टेज घटना लगभग समाप्त हो गई है और इसलिए प्रस्तावित अवधारणा के साथ, कनवर्टर से मोटर को बहुत लंबी दूरी पर स्थापित किया जा सकता है।

इस काम में, एचवीडीसी, लंबी केबल फेड मध्यम वोल्टेज ड्राइव, और ग्रिड से जुड़े अनुप्रयोगों के लिए फिल्टर के विभिन्न विन्यास वाले एमएमसी कनवर्टर सर्किट प्रस्तावित हैं। पारंपरिक एमएमसी टोपोलॉजी की तुलना में प्रस्तावित एमएमसी सर्किट टोपोलॉजी की समग्र निवेश लागत और जटिलता कम हो जाती है। एमएमसी के प्रस्तावित सर्किट टोपोलॉजी को MATLAB/Simulink का उपयोग करके सिमुलेटेड किया जाता है और प्रयोगात्मक प्रोटोटाइप को डिजाइन करके प्रयोगात्मक रूप से सत्यापित किया जाता है।

TABLE OF CONTENTS

Certificate	i
Acknowledgements	ii
Abstract	iv
Table of Contents	vii
List of Figures	xi
List of Tables	xviii
List of Abbreviations	xix
Chapter 1 Introduction	1-6
1.1 Background and Motivation of the Work	01
1.2 Research Area Identification	02
1.3 Main Contributions of the Thesis	03
1.4 Organization of the Thesis	04
Chapter 2 Literature Review	07-29
2.1 Need for Multilevel Converters	07
2.2 Conventional Multilevel Topologies	09
2.2.1 Neutral Point Clamped (NPC) Converter Topology	10
2.2.2 Flying Capacitor (FC) Converter Topology	11
2.2.3 Cascaded H Bridge (CHB) Converter Topology	12
2.2.4 Conventional Modular Multilevel Converter (MMC) Topology	14
2.2.5 Different Cell Configurations of MMC	16
2.3 Application of MMCs	17
2.3.1 HVDC Applications	17
2.3.2 Medium Voltage Drives Applications	19
2.3.3 Medium Voltage or High Voltage AC Grid Connected Application	20
2.4 Existing Topologies of MMC Family	22
2.4.1 MMC Topologies for AC-DC or DC-AC Conversion	22
2.4.2 DC-DC MMC Topologies	25

2.5	Summary	28
-----	---------------	----

Chapter 3 Analysis and Operation of Conventional Modular Multilevel Converter 30-51

3.1	Principle of Operation	30
3.1.1	Mathematical Modelling	32
3.1.2	Arm Energy Balancing	35
3.1.3	Arm Energy Oscillation	38
3.1.4	Sizing of Passive Components	39
3.2	Modulation Technique	40
3.2.1	Level Shifted PWM Technique (LSPWM)	41
3.2.2	Phase Shifted PWM Technique (PSPWM)	42
3.3	Cell Capacitor Voltage Balancing	43
3.3.1	Implementation of Sorting Algorithm in LSPWM	43
3.3.2	Individual Cell Balancing Implemented in PSPWM	48
3.4	Control Strategy for MMC	49
3.5	Summary	51

Chapter 4 New Modular Multilevel DC-AC-DC Converter Topology for HVDC Application 52-80

4.1	Background	52
4.2	Existing Modular Multilevel Converter Topologies for HVDC Application	54
4.3	Structure of Proposed Converter Circuit Topology	55
4.4	Principle of Operation	56
4.4.1	Mathematical Modelling	57
4.4.2	Arm Energy Balancing	61
4.4.3	Control Strategy	62
4.4.4	Modulation Technique	64
4.5	Filter design	65
4.5.1	Series <i>LC</i> Filter Design	66
4.5.2	Parallel <i>LC</i> Filter Design	68

4.5.2	Variation of Filter Parameters	71
4.6	Flow of DC through Primary Side of Intermediate Transformer	72
4.7	Simulation Results	74
4.8	Experimental Implementation	77
4.9	Summary	80

Chapter 5 A Modified Modular Multilevel Converter Topology for Grid Connected Application 81-98

5.1	Background	81
5.2	Structure of Proposed MMC Circuit Topology	82
5.3	Comparison between Conventional MMC and Proposed MMC Topology	83
5.4	Principle of Operation	83
5.4.1	Mathematical Modelling	84
5.4.2	Arm Energy Balancing	88
5.4.3	Modulation Technique and Voltage Balancing	89
5.5	Filter design	89
5.5.1	LC Filter Design	90
5.6	Simulation Results	92
5.7	Experimental Implementation	95
5.8	Summary	98

Chapter 6 Modular Multilevel Converter Topology with Filter Capacitor for Long Cable fed Drive Application 99-121

6.1	Background	100
6.2	Effects of Cable Resonance	101
6.3	Effects of Voltage Reflection	104
6.4	Techniques to Mitigate the Issues in Long Cable-based Systems	106
6.5	Long Cable fed MMC based Drive	107
6.6	Operation of MMC with Proposed Filter Capacitor	109
6.6.1	Selection of Arm Inductance, Filter Capacitance and Cell Capacitance	112
6.7	Selection of Number of Cells per Arm in MMC for drives Application	112

6.8	Simulation Results	114
6.8.1	MMC Operation with 6 km Long Cable without Filter Capacitor	116
6.8.2	MMC Operation with 6 km Long Cable with Filter Capacitor	116
6.9	Experimental Implementation	117
6.10	Summary	121
Chapter 7 Conclusion and Future Scope of Work		122-124
7.1	Findings of the Research	122
7.2	Future Scope	124
Bibliography		126-136
Appendix-A		139-142
Appendix-B		143-151
List of Publications		152

LIST OF FIGURES

2.1	Classification of multilevel converter topologies.....	09
2.2	Single phase neutral point clamped converter (a) three level configuration (b) five level configuration.....	10
2.3	Single phase flying capacitor converter (a) three level configuration (b) four level configuration.....	12
2.4	Seven level CHB converter.....	13
2.5	Conventional MMC topology.....	14
2.6	Different MMC cell configurations, switching states, and voltage levels. (a) half bridge (b) full bridge (c) mixed multilevel (d) NPC multilevel.....	16
2.7	Application of MMCs in HVDC technology (a) HVDC transmission (b) HVDC tapping (c) offshore wind energy converter station.....	19
2.8	MMC based medium voltage drives.....	20
2.9	(a) MMC based BESS interfaced with AC grid (b) PV cell based MMC interfaced with AC grid.....	21
2.10	Application of MMC as a unified power quality compensator.....	22
2.11	Hybrid MMC topology for DC-AC or AC-DC conversion.....	22
2.12	Alternate arm topology for DC-AC or AC-DC conversion.....	23
2.13	Middle cell based MMC topology for AC-DC or DC-AC conversion.....	24
2.14	Cross connected arm MMC topology for AC-DC or DC-AC conversion.....	24
2.15	Auto transformer based non-isolated DC-DC MMC Topology.....	25
2.16	DC-MMC topologies (a) four arm configuration (b) two arm configuration.....	26
2.17	Isolated DC-DC converter topology using three phase MMCs.....	27
2.18	Isolated DC-DC converter topology using two phase MMCs.....	28
3.1	Conventional MMC topology.....	31
3.2	Equivalent circuit diagram of conventional MMC.....	32
3.3	Instantaneous voltage generated by the upper and lower arm of the conventional MMC topology.....	35

3.4	In-phase disposition level shifted PWM technique (a) upper arm (b) lower arm.....	41
3.5	Phase opposite disposition level shifted PWM technique (a) upper arm (b) lower arm.....	41
3.6	Interleaved disposition phase shifted PWM technique (a) upper arm (b) lower arm.....	42
3.7	Evenly spaced disposition phase shifted PWM technique (a) upper arm (b) lower arm.....	42
3.8	Cell inserted (a) with positive arm current direction (b) with negative arm current direction.....	44
3.9	Cell bypassed a) with positive arm current direction (b) with negative arm current direction.....	44
3.10	Status of cells during a) upper arm modulation (b) lower arm modulation.....	45
3.11	Individual capacitor voltage balancing.....	48
3.12	Control scheme used in MMC.....	49
4.1	HVDC tapping scheme.....	53
4.2	Proposed circuit topology.....	56
4.3	Equivalent circuit diagram of the proposed converter topology.....	57
4.4	Ideal waveforms (a) arm voltage (b) transformer primary side voltage (c) arm current (d) transformer secondary side voltage (e) transformer secondary side current.....	59
4.5	Control block diagram (a) DC-AC MMC control scheme (b) AC-DC VSC control scheme.....	63
4.6	Level shifted (LS) PWM technique.....	64
4.7	Simplified equivalent circuit of the proposed converter at primary side of transformer in ideal conditions (a) AC equivalent circuit (b) DC equivalent circuit.....	65
4.8	(a)series LC filter (b) impedance characteristic of the series LC filter.....	66

4.9	(a) Parallel <i>LC</i> filter (b) impedance characteristic of the parallel <i>LC</i> filter.....	68
4.10	Equivalent circuit diagram of the power transformer used in the proposed converter.....	72
4.11	Hysteresis loop.....	73
4.12	Simulation waveforms: (a) HVDC and MVDC voltages (b) HVDC and MVDC currents (c) upper arm voltage (d) lower arm voltage	75
4.13	Simulation waveforms during forward power flow: (a) primary side voltage (b) primary side current (c) secondary side voltage (d) secondary side current.....	75
4.14	Simulation waveforms during reverse power flow: (a) primary side voltage (b) primary side current (c) secondary side voltage (d) secondary side current.....	75
4.15	Experimental setup.....	77
4.16	Experimental results at no load: (a) (i) input DC bus voltage [400 V/div] (a) (ii) output voltage [400 V/div] (b) (i) upper arm voltage of MMC [500 V/div] (ii) transformer primary voltage [500 V/div] (iii) transformer secondary voltage [300 V/div] (iv) transformer primary current [1 A/div].....	78
4.17	Experimental results at 1 kW rated load: (a) (i) input DC bus voltage [200 V/div] (a) (ii) input DC current [2 A/div] (b) (i) upper arm voltage of MMC [500 V/div] (ii) series filter current [10 A/div] (iii) transformer primary voltage [500 V/div] (c) (i) upper arm voltage of MMC [200 V/div] (b) (ii) transformer primary current [10 A/div] (d) (i) lower arm Voltage of MMC [200 V/div] (ii) transformer secondary voltage [300 V/div] (iii) transformer secondary current [10A/div] (e) upper arm cell capacitor voltages [100 V/div] (f) (i) output voltage [200 V/div] (ii) output current [10 A/div].....	79
5.1	Proposed MMC circuit topology.....	82
5.2	Single phase equivalent circuit of proposed MMC circuit topology.....	84
5.3	Single phase fundamental equivalent circuit of proposed MMC circuit topology.....	85

5.4	Instantaneous voltage generated by the upper arm of the proposed MMC topology.....	86
5.5	DC equivalent circuit of proposed circuit topology.....	87
5.6	(a) <i>LC</i> filter circuit (b) Frequency response of <i>LC</i> filter Circuit.....	91
5.7	Harmonic equivalent circuit of proposed converter topology.....	92
5.8	Simulation waveforms of the proposed converter at no load (a) upper arm voltage (b) upper arm current (c) load voltages (d) load currents (e) capacitor voltages of four cells in phase 'a' (f) filter current in the lower arms.....	93
5.9	Simulation waveforms of the proposed converter with 1 MVA rating (a) upper arm voltage (b) upper arm current (c) load phase voltages (d) load currents (e) capacitor voltages of four cells in phase 'a' (f) filter current in the lower arms.....	93
5.10	Simulation waveform of load side AC phase voltage of conventional MMC.....	95
5.11	THD analysis of output AC voltage waveform of (a) proposed topology (b) conventional MMC.....	95
5.10	Experimental setup block diagram.....	96
5.11	Experimental setup.....	96
5.12	Experimental waveforms (a) upper arm voltage (b) upper arm current (c) filter current (d) load AC line voltages (e) load AC currents (f) cell capacitor voltages.....	97
6.1	Distributed <i>LC</i> based model of a cable.....	100
6.2	Block diagram of a long cable fed drive.....	100
6.3	(a) voltage transmission ratio of a 3 km long cable (b) voltage transmission ratio of a 6 km long cable (c) harmonic spectrum of inverter output voltage.....	102
6.4	Motor terminal voltage with a 6km long cable with an ideal sinusoidal input voltage (dotted line) at motor terminal.....	103
6.5	Block diagram of a long cable fed drive shown in frequency domain.....	104
6.6	Long cable fed MMC based drive.....	108
6.7	Single phase equivalent circuit of MMC.....	108
6.8	Thevenin equivalent circuit of MMC in frequency domain.....	109
6.9	Long cable fed MMC based drive with filter capacitor.....	110

6.10	Thevenin equivalent circuit of MMC with filter capacitor.....	110
6.11	Bode magnitude plot of filter circuit.....	111
6.12	Simulation results without filter capacitor (a) arm voltage of MMC (b) upper arm capacitor voltages (c) MMC output voltage (d) motor terminal voltage (e) motor current.....	115
6.13	Simulation results with filter capacitor (a) arm voltage of MMC (b) upper arm capacitor voltages (c) MMC output voltage (d) motor terminal voltage (e) motor current.....	115
6.14	Harmonic spectrum analysis of a 6 km long cable fed motor terminal voltage without filter at converter terminal.....	115
6.15	Harmonic spectrum analysis of a 6 km long cable fed motor terminal voltage with filter at converter terminal.....	117
6.16	Experimental setup.....	118
6.17	Experimental results of converter voltage (a) upper arm voltage of phase 'a' of MMC [200 V/div] (b) lower arm voltage of phase 'a' of MMC [200 V/div] (c) MMC line output voltage [500 V/div] (d) upper arm cell capacitor voltages in phase 'a' [100 V/div].....	118
6.18	Experimental results of converter voltage (a) upper arm voltage of phase 'a' of MMC [200 V/div] (b) lower arm voltage of phase 'a' of MMC [200 V/div] (c) MMC line to line output voltage [500 V/div] (d) upper arm cell capacitor voltages in phase 'a' [100 V/div].....	118
6.19	Experimental results with 100 m cable fed drive and filter capacitor at converter terminal at steady state (a) lower arm Voltage of phase 'a' of MMC [200 V/div] (b) MMC line output voltage [500 V/div] (c) motor terminal voltage [500 V/div] (d) upper arm current of phase 'a' of MMC [2 A/div] (e) filter current [1 A/div] (f) motor current [2 A/div].....	119
6.20	Experimental results with 100 m cable fed drive and filter capacitor at converter terminal at motor start up from 5 Hz to 20 Hz (a) upper arm Voltage of phase 'a' of MMC [500 V/div] (b) motor terminal voltage [500 V/div] (c) motor terminal current [1 A/div].....	120

6.21	Experimental results with 100 m cable fed drive and filter capacitor at converter terminal during motor acceleration from 20 Hz to 50 Hz (a) upper arm Voltage of phase 'a' of MMC [200 V/div] (b) motor terminal voltage [200 V/div] (c) motor terminal current [1 A/div].....	120
6.22	Experimental results with 100 m cable fed drive and filter capacitor at converter terminal during motor deceleration from 30 Hz to 20 Hz (a) upper arm voltage of phase 'a' of MMC [200 V/div] (b) motor terminal voltage [200 V/div] (c) motor terminal current [1 A/div]	120
A.1	Experimental setup components.....	137
A.2	Front view of IPM board.....	138
A.3	Back view of IPM board.....	138
B.1	Equivalent circuit diagram of the power transformer in the proposed converter.....	140
B.2	Hysteresis loop.....	141
B.3	Single phase core type transformer.....	144

LIST OF TABLES

2.1	Commercial ratings of multilevel converters in medium voltage applications.....	10
2.2	Commercial ratings of MMCs for HVDC application.....	19
2.3	Commercial ratings of MMC based medium voltage drives.....	20
2.4	Commercial ratings of MMC based STATCOM.....	21
4.1	Variation of parameters.....	41
4.2	Simulation parameters.....	74
4.3	Experimental parameters.....	77
5.1	Simulation parameters.....	92
5.2	Experimental parameters.....	96
6.1	Simulation parameters.....	114
6.2	Experimental parameters.....	117
b.1	Transformer input parameters.....	142
b.2	List of variables for design of transformer.....	142
b.3	List of core material parameters (from data sheet).....	143
b.4	List of variables for core dimension design.....	143

LIST OF ABBREVIATIONS

MMC	Modular Multilevel Converters
NPC	Neutral Point Clamped
FC	Flying Capacitor
CHB	Cascaded H Bridge
HVDC	High Voltage DC
MVDC	Medium Voltage DC
HVAC	High voltage AC
FACTS	Flexible Alternating Current Transmission System
STATCOM	Static Synchronous Compensator
UPQC	Unified Power Quality Conditioner
PV	Photo Voltaic
BESS	Battery Energy Storage System
F2F	Front-to-Front
VSC	Voltage Source Converter
VSI	Voltage Source Inverter
PWM	Pulse Width Modulation
LSPWM	Level Shifted Pulse Width Modulation
PSPWM	Phase Shifted Pulse Width Modulation
THD	Total Harmonic Distortion
WTHD	Weighted Total Harmonic Distortion
IGBT	Insulated Gate Bipolar Transistor
PI	Proportional-Integral
PF	Power Factor
MATLAB	Matrix Laboratory
DSP	Digital Signal Processor
IPM	Intelligent Power Module