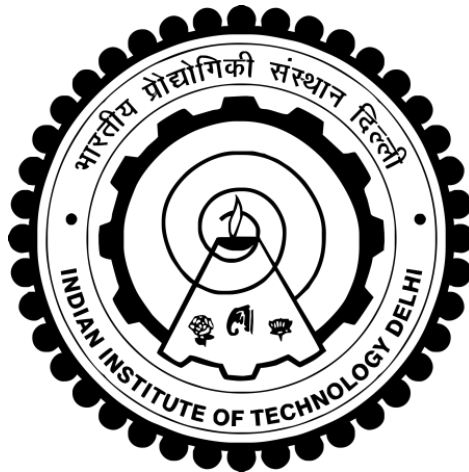


INVESTIGATIONS ON HIGH POWER CONVERTERS BASED GRID INTERFACED SOLAR PV POWER GENERATING SYSTEMS

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**DEPARTMENT OF ELECTRICAL ENGINEERING
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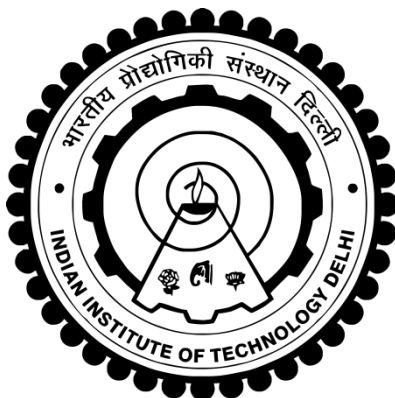
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Submitted

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

to the



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CERTIFICATE

It is certified that the thesis entitled “**Investigations on High Power Converters Based Grid Interfaced Solar PV Power Generating Systems,**” being submitted by **Mr. Ikhlaq Hussain** for award of the degree of **Doctor of Philosophy** in the Department of Electrical Engineering, Indian Institute of Technology Delhi, is a record of the student work carried out by him under my supervision and guidance. The matter embodied in this thesis has not been submitted for award of any other degree or diploma.

Dated: July 09, 2018

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Ikhlaq Hussain

ABSTRACT

During last decade, solar photovoltaic (PV) power generation has become a focus area of research and development as it is ecofriendly, renewable and available in large quantity. Because of availability of the PV energy everywhere, it is possible to use it in both isolated and grid connected systems. In this thesis work, the various system configurations for single stage high power grid tied PV power generating systems based on two level, multilevel (diode clamped, flying capacitor, binary and ternary cascaded) and multipulse converters, are investigated in detail. The design, control and implementation of various system configurations of PV power generating systems are carried out and their performance are evaluated under varying solar insolation levels.

This research work focuses on investigations of grid tied PV power generating systems such as two level VSC (Voltage Source Converter) based PV-DSTATCOM (Distribution Static Compensator), multilevel VSC based PV-STATCOM (Static Compensator) and other multilevel converters. In PV-DSTATCOM system, two level converter is utilized to do multiple functions in three modes. In mode 1, it transfers active power to the grid and connected loads while mitigating the power quality issues in the distribution network. In mode 2, it transfers only active power to the grid at unity power factor while in mode 3, it does only power quality mitigations. In PV-STATCOM system, it transfers large power at high voltage to the three phase AC grid with STATCOM capabilities thereby increasing the transmission transferring capability. For PV-STATCOM system working in three modes, five and seven level converters are utilized to integrate the PV arrays with the grid at low switching frequency with STATCOM capabilities. In both systems, the VSCs are fully utilized to their full capacity in the proposed system for 24 hours. To improve the efficiency of the system, a single stage topology is adopted over double stage topology in the PV grid tied systems.

However, to transfer large power from a PV array to the three phase grid at high voltage, multilevel and multipulse VSCs are viable solution as losses in the VSC, are decreased due to low switching frequency. The various configurations (binary cascaded 31 level converter, ternary cascaded 9 and 27 level converters, 12 and 18 pulse converter) of the PV system operating at FFS (Fundamental Frequency Switching) are investigated. Due to FFS, the switching losses of the converters are reduced, thereby, increasing overall efficacy of the system, which results in reduction of unit cost of electricity. The binary and ternary cascaded converters operating at FFS and single stage topology, offers advantages viz. high number of voltage levels, less number of switching devices, low THD, low switching losses, ease of operation at high voltages that leads to the improvement in power quality of the system. All these converter based grid tied power generating systems are simulated in MATLAB and the responses are verified through experimental results achieved on the developed prototype in the laboratory, to demonstrate the system performance under varying conditions. The major focus of this research work, is investigations of high power converter based PV grid tied system, for active power transfer to the grid as well as mitigating power quality (PQ) issues, while satisfying the IEEE standards.

अब्स्ट्रक्ट

दूरिंग लास्ट डिकेड ,सोलर फोटोवोल्टाइक (पीवी) पावर जनरेशन हैस बिकम ऐ फोकस एरिया ऑफ़ रिसर्च एंड डेवलपमेंट एस इट इस इकोफ्रेंडली,रिन्यूएबल एंड अवेलेबल इन लार्ज क्वांटिटी .बिकॉज़ ऑफ़ अवेलेबिलिटी ऑफ़ दा पीवी एनर्जी एवरीक्वेर,इट इस पॉसिबल तू यूज आईटी इन बोथ आइसोलेटेड एंड ग्रिड कनेक्टेड सिस्टम्स. इन थिस थीसिस वर्क,दा वेरियस सिस्टम कॉन्फ़िगरेशंस फॉर सिंगल स्टेज हाई पावर ग्रिड टाईड पीवी पावर जनरेटिंग सिस्टम्स बेस्ड आन तू लेवल, मल्टीलेवल (डायोड क्लाम्पेड , फ्लाइंग कपैसिटर, बाइनरी एंड टेरनरी कास्केडेड) एंड मल्टीपल्स कन्वर्टर्स, आर इन्वेस्टीगेटेड इन डिटेल्. दा डिज़ाइन, कण्ट्रोल एंड इम्प्लीमेंटेशन ऑफ़ वेरियस सिस्टम कॉन्फ़िगरेशंस ऑफ़ पीवी पावर जनरेटिंग सिस्टम्स आर कर्रिएड आउट एंड थेइर परफॉरमेंस आर एवलुएटेड अंडर वैरीइंग सोलर इन्सुलेशन लेवल्स.

थिस रिसर्च वर्क फॉक्सेस आन इन्वेस्टीगेशंस ऑफ़ ग्रिड टाईड पीवी पावर जनरेटिंग सिस्टम्स सच एस टू लेवल वीएससी (वोल्टेज सोर्स कनवर्टर) बेस्ड पीवी-डिस्टॉटकॉम (डिस्ट्रीब्यूशन स्थैतिक कम्पेन्सेटर), मल्टीलेवल वीएससी बेस्ड पीवी-डिस्टॉटकॉम एंड अदर मल्टीलेवल कन्वर्टर्स. इन पीवी-डिस्टॉटकॉम सिस्टम, टू लेवल कनवर्टर इस युटीलीज़ेड तू डॉ मल्टीप्ल फंक्शन्स इन थ्री मोड्स. इन मोड 1, इट ट्रान्सफर एक्टिव पावर तू दा ग्रिड एंड कनेक्टेड लोड्स व्हाइल मिटिगेटिंग दा पावर क्वालिटी इश्यूज इन दा डिस्ट्रीब्यूशन नेटवर्क. इन मोड 2, इट ट्रान्सफर्स ओनली एक्टिव पावर तू दा ग्रिड येत यूनिटी पावर फैक्टर व्हाइल इन मोड 3, इट डस ओनली पावर क्वालिटी मिटिगेशंस. इन पीवी-डिस्टॉटकॉम सिस्टम, इट ट्रान्सफर्स लार्ज पावर अत हाई वोल्टेज तू दा थ्री फेज ऐसी ग्रिड विथ स्टॉटकॉम कैपेबिलिटीज देयेरबाई इन्क्रेअसिंग दा ट्रान्समिशन ट्रान्सफरिंग कपाबिलिटी. फॉर पीवी-डिस्टॉटकॉम सिस्टम वर्किंग इन थ्री मोड्स, फाइव एंड सेवन लेवल कन्वर्टर्स आर युटीलीज़ेड तू इंटैग्रेटे डा पीवी एर्रे विथ दा ग्रिड येत लो स्वीचिंग फेक्वेन्सी विथ स्टॉटकॉम कैपेबिलिटीज. इन बोथ सिस्टम्स, दा वीएससीस आर फुल्ली युटीलीज़ेड तू थेइर फुल कैपेसिटी इन दा प्रोपोसड सिस्टम फॉर 24 हॉर्स. तू इम्प्रोव दा एफिशिएंसी ऑफ़ दा सिस्टम , अ सिंगल स्टेज टोपोलॉजी इस अडॉप्टेड ओवर डबल स्टेज टोपोलॉजी इन दा पीवी ग्रिड टाईड सिस्टम्स.

हाउएवर, तू ट्रान्सफर लार्ज पावर फ्रॉम अ पीवी ऐरे तू दा थ्री फेज ग्रिड येत हाई वोल्टेज, मल्टीलेवल एंड मल्टीपल्स वीएससीस आर वाइएबल सलूशन एस लॉसेस इन दा वीएसी, आर डिक्लीज़ड टू तू लो स्वीचिंग फ्रीक्वेंसी. दा वेरियस कॉन्फ़िगरेशंस (बाइनरी कास्केडेड 31 लेवल कनवर्टर, टेरनरी कास्केडेड 9 एंड 27 लेवल कन्वर्टर्स, 12 एंड 18 पल्स कनवर्टर) ऑफ़ दा पीवी सिस्टम

ऑपरेटिंग अत फफस (फंडामेंटल फ्रीक्वेंसी स्विचन) आर इंवेस्टीगेटेड. डुए तू फफस, दा स्वीचिंग लॉसेस ऑफ़ दा कन्वर्टर्स आर रेड्यूसेड , देयेरबाई , इन्क्रेअसिंग ओवरआल एफ़िफ़िकेसी ऑफ़ दा सिस्टम, व्हिच रिजल्ट्स इन रिडक्शन ऑफ़ यूनिट कॉस्ट ऑफ़ इलेक्ट्रिसिटी. दा बाइनरी एंड टेरनरी कास्केडेड कन्वर्टर्स ऑपरेटिंग येत फफस एंड सिंगल स्टेज टोपोलॉजी, ऑफ़र्स अडवांटागेस विज. हाई नंबर ऑफ़ वोल्टेज लेवल्स, लेस्स नंबर ऑफ़ स्वीचिंग डिवाइसेस, लो टीयाचडी, लो स्वीचिंग लॉसेस, ईज ऑफ़ ऑपरेशन अत हाई वोल्टागेस तहत लीडस् तू दा इम्प्रूवमेंट इन पावर क्वालिटी ऑफ़ दा सिस्टम. आल दीज कनवर्टर बेस्ड ग्रिड टाईड पावर जनरेटिंग सिस्टम्स आर सिमुलेटेड इन मैटलैब एंड दा रेस्पॉन्सेस आर वेरिफ़िएड थ्रू एक्सपेरिमेंटल रिजल्ट्स अचीवेद ओन दा डेवलप्ड प्रोटोटाइप इन दा लेबोरेटरी, तू डेमोंस्ट्रेटे दा सिस्टम परफॉरमेंस अंडर वारियिंग कंडीशंस. दा मेजर फोकस ऑफ़ थिस रिसर्च वर्क, इस इंवेस्टीगेशंस ऑफ़ हाई पावर कनवर्टर बेस्ड पीवी ग्रिड टाईड सिस्टम, फॉर एक्टिव पावर ट्रान्सफर तू दा ग्रिड एस वेल एस मिटिगेटिंग पावर क्वालिटी (पिक्की) इश्यूज, व्हाइल सटिस्फीइंग दा आई ट्रिप्ल इ स्टैंडर्ड्स.

TABLE OF CONTENTS

Certificate	i
Acknowledgement	ii
Abstract	v
Abstract (Hindi)	vii
Table of Contents	ix
List of Figures	xviii
List of Tables	xxix
List of Abbreviations	xxx
List of Symbols	xxxiii
CHAPTER I INTRODUCTION	
1.1 General	1
1.2 State of Art on PV Power Generating Systems	2
1.3 Objectives and Scope of Work	4
1.3.1 Two-Level Converter Based PV Grid Tied Power Generating System	4
1.3.2 Diode Clamped Multilevel Converter Based PV Grid Tied Power Generating System	5
1.3.3 Flying Capacitor Multilevel Converter Based PV Grid Tied Power Generating System	5
1.3.4 Symmetrical Cascaded H-Bridge Multilevel Converters Based PV Grid Tied Power Generating System	5
1.3.5 Binary Cascaded H-Bridge Multilevel Converters Based PV Grid Tied Power Generating System	6
1.3.6 Ternary Cascaded H-Bridge Multilevel Converters Based PV Grid Tied Power Generating System	6
1.3.7 Multipulse Two-Level Converters Based PV Grid Tied Power Generating System	6
1.4 Outline of the Chapters	7
CHAPTER II LITERATURE REVIEW	
2.1 General	10
2.2 Developments and Standards of PV Power Generating Systems	11
2.3 Literature Survey	12
2.3.1 Review of MPPT Techniques for PV Power Generating Systems	12
2.3.2 Review of Two-Level VSCs for PV Power Generating Systems	14
2.3.3 Review of Multilevel and Multipulse VSCs for PV Power Generating Systems	17
2.4 Identified Research Areas	20
2.5 Conclusions	22
CHAPTER III TWO LEVEL CONVERTER BASED PV GRID TIED POWER GENERATING SYSTEMS	
3.1 General	23
3.2 Configuration of Two-Level Converter Based PV Grid Tied Power Generating System	23

3.3	Design of Two-Level Converter Based PV Grid Tied Power Generating System		24
	3.3.1	Design of PV Array	25
	3.3.2	Design of DC Link Voltage	25
	3.3.3	Design of DC Link Capacitor	26
	3.3.4	Design of Interfacing Inductor	26
	3.3.5	Design of Ripple Filter	26
3.4	Control of Two-Level Converter Based PV Grid Tied Power Generating System		26
	3.4.1	MPPT Algorithm	27
	3.4.2	VSC Algorithm	28
		3.4.2.1 Evaluation of Amplitude of Terminal Voltage	28
		3.4.2.2 Estimation of In-Phase and Quadrature Unit Templates	29
		3.4.2.3 Estimation of Active and Reactive Loss Components	30
		3.4.2.4 Estimation of PV Feed Forward Component	30
		3.4.2.5 Extraction of Weight of Fundamental Active and Reactive Components	31
		3.4.2.6 Generation of Reference Grid Currents	32
3.5	MATLAB Based Modeling of Two-Level Converter Based PV Grid Tied Power Generating System		33
3.6	Hardware Implementation of Two-Level Converter Based PV Grid Tied Power Generating System		34
	3.6.1	Hardware Configuration of DSP d-SPACE 1202 MicroLab Box Controller	35
	3.6.2	Development of Interfacing Circuit for Hall Effect Current Sensors	35
	3.6.3	Development of Interfacing Circuit for Hall Effect Voltage Sensors	36
	3.6.4	Interfacing Circuit for Gate Driver	37
3.7	Results and Discussion		37
	3.7.1	Simulated Performances of Two-Level Converter Based PV Grid Tied Power Generating System	38
		3.7.1.1 Behaviour of the System under Load Unbalancing	39
		3.7.1.2 Behaviour of the System under Variation of Solar Insolation	39
		3.7.1.3 Power Quality Performances	41
	3.7.2	Experimental Performances of Two-Level Converter Based PV Grid Tied Power Generating System	41
		3.7.2.1 Steady State Performances	41
		3.7.2.2 Dynamic Performances	44
		3.7.2.3 Power Quality Performances	48
3.8	Conclusions		48
CHAPTER IV		DIODE CLAMPED MULTILEVEL CONVERTER BASED PV GRID TIED POWER GENERATING SYSTEMS	50
4.1	General		50
4.2	Configuration of Diode Clamped Three-Level Converter Based PV Grid Tied Power Generating System		50
4.3	Design of Diode Clamped Three-Level Converter Based PV Grid Tied Power Generating System		51
	4.3.1	Design of PV Array	51
	4.3.2	Design of DC Link Capacitor	51
	4.3.3	Design of Interfacing Inductor	52

4.4	Control of Diode Clamped Three-Level Converter Based PV Grid Tied Power Generating System		52
	4.4.1 MPPT Algorithm		52
	4.4.2 VSC Algorithm		54
4.5	MATLAB Based Modeling of Diode Clamped Three-Level Converter Based PV Grid Tied Power Generating System		57
4.6	Hardware Implementation of Diode Clamped Three-Level Converter Based PV Grid Tied Power Generating System		58
4.7	Results and Discussion		59
	4.7.1	Simulated Performance of Diode Clamped Three-Level Converter Based PV Grid Tied Power Generating System	59
		4.7.1.1 Steady State Performances	59
		4.7.1.2 Dynamic Performances	63
		4.7.1.3 Power Quality Performances	63
	4.7.2	Experimental Performance of Diode Clamped Three-Level Converter Based PV Grid Tied Power Generating System	65
		4.7.2.1 Steady State Performances	66
		4.7.2.2 Dynamic Performances	69
		4.7.2.3 Power Quality Performances	74
4.8	Conclusions		75
CHAPTER V		FLYING CAPACITOR MULTILEVEL CONVERTER BASED PV GRID TIED POWER GENERATING SYSTEMS	76
5.1	General		76
5.2	Configuration of Flying Capacitor Three-Level Converter Based PV Grid Tied Power Generating System		76
5.3	Design of Flying Capacitor Three-Level Converter Based PV Grid Tied Power Generating System		76
	5.3.1 Design of PV Array		77
	5.3.2 Design of DC Link Capacitor		77
	5.3.3 Design of Interfacing Inductor		78
	5.3.4 Operating Principle of Flying Capacitor Three-Level VSC		78
5.4	Control of Flying Capacitor Three-Level Converter Based PV Grid Tied Power Generating System		79
	5.4.1 MPPT Algorithm		79
	5.4.2 VSC Algorithm		80
5.5	MATLAB Based Modeling of Flying Capacitor Three-Level Converter Based PV Grid Tied Power Generating System		83
5.6	Hardware Implementation of Flying Capacitor Three-Level Converter Based PV Grid Tied Power Generating System		83
5.7	Results and Discussion		85
	5.7.1	Simulated Performance of Flying Capacitor Three-Level Converter Based PV Grid Tied Power Generating System	85
		5.7.1.1 Steady State Performances	85
		5.7.1.2 Dynamic Performances	86
		5.7.1.3 Power Quality Performances	89
	5.7.2	Experimental Performance of Flying Capacitor Three-Level Converter Based PV Grid Tied Power Generating System	90

		5.7.2.1	Steady State Performances	92
		5.7.2.2	Dynamic Performances	92
5.8	Conclusions			94
CHAPTER VI		SYMMETRICAL CASCADED H-BRIDGE MULTILEVEL CONVERTER BASED PV GRID TIED POWER GENERATING SYSTEMS		95
6.1	General			96
6.2	Configurations of Symmetrical Cascaded H-Bridge Multilevel Converter Based PV Grid Tied Power Generating Systems			96
	6.2.1	Configurations of Symmetrical Cascaded H-Bridge Five-Level Converter Based PV Grid Tied Power Generating System		97
	6.2.2	Configurations of Symmetrical Cascaded H-Bridge Seven-Level Converter Based PV Grid Tied Power Generating System		97
6.3	Design of Symmetrical Cascaded H-Bridge Multilevel Converter Based PV Grid Tied Power Generating Systems			97
	6.3.1	Design of Symmetrical Cascaded H-Bridge Five-Level Converter Based PV Grid Tied Power Generating System		98
		6.3.1.1 Design of PV Array		98
		6.3.1.2 Design of DC Link Capacitor		98
		6.3.1.3 Design of Interfacing Inductor		99
		6.3.1.4 Operating Principle of Symmetrical Cascaded Five-level VSC		99
	6.3.2	Design of Symmetrical Cascaded H-Bridge Seven-Level Converter Based PV Grid Tied Power Generating System		100
		6.3.2.1 Design of PV Array		100
		6.3.2.2 Design of DC Link Capacitor		101
		6.3.2.3 Design of Interfacing Inductor		101
		6.3.2.4 Operating Principle of Symmetrical Cascaded Seven-level VSC		101
6.4	Control of Symmetrical Cascaded H-Bridge Multilevel Converter Based PV Grid Tied Power Generating Systems			103
	6.4.1	Control of Symmetrical Cascaded H-Bridge Five-Level Converter Based PV Grid Tied Power Generating System		103
		6.4.1.1 MPPT Algorithm		103
		6.4.1.2 VSC Algorithm		105
	6.4.2	Control of Symmetrical Cascaded H-Bridge Seven-Level Converter Based PV Grid Tied Power Generating System		107
		6.4.2.1 MPPT Algorithm		108
		6.4.2.2 VSC Algorithm		108
6.5	MATLAB Based Modeling of Symmetrical Cascaded H-Bridge Multilevel Converter Based PV Grid Tied Power Generating System			110
	6.5.1	Modeling of Symmetrical Cascaded H-Bridge Five-Level Converter Based PV Grid Tied Power Generating System		110
	6.5.2	Modeling of Symmetrical Cascaded H-Bridge Seven-Level Converter Based PV Grid Tied Power Generating System		112
6.6	Hardware Implementation of Symmetrical Cascaded H-Bridge Seven-Level Converter Based PV Grid Tied Power Generating System			112
6.7	Results and Discussion			114
	6.7.1	Simulated Performance of Symmetrical Cascaded H-Bridge Five-Level Converter Based PV Grid Tied Power Generating System		114

		6.7.1.1	Steady State Performances	115
		6.7.1.2	Dynamic Performances	115
		6.7.1.3	Power Quality Performances	119
	6.7.2	Simulated Performance of Symmetrical Cascaded H-Bridge Seven-Level Converter Based PV Grid Tied Power Generating System		121
		6.7.2.1	Steady State Performances	122
		6.7.2.2	Dynamic Performances	122
		6.7.2.3	Power Quality Performances	128
	6.7.3	Experimental Performance of Symmetrical Cascaded H-Bridge Seven-Level Converter Based PV Grid Tied Power Generating Systems		133
		6.7.3.1	Steady State Performances	133
		6.7.3.2	Dynamic Performances	134
6.8	Conclusions			137
CHAPTER VII		BINARY CASCADED H-BRIDGE MULTILEVEL CONVERTER BASED PV GRID TIED POWER GENERATING SYSTEMS		139
7.1	General			139
7.2	Configurations of Binary Cascaded H-Bridge Multilevel Converter Based PV Grid Tied Power Generating System			139
	7.2.1	Configuration of Binary Cascaded H-Bridge Seven-Level Converter Based Multiple Source PV Grid Tied Power Generating System		140
	7.2.2	Configuration of Binary Cascaded H-Bridge Seven-Level Converter Based Single Source PV Grid Tied Power Generating System		140
	7.2.3	Configuration of Binary Cascaded H-Bridge Thirty One-Level Converter Based PV Grid Tied Power Generating System		141
7.3	Design of Binary Cascaded H-Bridge Multilevel Converter Based PV Grid Tied Power Generating System			142
	7.3.1	Design of Binary Cascaded H-Bridge Seven-Level Converter Based Multiple Source PV Grid Tied Power Generating System		143
		7.3.1.1 Design of PV Array		143
		7.3.1.2 Design of DC Link Capacitor		143
		7.3.1.3 Operating Principle of Binary Cascaded Seven-Level VSC		144
	7.3.2	Design of Binary Cascaded H-Bridge Seven-Level Converter Based Single Source PV Grid Tied Power Generating System		145
		7.3.2.1 Design of PV Array		145
		7.3.2.2 Design of DC Link Capacitor		145
		7.3.2.3 Operating Principle of Binary Cascaded Seven-Level VSC		146
	7.3.3	Design of Binary Cascaded H-Bridge Thirty One-Level Converter Based PV Grid Tied Power Generating System		148
		7.3.3.1 Design of PV Array		148
		7.3.3.2 Design of DC Link Capacitor		148
		7.3.3.3 Operating Principle of Binary Cascaded 31-Level VSC		149
7.4	Control of Binary Cascaded H-Bridge Multilevel Converter Based PV Grid Tied Power Generating System			150
	7.4.1	Control of Binary Cascaded H-Bridge Seven-Level Converter Based Multiple Source PV Grid Tied Power Generating System		151
		7.4.1.1 MPPT Algorithm		151
		7.4.1.2 VSC Algorithm		151

	7.4.2	Control of Binary Cascaded H-Bridge Seven-Level Converter Based Single Source PV Grid Tied Power Generating System		153
		7.4.2.1 MPPT Algorithm		153
		7.4.2.2 VSC Algorithm		153
	7.4.3	Control of Binary Cascaded H-Bridge Thirty One-Level Converter Based PV Grid Tied Power Generating System		155
		7.4.3.1 MPPT Algorithm		155
		7.4.3.2 VSC Algorithm		155
7.5	MATLAB Based Modeling of Binary Cascaded H-Bridge Multilevel Converter Based PV Grid Tied Power Generating System			157
	7.5.1	MATLAB Modeling of Binary Cascaded H-Bridge Seven-Level Converter Based Multiple Source PV Grid Tied Power Generating System		157
	7.5.2	MATLAB Modeling of Binary Cascaded H-Bridge Seven-Level Converter Based Single Source PV Grid Tied Power Generating System		157
	7.5.3	MATLAB Modeling of Binary Cascaded H-Bridge Thirty One-Level Converter Based PV Grid Tied Power Generating System		160
7.6	Hardware Implementation of Binary Cascaded H-Bridge Seven-Level Converter Based Multiple Source PV Grid Tied Power Generating System			160
7.7	Results and Discussion			162
	7.7.1	Simulated Performance of Binary Cascaded H-Bridge Seven-Level Converter Based Multiple Source PV Grid Tied Power Generating System		162
		7.7.1.1	Steady State Performances	163
		7.7.1.2	Dynamic Performances	163
		7.7.1.3	Power Quality Performances	165
	7.7.2	Simulated Performance of Binary Cascaded H-Bridge Seven-Level Converter Based Single Source PV Grid Tied Power Generating System		167
		7.7.2.1	Steady State Performances	167
		7.7.2.2	Dynamic Performances	167
		7.7.2.3	Power Quality Performances	167
	7.7.3	Simulated Performance of Binary Cascaded H-Bridge Thirty One-Level Converter Based PV Grid Tied Power Generating System		170
		7.7.3.1	Steady State Performances	170
		7.7.3.2	Dynamic Performances	173
		7.7.3.3	Power Quality Performances	177
	7.7.4	Experimental Performance of Binary Cascaded H-Bridge Seven-Level Converter Based Multiple Source PV Grid Tied Power Generating System		178
		7.7.4.1	Steady State Performances	178
		7.7.4.2	Dynamic Performances	178
7.8	Conclusions			181
CHAPTER VIII		TERNARY CASCADED H-BRIDGE MULTILEVEL CONVERTER BASED PV GRID TIED POWER GENERATING SYSTEMS		182
8.1	General			182

8.2	Configurations of Ternary Cascaded H-Bridge Multilevel Converters Based PV Grid Tied Power Generating System		182
	8.2.1	Configuration of Ternary Cascaded H-Bridge Nine-Level Converter Based Multiple Source PV Grid Tied Power Generating System	182
	8.2.2	Configuration of Ternary Cascaded H-Bridge Twenty Seven-Level Converter Based Multiple Source PV Grid Tied Power Generating System	183
	8.2.3	Configuration of Ternary Cascaded H-Bridge Twenty Seven-Level Converter Based Single Source PV Grid Tied Power Generating System	184
8.3	Design of Ternary Cascaded H-Bridge Multilevel Converters Based PV Grid Tied Power Generating System		185
	8.3.1	Design of Ternary Cascaded H-Bridge Nine-Level Converter Based Multiple Source PV Grid Tied Power Generating System	185
		8.3.1.1 Design of PV Array	185
		8.3.1.2 Design of DC Link Capacitor	186
		8.3.1.3 Operating Principle of Ternary Cascaded Nine-Level VSC	186
	8.3.2	Design of Ternary Cascaded H-Bridge Twenty Seven-Level Converter Based Multiple Source PV Grid Tied Power Generating System	187
		8.3.2.1 Design of PV Array	188
		8.3.2.2 Design of DC Link Capacitor	188
		8.3.2.3 Operating Principle of Ternary Cascaded 27-Level VSC	189
	8.3.3	Design of Single Source PV Grid Tied Power Generating System Using Ternary Cascaded H-Bridge Twenty Seven-Level Converter	190
		8.3.3.1 Design of PV Array	190
		8.3.3.2 Design of DC Link Capacitor	190
		8.3.3.3 Operating Principle of Ternary Cascaded Nine-Level VSC	191
8.4	Control of Ternary Cascaded H-Bridge Multilevel Converters Based PV Grid Tied Power Generating System		192
	8.4.1	Control of Ternary Cascaded H-Bridge Nine-Level Converter Based Multiple Source PV Grid Tied Power Generating System	192
		8.4.1.1 MPPT Algorithm	192
		8.4.1.2 VSC Algorithm	193
	8.4.2	Control of Ternary Cascaded H-Bridge Twenty Seven-Level Converter Based Multiple Source PV Grid Tied Power Generating System	194
	8.4.2	Control of Ternary Cascaded H-Bridge Twenty Seven-Level Converter Based Single Source PV Grid Tied Power Generating System	196
		8.4.3.1 MPPT Algorithm	197
		8.4.3.2 VSC Algorithm	198
8.5	MATLAB Based Modeling of Ternary Cascaded H-Bridge Multilevel Converters Based PV Grid Tied Power Generating System		199
	8.5.1	Modeling of Ternary Cascaded H-Bridge Nine-Level Converter Based Multiple Source PV Grid Tied Power Generating System	199
	8.5.2	Modeling of Ternary Cascaded H-Bridge Twenty Seven-Level Converter Based Multiple Source PV Grid Tied Power Generating System	199
	8.5.3	Modeling of Ternary Cascaded H-Bridge Twenty Seven-Level Converter Based Single Source PV Grid Tied Power Generating System	201
8.6	Hardware Implementation of Ternary Cascaded H-Bridge Nine-Level Converter Based Multiple Source PV Grid Tied Power Generating System		203

8.7	Results and Discussion		205
	8.7.1	Simulated Performance of Ternary Cascaded H-Bridge Nine-Level Converter Based Multiple Source PV Grid Tied Power Generating System	205
		8.7.1.1 Steady State Performances	205
		8.7.1.2 Dynamic Performances	206
		8.7.1.3 Power Quality Performances	208
	8.7.2	Simulated Performance of Ternary Cascaded H-Bridge Twenty Seven-Level Converter Based Multiple Source PV Grid Tied Power Generating System	208
		8.7.2.1 Steady State Performances	208
		8.7.2.2 Dynamic Performances	210
		8.7.2.3 Power Quality Performances	211
	8.7.3	Simulated Performance of Ternary Cascaded H-Bridge Twenty Seven-Level Converter Based Single Source PV Grid Tied Power Generating System	212
		8.7.3.1 Steady State Performances	213
		8.7.3.2 Dynamic Performances	213
		8.7.3.3 Power Quality Performances	214
	8.7.4	Experimented Performance of Ternary Cascaded H-Bridge Nine-Level Converter Based Multiple Source PV Grid Tied Power Generating System	216
		8.7.4.1 Steady State Performances	216
		8.7.4.2 Dynamic Performances	216
8.8	Conclusions		219
CHAPTER IX MULTIPULSE TWO LEVEL CONVERTER BASED PV GRID TIED POWER GENERATING SYSTEMS			220
9.1	General		220
9.2	Configurations of Multipulse Two-Level Converters Based PV Grid Tied Power Generating System		220
	9.2.1	Configuration of 12-Pulse Two-Level Converter Based PV Grid Tied Power Generating System	220
	9.2.2	Configuration of 18-Pulse Two-Level Converter Based PV Grid Tied Power Generating System	221
9.3	Design of Multipulse Two-Level Converters Based PV Grid Tied Power Generating System		221
	9.3.1	Design of 12-Pulse Two-Level Converter Based PV Grid Tied Power Generating System	221
		9.3.1.1 Design of PV Array	221
		9.3.1.2 Design of DC Capacitor Voltage	222
		9.3.1.3 Design of DC link Capacitor	222
		9.3.1.4 Design of Multipulse VSC	223
		9.3.1.5 Design of Interfacing Inductor	223
	9.3.2	Design of 18-Pulse Two-Level Converter Based PV Grid Tied Power Generating System	224
		9.3.2.1 Design of PV Array	224
		9.3.2.2 Design of DC link Capacitor	224
		9.3.2.3 Design of DC Capacitor Voltage	225

		9.3.2.4 Design of Multipulse VSC	225
		9.3.2.5 Design of Interfacing Inductor	226
9.4	Control of Multipulse Two-Level Converter Based PV Grid Tied Power Generating System		226
	9.4.1	Control of 12-Pulse Two-Level Converter Based PV Grid Tied Power Generating System	226
		9.4.1.1 MPPT Algorithm	227
		9.4.1.2 VSC Algorithm	227
	9.4.2	Control of 18-Pulse Two-Level Converters Based PV Grid Tied Power Generating System	229
		9.4.2.1 MPPT Algorithm	229
		9.4.2.2 VSC Algorithm	230
9.5	MATLAB Based Modeling of Multipulse Two-Level Converters Based PV Grid Tied Power Generating System		232
	9.5.1	Modeling of 12-Pulse Two-Level Converters Based PV Grid Tied Power Generating System	232
	9.5.2	Modeling of 18-Pulse Two-Level Converters Based PV Grid Tied Power Generating System	234
9.6	Results and Discussion		235
	9.6.1	Simulated Performance of 12-Pulse Two-Level Converters Based PV Grid Tied Power Generating System	235
		9.6.1.1 Steady State Performances	235
		9.6.1.2 Dynamic Performances	237
		9.6.1.3 Power Quality Performances	238
	9.6.2	Simulated Performance of 18-Pulse Two-Level Converters Based PV Grid Tied Power Generating System	238
		9.6.2.1 Steady State Performances	238
		9.6.2.2 Dynamic Performances	239
		9.6.2.3 Power Quality Performances	240
9.7	Conclusions		243
CHAPTER X		MAIN CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK	244
10.1	General		244
10.2	Main Conclusions		244
10.3	Suggestion for Further Work		249
APPENDICES			250
REFERENCES			254
LIST OF PUBLICATIONS			271
BIO-DATA			273

LIST OF FIGURES

- Fig. 3.1 System configuration for two-level converter based PV power generating system
- Fig. 3.2 Control architecture of the adaptive RZA based control with MPPT
- Fig. 3.3 Flowchart of P&O MPPT
- Fig. 3.4 Flowchart showing operation of PV-DSTATCOM System
- Fig. 3.5 MATLAB modeling for single-stage PV-DSTATCOM system
- Fig. 3.6 Photograph of developed laboratory prototype for three-phase PV-DSTATCOM system.
- Fig. 3.7 Photograph of d-SPACE 1202 Microlab box
- Fig. 3.8 Current sensor board (a) schematic (b) photograph
- Fig. 3.9 Voltage sensor board (a) schematic (b) photograph
- Fig. 3.10 Opto isolation board (a) schematic (b) photograph
- Fig. 3.11 Performance of the PV-DSTATCOM system under (a-b) load unbalancing (c-d) variation under solar insolation (a) v_{sabc} , i_{sabc} , i_{La} , i_{cnv} , P_s , Q_s (b) V_{dc} , I_{pv} , V_{pv} , P_{pv} , W_{pv} , W_{cp} (c) G , v_{sabc} , i_{sabc} , i_{La} , i_{cnv} , P_s (d) V_{dc} , I_{pv} , V_{pv} , P_{pv} , W_{pv} , W_{cp}
- Fig. 3.12 (a-c) Waveform and harmonic spectra of PV-DSTATCOM system (a) grid current and (b) load current and (c) VSC current
- Fig. 3.13 Steady state response of the PV-DSTATCOM grid tied system with linear loads (a) v_{sab} with i_{sc} (b) v_{ab} with i_a (c) v_{sab} with i_{sb} (d) grid power with i_{sc} (e) v_{sab} with i_{Lc} (f) v_{sab} with i_{La} (g) v_{sab} with i_{Lb} (h) load power with i_{Lc} (i) v_{sab} with i_{cnvc} (j) v_{sab} with i_{cnva} (k) v_{sab} with i_{cnvb} (l) VSC Power with i_{cnvc}
- Fig. 3.14 Steady state responses of the PV-DSTATCOM system under nonlinear loads (a) v_{sab} with i_{sc} (b) THD of i_{sc} (c) v_{sab} with i_{Lc} (d) THD of i_{Lc} , v_{sab} with i_{cnvc} (e-g) grid power, (h) load power and PV-VSC power.
- Fig. 3.15 (a-b) Steady state response of PV-DSTATCOM system at 1000 W/m² insolation
- Fig. 3.16 (a-b) Dynamic responses of the PV-DSTATCOM system under unbalanced nonlinear load in phase a (c-d) Dynamic responses of the PV-DSTATCOM system under unbalanced nonlinear load in phase a on phase c (e-h) Response of internal signals of control under unbalanced nonlinear load
- Fig. 3.17 Dynamic performance of the PV-DSTATCOM grid tied system (a) decrease in solar intensity (b) increase in solar intensity

- Fig. 3.18 MPPT performance of the PV-DSTATCOM system (a) 600 W/m² (b) 1000
- Fig. 3.19 Response of the PV-DSTATCOM grid tied system (a-b) Change from PV-DSTATCOM to DSTATCOM mode (c-d) Change from DSTATCOM to PV-DSTATCOM mode
- Fig. 4.1 System configuration for diode clamped three-level VSC based PV grid tied system
- Fig. 4.2 Block diagram of control approach for diode clamped three-level converter based PV grid tied system
- Fig. 4.3 IC based MPPT approach
- Fig. 4.4 MATLAB modeling for diode clamped three-level converter based grid tied PV power generating system
- Fig. 4.5 Prototype of diode clamped three level VSC based PV grid tied system
- Fig. 4.6 Steady state response of proposed system at 1000 W/m² solar insolation and 360 V supply voltage
- Fig. 4.7 Steady state response of proposed system at 1000 W/m² solar insolation and 415 V supply voltage
- Fig. 4.8 Steady state response of proposed system at 1000 W/m² solar insolation and 460 V supply voltage
- Fig. 4.9 Dynamic response of proposed system at varying solar insolation (400 to 1000 W/m² at 0.6 s) and 360 V supply voltage
- Fig. 4.10 Fig. Dynamic response of proposed system at varying solar insolation (400 to 1000 W/m² at 0.6 s) and 415 V supply voltage
- Fig. 4.11 Dynamic response of proposed system at varying solar insolation (400 W/m² to 1000 W/m² at 0.6 s) and 460 V supply voltage
- Fig. 4.12 Waveforms and harmonic spectra of three-level VSC based PV grid tied system (a) VSC line current and (b) VSC line voltage at 400 W/m² solar irradiance and 415 V supply voltage.
- Fig. 4.13 Waveforms and harmonic spectra of three-level VSC based PV grid tied system (a) VSC line current and (b) VSC line voltage at 1000 W/m² solar irradiance and 415 V supply voltage
- Fig. 4.14 Comparison of VSC line voltage THD at different insolation (W/m²) and supply grid voltages of three-level VSC based PV grid tied system

- Fig. 4.15 Comparison of VSC line current THD at different insolation (W/m^2) and supply grid currents of three-level VSC based PV grid tied system
- Fig. 4.16 MPPT performance of three-level VSC based PV grid tied system at (a) 1000W/m^2 (b) 600W/m^2
- Fig. 4.17 (a) Grid side parameters and power quality indices at 1000 W/m^2 (b) steady state performance of diode clamped three-level converter based PV grid tied system at 1000 W/m^2
- Fig. 4.18 Responses of internal signals of diode clamped three-level converter based PV grid tied system when PV intensity is decreased (600 W/m^2 from 1000 W/m^2)
- Fig. 4.19 Responses of internal signals of diode clamped three-level converter based PV grid tied system when PV intensity is increased (600 W/m^2 to 1000 W/m^2)
- Fig. 4.20 (a-b) Dynamic-state response of diode clamped three-level converter based PV grid tied system when irradiance level is decreased (600 W/m^2 from 1000 W/m^2)
- Fig. 4.21 (a-b) Dynamic-state response of diode clamped three-level converter based PV grid tied system when irradiance is increased from 600 W/m^2 to 1000 W/m^2 .
- Fig. 5.1 System configuration for flying capacitor three- level VSC based PV grid tied system
- Fig. 5.2 Control algorithm for proposed flying capacitor three- level VSC based PV grid tied system
- Fig. 5.3 Flowchart of IC based MPPT technique
- Fig. 5.4 (a-b) MATLAB modeling for flying capacitor three-level converter based grid tied solar power generating system
- Fig. 5.5 Schematic of HIL for proposed flying capacitor three- level VSC based PV grid tied system
- Fig. 5.6 Steady state response of flying capacitor three-level converter based PV grid tied system at 1000W/m^2 solar insolation
- Fig. 5.7 Dynamic response of flying capacitor three-level converter based PV grid tied system at varying solar insolation (600 to 800 W/m^2 at 1.26 s and 800 to 1000 W/m^2 at 1.44 s)

- Fig. 5.8 (a-c) Dynamic response of internal signals of the system control at varying solar insolation (600 to 800 W/m² at 1.26 s and 800 to 1000 W/m² at 1.44 s)
- Fig. 5.9 Waveforms and harmonic spectra of flying capacitor three-level based PV grid tied system (a) VSC line current and (b) VSC line voltage at 1000 W/m² solar irradiance
- Fig. 5.10 Variation of grid current THD (%) with solar insolation (W/m²) of flying capacitor three-level based PV grid tied system
- Fig. 5.11 Steady State response of HIL system (a) v_{sa} , i_{sa} , V_{Cab} , V_{dc} (b) V_{dc1} , V_{dc2} , I_{pv} , V_{pv} (c) P_{pv} , P , Q^* , Q (d) v_{sa} , i_{sa} , V_{Cab} , V_{dc} (e) V_{dc1} , V_{dc2} , I_{pv} , V_{pv} (f) P_{pv} , P , Q^* , Q
- Fig. 5.12 Response of HIL system on changing the isolation level from 600 to 1000 W /m² (a) v_{sa} , v_{sb} , v_{sc} , V_{dc} (b) i_{sa} , i_{sb} , i_{sc} , V_{dc2} (c) V_{Cab} , V_{Cbc} , V_{Cca} , V_{dc1} (d) I_{pv} , P_{pv} , P , Q
- Fig. 5.13 Response of internal signals of the control algorithm in HIL system on changing the isolation level from 600 to 1000 W /m² (a) I_{pv} , I_{dc} , I_d^* , I_d (b) I_q^* , I_q , dV_q , V_c (c) V_d , dV_d , V_d^* , V_q^* (d) m , v_{sa}^* , v_{sb}^* , v_{sc}^*
- Fig. 6.1 System configuration for symmetrical cascaded five level VSC based PV grid tied system
- Fig. 6.2 System configuration for symmetrical cascaded seven-level VSC based PV grid tied system
- Fig. 6.3 Control algorithm for proposed symmetrical cascaded five-level VSC based PV-STATCOM system
- Fig. 6.4 Flow-chart for IC based MPPT
- Fig. 6.5 Block diagram of DDSRF-PLL algorithm
- Fig. 6.6 (a) Control algorithm for symmetrical cascaded five-level VSC based PV-STATCOM system (b) PSD-dqPLL
- Fig. 6.7 (a-c) MATLAB modeling for symmetrical cascaded five-level converter based grid tied solar power generating system
- Fig. 6.8 (a-c) MATLAB modeling for symmetrical cascaded seven-level converter based grid tied solar power generating system
- Fig. 6.9 Schematic of HIL for proposed seven level based PV system.
- Fig. 6.10 Steady state response of the symmetrical cascaded five-level converter based PV grid tied system at 1000 W/m²

- Fig. 6.11 Dynamic response of PV currents of system at varying irradiance level (500 to 1000 W/m² at 0.5 s)
- Fig. 6.12 Dynamic response of PV voltages of system at varying irradiance level (500 to 1000 W/m² at 0.5 s)
- Fig. 6.13 Dynamic response of PV powers of system at varying irradiance level (500 to 1000 W/m² at 0.5 s)
- Fig. 6.14 Dynamic response of system at varying irradiance level (500 to 1000 W/m² at 0.5 s)
- Fig. 6.15 Performance of the PV-STATCOM in Mode-2 at 1000 W/m² irradiance level
- Fig. 6.16 Performance of the PV-STATCOM in Mode-3 at zero solar irradiance level
- Fig. 6.17 Waveforms and harmonic spectra of symmetrical cascaded five-level converter based PV grid tied system (a) i_{sa} and (b) V_{Cab} at 500 W/m²
- Fig. 6.18 Waveforms and harmonic spectra of symmetrical cascaded five-level converter based PV grid tied system (a) i_{sa} and (b) V_{Cab} at 1000 W/m²
- Fig. 6.19 Steady state response of proposed symmetrical cascaded seven-level converter based PV-STATCOM system in Mode 1 at 1000 W/m² solar irradiance
- Fig. 6.20 Dynamic response of PV currents of symmetrical cascaded seven-level converter based PV-STATCOM system at varying irradiance
- Fig. 6.21 Dynamic response of PV voltages of symmetrical cascaded seven-level converter based PV-STATCOM system at varying irradiance
- Fig. 6.22 Dynamic response of PV powers of symmetrical cascaded seven-level converter based PV-STATCOM system at varying irradiance
- Fig. 6.23 Dynamic response of symmetrical cascaded seven-level converter based PV-STATCOM system at varying irradiance
- Fig. 6.24 Dynamic response of PV power of proposed system under unbalance power generation from the PV at varying solar insolation at 0.5 s
- Fig. 6.25 Dynamic response of system under unbalance power generation from the PV at varying solar insolation at 0.5 s
- Fig. 6.26 Performance of the symmetrical cascaded seven-level converter based PV-STATCOM system in Mode-2 at 1000 W/m² irradiance level
- Fig. 6.27 Performance of the symmetrical cascaded seven-level converter based PV-STATCOM system in Mode-3 at zero solar irradiance level

- Fig. 6.28 Harmonic spectrum of symmetrical cascaded seven-level converter based PV-STATCOM system (a) i_{sa} and (b) v_{Cab} at 1000 W/m^2
- Fig. 6.29 Harmonic spectrum of symmetrical cascaded seven-level converter based PV-STATCOM system (a) i_{sa} and (b) v_{Cab} at 400 W/m^2
- Fig. 6.30 Harmonic spectrum of i_{sa} of symmetrical cascaded seven-level converter based PV-STATCOM system in Mode-2 at zero reactive power reference
- Fig. 6.31 Harmonic spectrum of i_{sa} of symmetrical cascaded seven-level converter based PV-STATCOM system in Mode-2 at positive reactive power reference
- Fig. 6.32 Harmonic spectrum of i_{sa} of symmetrical cascaded seven-level converter based PV-STATCOM system in Mode-2 at negative reactive power reference
- Fig. 6.33 Harmonic spectrum of i_{sa} of symmetrical cascaded seven-level converter based PV-STATCOM system in Mode-3 at negative reactive power reference
- Fig. 6.34 Harmonic spectrum of i_{sa} of symmetrical cascaded seven-level converter based PV-STATCOM system in Mode-3 at negative reactive power reference
- Fig. 6.35 Steady state response of proposed PV-STATCOM HIL system in Mode 1 at 1000 W/m^2 solar insolation (a) v_{sa} , i_{sa} , i_{sb} , i_{sc} (b) V_{dc} , v_{Ca} , v_{Cb} , v_{Cc} .
- Fig. 6.36 Dynamic response of proposed HIL system under unbalance power generation at varying solar insolation of all nine PV array from 400 W/m^2 to 1000 W/m^2 at different times (a) v_{sa} , i_{sa} , v_{Ca} , V_{dc} , (b) P_{pv} , P , Q^* , Q (c) V_{pv1} , I_{pv1} , I_{pv2} , I_{pv3} (d) I_{pv4} , I_{pv5} , I_{pv6} (e) I_{pv7} , I_{pv8} , I_{pv9}
- Fig. 6.37 Performance of the PV-STATCOM HIL system in Mode-2 at 1000 W/m^2 irradiance level and $Q^* = 40 \text{ kVAR}$ (a) v_{sa} , i_{sa} , v_{Ca} , V_{dc} , (b) P_{pv} , P , Q^* , Q
- Fig. 6.38 Performance of the PV-STATCOM HIL system in Mode-2 at 1000 W/m^2 irradiance level and $Q^* = -40 \text{ kVAR}$ (a) v_{sa} , i_{sa} , v_{Ca} , V_{dc} , (b) P_{pv} , P , Q^* , Q
- Fig. 6.39 Performance of the PV-STATCOM HIL system in Mode-3 at $P_{pv} = 0$ (a) v_{sa} , i_{sa} , v_{Ca} , V_{dc} at $Q^* = 40 \text{ kVAR}$ (b) v_{sa} , i_{sa} , v_{Ca} , V_{dc} at $Q^* = -40 \text{ kVAR}$
- Fig. 7.1 Schematic diagram of binary cascaded seven-level VSC based grid tied multiple source PV system
- Fig. 7.2 Schematic diagram of binary cascaded seven level based grid tied single source PV system
- Fig. 7.3 Schematic diagram of binary cascaded 31-level VSC based grid tied multiple source PV system

- Fig. 7.4 Switching diagram of binary cascaded seven-level converter
- Fig. 7.5 Control algorithm for proposed asymmetric cascaded seven-level VSC based PV system
- Fig. 7.6 Switching diagram of binary cascaded seven-level converter
- Fig. 7.7 Control algorithm for proposed single source PV system using seven-level VSC
- Fig. 7.8 Logic for step generation using level shifted IPD PWM technique for ternary cascaded 31-level VSC based PV grid tied system
- Fig. 7.9 Control algorithm for proposed asymmetric cascaded thirty one-level VSC based PV system
- Fig. 7.10 (a-c) MATLAB model of binary cascaded seven-level converter based grid tied solar power generating system
- Fig. 7.11 (a-c) MATLAB model of single source binary cascaded seven-level converter based grid tied PV generating system
- Fig. 7.12 (a-c) MATLAB model of binary cascaded thirty one-level converter based grid tied PV system
- Fig. 7.13 Schematic of HIL for proposed binary seven-level converter based PV system
- Fig. 7.14 Steady state performance of proposed system at solar irradiance 1000 W/m^2
- Fig. 7.15 (a-b) Dynamic performance of binary cascaded seven-level converter based PV grid tied system at varying solar insolation (600 to 1000 W/m^2 at 0.8 s)
- Fig. 7.16 Waveforms and harmonic spectra of binary cascaded seven-level converter based PV grid tied system (a) VSC line current and (b) VSC line voltage at 600 W/m^2 solar irradiance
- Fig. 7.17 Waveforms and harmonic spectra of binary cascaded seven-level converter based PV grid tied system (a) VSC line current and (b) VSC line voltage at 1000 W/m^2 solar irradiance
- Fig. 7.18 Steady state performance of binary cascaded seven-level converter based single source PV grid tied system at 1000 W/m^2 solar insolation
- Fig. 7.19 Dynamic performance of binary cascaded seven-level converter based single source PV grid tied system at varying solar insolation (500 to 1000 W/m^2 at 1 s)

- Fig. 7.20 Waveforms and harmonic spectra of binary cascaded seven-level converter based single source PV grid tied system (a) line current and (b) VSC line voltage at 500 W/m^2 solar irradiance
- Fig. 7.21 Waveforms and harmonic spectra of binary cascaded seven-level converter based single source PV grid tied system (a) line current and (b) VSC line voltage at 1000 W/m^2 solar irradiance
- Fig. 7.22 (a-d) Steady state performance of binary cascaded H-bridge 31-level VSC based PV grid tied system at 1000 W/m^2 irradiance level
- Fig. 7.23 (a-b) Steady state performance of internal signals of the proposed control algorithm for binary cascaded H-bridge 31-level VSC based PV grid tied system at 1000 W/m^2 irradiance level
- Fig. 7.24 (a-d) Dynamic performance of binary cascaded H-bridge 31-level VSC based PV grid tied system under varying irradiance level
- Fig. 7.25 (a-b) Dynamic performance of internal signals of the proposed control algorithm for binary cascaded H-bridge 31-level VSC based PV grid tied system under varying irradiance level
- Fig. 7.26 Waveforms and harmonic spectra of binary cascaded H-bridge 31-level VSC based PV grid tied system (a) VSC line voltage (b) line current and at 1000 W/m^2 solar irradiance
- Fig. 7.27 Steady State response of HIL system (a) v_{sa} , v_{sb} , v_{sc} , V_{dc1} , (b) i_{sa} , i_{sb} , i_{sc} , V_{dc2} , (c) v_{Ca} , v_{Cb} , v_{Cc} , I_{pv1} (d) P_{pv} , P , Q^* , Q
- Fig. 7.28 Performance of binary cascaded 7-level based multiple source PV grid tied system on changing the irradiance level from 600 to 1000 W/m^2 (a) v_{sa} , v_{sb} , v_{sc} , V_{dc1} (b) i_{sa} , i_{sb} , i_{sc} , V_{dc2} (c) v_{Cab} , v_{Cbc} , v_{Cca} , I_{pv1} (d) P , Q , P_{pv}
- Fig. 7.29 Response of intermediate signals of the control algorithm of binary cascaded 7-level based multiple source PV grid tied system on changing the isolation level from 600 to 1000 W/m^2 (a) I_{pv} , I_{loss} , I_d^* , I_d (b) I_q^* , I_q , dV_q (c) V_d , dV_d , V_d^* , V_q^* (d) m , v_{sa}^* , v_{sb}^* , v_{sc}^*
- Fig. 8.1 Schematic diagram of proposed ternary cascaded nine-level based PV grid tied system
- Fig. 8.2 Schematic diagram of multiple source 27-level cascaded VSC based PV grid tied system

- Fig. 8.3 Schematic diagram of single source 27-level cascaded VSC based PV grid tied system
- Fig. 8.4 SHE switching angles in output voltage level pattern for Nine-level cascaded H-bridge converter
- Fig. 8.5 Logic for step generation using level shifted IPD PWM technique for 27 level converter
- Fig. 8.6 Control algorithm for proposed ternary cascaded 9-level VSC based PV system
- Fig. 8.7 Control algorithm for ternary cascaded 27-level converter based multiple source PV grid tied power generating system
- Fig. 8.8 IC based MPPT Control
- Fig. 8.9 Control scheme for ternary 27-level cascaded H-bridge VSC based single source PV grid tied system
- Fig. 8.10 (a-b) MATLAB model of ternary cascaded nine-level VSC based grid tied PV power generating system.
- Fig. 8.11 (a-c) MATLAB model of ternary cascaded 27-level converter based grid tied multiple source PV system.
- Fig. 8.12 (a-c) MATLAB model of ternary cascaded 27-level converter based grid tied single source PV system.
- Fig. 8.13 Schematic of HIL for proposed ternary nine-level converter based PV system.
- Fig. 8.14 Steady state performance of proposed PV grid tied system based on ternary 9 level converter at solar irradiance 1000 W/m^2
- Fig. 8.15 (a, b) Dynamic performance of proposed PV grid tied system based on ternary 9-level converter at varying solar insolation (600 to 1000 W/m^2 at 0.8 s)
- Fig. 8.16 (a-b) Dynamic performance of internal signals of the control algorithm for the ternary 9-level VSC based by PV system under varying irradiance level
- Fig. 8.17 Waveforms and harmonic spectra of ternary cascaded nine-level VSC based PV grid tied system (a) VSC line current and (b) VSC line voltage at 1000 W/m^2 solar irradiance.
- Fig. 8.18 Steady state performance of ternary cascaded 27-level VSC based PV grid tied system at 1000 W/m^2

- Fig. 8.19 Dynamic state performance of ternary cascaded 27-level VSC based PV grid tied system on changing solar irradiance level (500 to 1000 W/m²) at 0.5 s
- Fig. 8.20 Waveforms and the harmonic spectra of ternary cascaded 27-level VSC based PV grid tied system (a) i_{sa} and (b) v_{ca} at 500 W/m²
- Fig. 8.21 Waveforms and the harmonic spectra of ternary cascaded 27-level VSC based PV grid tied system (a) i_{sa} and (b) v_{ca} at 1000 W/m².
- Fig. 8.22 Steady state responses of 27-level ternary cascaded VSC based single source PV grid tied system at 1000 W/m² level
- Fig. 8.23 Dynamic state responses of 27-level ternary cascaded VSC based single source PV grid tied system on changing solar insolation from 500 W/m² to 1000 W/m² at 0.4 s
- Fig. 8.24 Harmonic analysis of ternary cascaded 27-level VSC based single source PV grid tied system (a) i_{sa} (A) and (b) V_{Ca} (V) at 500 W/m² solar irradiance
- Fig. 8.25 Harmonic analysis of ternary cascaded 27-level VSC based single source PV grid tied system (a) i_{sa} (A) and (b) V_{Ca} (V) at 1000 W/m² solar irradiance
- Fig. 8.26 Steady state response of ternary cascaded 9-level VSC based PV grid tied system on HIL platform (a) i_{sa} , v_{sa} , v_{sb} , v_{sc} , (b) v_{sa} , i_{sa} , i_{sb} , i_{sc} (c) v_{Ca} , v_{Cb} , v_{Cc} (d) P_{pv} , P , Q
- Fig. 8.27 Performance of ternary cascaded 9-level VSC based PV grid tied system on HIL platform subject to varying irradiance level from 600 to 1000 W /m² (a) v_{sa} , v_{sb} , v_{sc} , V_{dc1} (b) I_{pv1} , I_{pv2} V_{pv1} V_{pv2} (c) i_{sa} , v_{Ca} , v_{Cb} , v_{Cc} , (d) P_{pv} , P , Q
- Fig. 8.28 Fig. 8.28 Response of intermediate signals of the controller subject to varying isolation level from 600 to 1000 W /m² (a) I_d , I_d^* , V_d , V_d^* , (b) I_q , I_q , dV_q (c) V_d , dV_d , V_d^* , V_q^* (d) m , v_{sa}^* , v_{sb}^* , v_{sc}^*
- Fig. 9.1 Proposed configuration for 12-pulse VSC based PV grid integrated power generating system
- Fig. 9.2 Configuration of two-level double bridge 18-pulse VSC based PV grid interfaced power generating system
- Fig. 9.3 (a) Control algorithm for the proposed 12-pulse converter based grid tied PV system and (b) SSI-PLL
- Fig. 9.4 Control algorithm for proposed 18-pulse converter based PV grid tied system
- Fig. 9.5 Block diagram of robust synchronizing PLL

- Fig. 9.6 (a-c) MATLAB modeling for two-level 12-pulse converter based grid tied solar power generating system.
- Fig. 9.7 (a-c) MATLAB model of two-level 18-pulse converter based grid tied PV power generating system.
- Fig. 9.8 (a-b) Steady state responses of the proposed 12-pulse converter based grid tied PV system
- Fig. 9.9 (a-b) Dynamic performance of proposed 12-pulse converter based grid tied PV system
- Fig. 9.10 (a-b) Waveform and harmonic spectra of 12-pulse converter based grid tied PV system (a) grid current and (b) converter voltage at primary terminal of transformer
- Fig. 9.11 (a-b) Steady state response of proposed 18-pulse converter based grid tied PV system at solar irradiance 1000 W/m^2
- Fig. 9.12 (a-b) Dynamic performance of proposed 18-pulse converter based grid tied PV system
- Fig. 9.13 Current controller internal signals of the proposed 12-pulse converter based grid tied PV system
- Fig. 9.14 Waveform and harmonic spectra of 18-pulse converter based grid tied PV system (a) grid current and (b) converter voltage at primary terminal of transformer

LIST OF TABLES

Table 3.1	Details of PV array model
Table 4.1	Comparison of grid voltage THD and grid current THD AT 900 Hz and 6.5 mH
Table 4.2	Comparison of grid voltage THD and grid current THD AT 1800 Hz and 6.5 mH
Table 4.3	Comparison of grid voltage THD and grid current THD AT 1800 Hz and 4.9 mH
Table 5.1	Comparison of VSC line voltage THD and grid current THD at different insolation of flying capacitor three-level based PV grid tied system
Table 5.2	Comparison of VSC line voltage THD and grid current THD at different insolation of flying capacitor three-level based PV grid tied system
Table 5.3	Comparison of VSC line voltage THD and grid current THD at different insolation of flying capacitor three-level based PV grid tied system
Table 6.1	Switching states for five-level symmetrical cascaded VSC
Table 6.2	Switching states for symmetrical cascaded 7-level cascaded converter
Table 6.3	Variations of grid line current, VSC line voltage THD and power factor with irradiance at $f_{sw} = 900$ Hz of symmetrical cascaded five-level converter based PV grid tied
Table 6.4	Variations of grid line current, VSC line voltage THD and power factor with irradiance AT $f_{sw} = 1800$ Hz of symmetrical cascaded five-level converter based PV grid tied
Table 7.1	Switching state of seven-level asymmetric cascaded H-bridge inverter
Table 7.2	Design of PV arrays for 31-level cascaded VSC based PV system
Table 7.3	Variations of VSC line voltage THD, supply line current THD and power factor with solar insulations of binary cascaded seven-level converter based PV grid tied system
Table 7.4	Variations of VSC line voltage THD, supply line current THD and power factor with solar insulations of binary cascaded seven-level converter based single source PV grid tied system
Table 7.5	Variations of VSC line voltage THD, supply line current THD and power factor with solar insulations of binary cascaded H-bridge 31-level VSC based PV grid tied system

Table 8.1	Design of PV arrays for 9-level ternary cascaded VSC based PV system
Table 8.2	SHE angles for different modulation index
Table 8.3	Design of PV arrays for 27-level cascaded VSC based multiple source PV system
Table 8.4	Variations of VSC line voltage THD, supply line current THD and power factor with solar insulations of ternary cascaded 9-level VSC based PV grid tied system
Table 8.5	Variations of v_{ca} THD, i_{sa} THD and power factor with varying PV irradiances of ternary cascaded 27-level VSC based PV grid tied system
Table 8.6	Variations of V_{Ca} THD, i_{sa} THD and power factor at varying solar irradiance levels of ternary cascaded 27-level VSC based single source PV grid tied system
Table 9.1	Variations of VSC line voltage THD, supply line current THD and power factor with solar insulations of 18-pulse converter based PV grid tied system

LIST OF ABBREVIATIONS

PV	Solar photovoltaic
VSC	Voltage source converter
IEEE	Institute of Electrical and Electronics Engineers
IEC	International Electrotechnical Commission
MPPT	Maximum power point tracking
PLL	Phase locked loop
DSTATCOM	Distribution static compensator
STATCOM	STATIC COMPensator
THD	Total harmonic distortion
MATLAB	Matrix laboratory
HIL	Hardware in-loop
PWM	Pulse width modulation
PCC	Point of common coupling
IC	Incremental conductance
P&O	Perturb and observe
MPP	Maximum power point
DVR	Dynamic voltage restorers
UPQC	Unified power quality conditioners
LMF	Least mean fourth
EPLL	Enhanced phase locked loop
CTF	Current triangle function
NPC	Neutral-point-clamped
RZA	Adaptive reweighted zero-attracting
IGBT	Insulated gate bipolar transistor
DSP	Digital signal processor
DAC	Digital to analog converter
ADC	Analog to digital converter
PI	Proportional integral
RMS	Root mean square
LPF	Low pass filter
SRF	Synchronous reference frame
DDSRF	Decoupled double synchronous reference frame

kVAR	Kilo volt amperes reactive
KVA	Kilo volt amperes
kW	Kilo watts
PD	Phase deposition
SHE	Selective harmonic elimination
FFS	Fundamental switching frequency
SSI-PLL	Sinusoidal signal integrator-phase locked loop

LIST OF SYMBOLS

$V_{sab}, V_{sbc}, V_{sca}$	Grid Line voltages
V_{sa}, V_{sb}, V_{sc}	Phase voltages
i_{sa}, i_{sb}, i_{sc}	Grid line currents
N_s	Number of PV modules connected in series
N_p	Number of PV modules connected in parallel
V_{dc}	DC link voltage
m	Modulation index
V_{mp}	Voltage of one module at maximum power point
I_{mp}	Current of one module at maximum power point
P_{pv}	PV array power
V_{pv}	PV array voltage
I_{pv}	PV array current
V_{ripple}	Ripple in DC link voltage
L_i	Interfacing inductor
Δi	Current ripple
f_{sw}	Switching frequency of VSC
R_f, C_f	Ripple filter
V_t	Amplitude of terminal voltage
u_{pa}, u_{pb} and u_{pc}	In-phase unit templates
u_{qa}, u_{qb} and u_{qc}	Quadrature unit templates
w_{cq}	Reactive loss component
K_{pt} and K_{it}	Proportional and integral gain constants of AC voltage controller
V_{de}	DC voltage error
$V_{dc_{ref}}$	Reference DC bus voltage
V_{dc}	Sensed DC voltage
C_{dc}	DC link capacitor voltage
K_{pd} and K_{id}	Proportional and integral constant of DC link voltage controller
I_{ff}	PV feed-forward term
I_{loss}	AC loss component
i_{La}, i_{Lb}, i_{Lc}	Three phase load currents
e_{pa}	Error in the active load current component
e_{qa}	Error in the reactive load current component

w_{sp}	Total weight of active component of reference grid currents
$i_{sa}^*, i_{sb}^*, i_{sc}^*$	Three phase reference grid currents
T_s	Sampling time
$i_{cnva}, i_{cnvb}, i_{cnvc}$	VSC currents
G	Insulations level
P	Grid active power
Q	Grid reactive power
f	Grid frequency
I_d^*	Reference direct axis current component
I_d	Direct axis current component
I_q^*	Reference quadrature axis current component
I_q	Quadrature axis current component
V_d^*	Reference direct axis voltage component
V_d	Direct axis voltage component
V_q^*	Reference quadrature axis voltage component
V_q	Quadrature axis voltage component
v_{sa}^*, v_{sb}^* and v_{sc}^*	Reference phase voltages
V_{thd}	THD in the grid voltages
I_{thd}	Grid current THD