

INTELLIGENT CONTROL OF GRID INTERFACED AND OFF-GRID SOLAR PV SYSTEMS

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**DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
JANUARY 2020**

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by

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Submitted

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

to the



**INDIAN INSTITUTE OF TECHNOLOGY DELHI
JANUARY 2020**

CERTIFICATE

It is certified that the thesis entitled “**Intelligent Control of Grid-Interfaced and Off-Grid Solar PV Systems**,” being submitted by **Mr. Vedantham Lakshmi Srinivas** 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.

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ACKNOWLEDGEMENTS

I wish to express my deepest gratitude and indebtedness to **Prof. Bhim Singh** and **Prof. Sukumar Mishra** for providing me guidance and constant supervision to carry out the Ph.D. work. Working under him has been a wonderful experience, which has provided a deep insight to the world of research. Determination, dedication, innovativeness, resourcefulness and discipline of **Prof. Bhim Singh** and **Prof. Sukumar Mishra** have been the inspiration for me to complete this work. Their consistent encouragement, continuous monitoring and commitments to excellence have always motivated me to improve my work and use the best of my capabilities. Due to their blessing I have earned various experiences other than research which will help me throughout my life.

My sincere thanks and deep gratitude are to **Prof. G. Bhuvaneswari**, **Prof. N. Senroy** and **Dr. Ashu Verma**, all SRC members for their valuable guidance and consistent support during my research work.

I wish to convey my sincere thanks to **Prof. Bhim Singh**, **Prof. Sukumar Mishra**, **Prof. A. R. Abhayankar**, **Prof. B. K. Panigrahi**, **Prof. N. Senroy**, **Dr. Shubhendu Bhasin** and **Prof. P.R. Bijwe** for their valuable inputs during my course work which made the foundation for my research work. Moreover, my sincere thanks and deep gratitude are to **Prof. Bikash Pal**, **Prof. Chandan Chakraborty**, **Prof. Lie Xu**, **Prof. H. M. Suryawanshi** and **Prof. Vishal Verma** for their valuable support and guidance during collaborative work under “Indo-UK, RESCUES (Reliable and Efficient System for Community Energy Solutions)” and “Indo-UK, UKICERI (United Kingdom India Clean Energy Research Initiative)” projects. I am grateful to **IIT Delhi** for providing me the research facilities. I would wish to express my sincere gratitude to **Prof. G.**

Bhuvaneswari, in-charge, PG Machine Lab., for providing me immense facilities to carry out experimental work. Moreover, I express my thanks to **Dr. A. P. Prathosh** for valuable guidance at different times for collaboration work. Thanks are due to Sh. Srichand, Sh. Puran Singh, Sh. Jagbir Singh, Sh. Satey Singh Negi of PG Machines Lab, UG Machines Lab and Power Electronics Lab., IIT Delhi for providing me the facilities and assistance during this work.

I would like to offer my sincere thanks to Dr. Shailendra Dwivedi who suggested me to pursue Ph.D. with Prof. Bhim Singh. Moreover, I would like to thank all my seniors, Dr. Shailendra Kumar, Dr. Nishant Kumar, Dr. Ikhlq Hussain, Dr. Aniket Anand, Dr. N. K. Swami Naidu and Dr. Rajan Sonkar to motivate me in the starting of my research work. I would like to use this opportunity to thank Dr. Sachin Devassy, who has constantly helped me on all technical and non-technical issues. My sincere thanks to Mr. Priynak Mukeshkumar Shah and Mr Abdul Saleem Mir for co-operation and informal support in pursuing this research work.

Moreover, I would like to thank Mr. Anshul Varshney, Mr. Anjanee Mishra, Mr. Deepu Vijay, Mr. Shadab Murshid, Mr. Piyush Kant, Mr. Saurabh Shukla, Mr Shubam Sundeep, Mr Rakesh Panda, Mr. Aryadip and all PG machines lab group for their valuable support. How could I forget my room mates Mr. Varun Kumar Gupta, Mr. Jayanth Reddy Danda, Mr. Pavitra Kumar, Mr. Manishankar, Mr. Baljender Singh, Mr. Suryansh Jasuja and Mr Shivam who supported and inspired me during my stay in Delhi.

I would also like to thank Mr. Satish, Mr. Yatindra, Mr. Narendra, Mr. Sandeep and all other electrical engineering office staff for being supportive throughout. I am likewise thankful to those who have directly or indirectly helped me to finish my dissertation study.

Moreover, I would like to thank the **Ministry of Human Resource Development (MHRD)**, India for financial support during this research work.

I would like to thank my mother, **Mrs. V. Lalitha**, my father **Mr. V. Lakshmidhar** and my grandfather **Mr. V Lakshmipathi** for their dreams, blessings and constant encouragement. Moreover, I would like to thank all my family members for giving me the inner strength and wholehearted support. I declare that the prayers and blessings of my spiritual master, as the one and only key factor that contributed to all my achievements. I am beholden to almighty lord Krishna for His blessings to help me to raise my academic level to this stage, with different arrangements. I pray for His benediction in my future endeavors. His blessings may be showered on me for strength, wisdom and determination to achieve in future.

Dated:

Vedantham Lakshmi Srinivas

ABSTRACT

Rapid increasing trend of electric energy demand in the world and depletion of fossil fuel reserves motivate power generation from renewable energy sources. The renewable energy sources based distributed generation system contributes a minimization of greenhouse gas emissions and environmental impacts caused thereby. For this reason, renewable energy systems have been promoted worldwide to address the issues of energy poverty, pollution and climate change. An increased dependence on renewable energy resources is exhibited in recent years. Over 13.5% of global energy demand at present is met through renewable energy sources. Solar energy is an important renewable energy source that is expected to play a significant role in the future energy supply and consequently, solar photovoltaic based renewable energy system has emerged as a prominent contender.

The growing interest has been exhibited in grid integrated PV systems and also off-grid systems. Several issues are associated with operation of solar PV systems in grid-interfaced and off-grid operational modes. Firstly, the use of nonlinear loads in power conversion devices as lighting, medical equipment and electric traction has increased the concerns to maintain power quality in the distribution network. These nonlinear loads introduce the harmonics current which lead to reduced life and mal-operation of the power devices. Secondly, the load side neutral currents happen to cause the grid neutral current flow, thereby obstructing the general safety to personnel and the equipment. Thirdly, the leakage currents caused by the parasitic capacitance between the solar PV array and the ground, reduce the life-span of the solar PV array and cause safety issues to the operating personnel. Besides these, the grid integration of inertia-less solar PV system cannot support frequency regulation in the system. Moreover, the uninterrupted

operation of solar PV system under grid-side faults and sensor malfunctioning events is desired. Since the power electronic technology plays a major role, the research is focused on developing intelligent control techniques in addressing the aforementioned issues.

This research work aims at development and implementation of intelligent control strategies to address various challenges faced in three-phase grid-interfaced and off-grid solar photovoltaic systems. The strategies developed are simulated in MATLAB based environment for successful operation, and the laboratory prototypes are built to validate the simulation results through various experiments.

This research work mainly focusses on the solar PV systems connected in the distribution network. The different problems addressed in this work are classified as- (i) power quality improvement in three phase grid interfaced solar PV system under weak distribution grids (ii) low-voltage ride-through strategy in double stage solar PV system enabling load compensation capabilities (iii) leakage current suppression in grid-interfaced transformer-less PV system with power quality improvement features (iv) Inertia emulated solar PV system and its seamless transition under unintentional islanding events (v) control design for resilient operation of solar PV system under sensor malfunctioning events and cyber-attacks. In case of two-stage PV system, the first stage is a boost converter which serves for MPPT (Maximum Power Point Tracking) and the second stage is a grid tied VSC (Voltage Source Converter).

Initially, a methodology for three-phase grid-interfaced two-stage solar PV system for grid-currents balancing, grid harmonic-currents mitigation and reactive-power compensation under abnormal grid scenarios is contemplated. This system also ensures crest power extraction, neutral current compensation capability, VSC loss minimization, even during distorted grid voltages that occur at far radial ends in the distribution system. Then after, a low-voltage ride-through method

for double stage solar PV array system is proposed which enables inherent VSC overcurrent protection and supplies reactive power compensation as per revised grid code. A methodology for leakage current elimination in two-stage PV system is then developed, to improve the life-span of a solar PV array system, without compromising the power quality improvement features such as grid-currents balancing, grid harmonic-currents mitigation and reactive-power compensation. Then after, a generalized predictive control based harmonic-voltage controller for three-phase grid-interfaced and off-grid distributed generation system. A minimization criterion is used in generalized predictive controller to achieve accurate output voltage tracking performance and flexibly control the output harmonic voltage, and thereby, the harmonic currents entering the grid, are regulated in grid interfaced operation. Moreover, a method for seamless transition of a distributed generation source based virtual synchronous generator is investigated, where the seamless transition is realized without any need for separate synchronizing tools or separate islanding detection algorithms. It inherits the grid-synchronization and islanding detection within itself, without dependency on the signal from the dedicated synchronization units. The system is not prone to delays in islanding detection during unintentional islanding events. Finally, a methodology is developed for uninterrupted operation of grid-interfaced solar PV system, which provides resilient operation under current-sensor malfunctioning events and various false-data injections. This control technique effectively identifies the malfunction/attack signal and generates corrective action. The performance evaluation of different aforementioned methodologies has been carried out under practical operating conditions. This work is expected to provide a good exposure to develop resilient solar PV systems in distribution network, with multifunctional capabilities.

सार

दुनिया में इलेक्ट्रिक एनर्जी डिमांड का तेजी से बढ़ता चलन और जीवाश्म ईंधन के भंडार में कमी बिजली उत्पादन को अक्षय ऊर्जा स्रोतों से प्रेरित करती है। वितरित ऊर्जा स्रोत आधारित अक्षय ऊर्जा स्रोत ग्रीनहाउस गैस उत्सर्जन और पर्यावरणीय प्रभावों को कम करने में योगदान देता है। इस कारण से, ऊर्जा गरीबी, प्रदूषण और जलवायु परिवर्तन के मुद्दों के समाधान के लिए दुनिया भर में नवीकरणीय ऊर्जा प्रणालियों को बढ़ावा दिया गया है। नवीकरणीय ऊर्जा संसाधनों पर एक बढ़ी हुई निर्भरता हाल के वर्षों में प्रदर्शित की गई है। वर्तमान में वैश्विक ऊर्जा मांग का 13.5% से अधिक नवीकरणीय ऊर्जा स्रोतों के माध्यम से पूरा किया जाता है। सौर ऊर्जा एक महत्वपूर्ण नवीकरणीय ऊर्जा स्रोत है जो भविष्य की ऊर्जा आपूर्ति में महत्वपूर्ण भूमिका निभाने की उम्मीद करता है और परिणामस्वरूप, सौर फोटोवोल्टिक आधारित नवीकरणीय ऊर्जा प्रणाली एक प्रमुख दावेदार के रूप में उभरा है।

ग्रिड इंटीग्रेटेड पीवी सिस्टम और ऑफ-ग्रिड सिस्टम में बढ़ती रुचि को प्रदर्शित किया गया है। ग्रिड-इंटरफ़ेड और ऑफ-ग्रिड परिचालन मोड में सौर पीवी सिस्टम के संचालन के साथ कई मुद्दे जुड़े हुए हैं। सबसे पहले, बिजली रूपांतरण उपकरणों में प्रकाश, चिकित्सा उपकरण और बिजली कर्षण के रूप में नॉनलाइनियर लोड के उपयोग ने वितरण नेटवर्क में बिजली की गुणवत्ता को बनाए रखने के लिए चिंताओं को बढ़ा दिया है। ये नॉनलाइनियर लोड हार्मोनिक्स करंट का परिचय देते हैं जिससे जीवन में कमी आती है और बिजली उपकरणों का संचालन होता है। दूसरे, लोड साइड न्यूट्रल धाराएं ग्रिड न्यूट्रल करंट प्रवाह का कारण बनती हैं, जिससे कर्मियों और उपकरणों को सामान्य सुरक्षा बाधित होती है। तीसरा, सौर पीवी सरणी और जमीन के बीच परजीवी समाई के कारण रिसाव रिसाव, सौर पीवी सरणी के जीवन-काल को कम करता है और परिचालन कर्मियों को सुरक्षा के मुद्दों का कारण बनता है। इन के अलावा, जड़ता-कम सौर

पीवी प्रणाली का ग्रिड एकीकरण सिस्टम में आवृत्ति विनियमन का समर्थन नहीं कर सकता है। इसके अलावा, ग्रिड-साइड दोष और सेंसर की खराबी के तहत सौर पीवी प्रणाली का निर्बाध संचालन वांछित है। चूँकि पावर इलेक्ट्रॉनिक तकनीक एक प्रमुख भूमिका निभाती है, इसलिए अनुसंधान उपरोक्त मुद्दों को संबोधित करने में बुद्धिमान नियंत्रण तकनीकों को विकसित करने पर केंद्रित है।

इस शोध कार्य का उद्देश्य तीन चरण ग्रिड-बाधित और ऑफ-ग्रिड सौर फोटोवोल्टिक प्रणालियों में आने वाली विभिन्न चुनौतियों का सामना करने के लिए बुद्धिमान नियंत्रण रणनीतियों के विकास और कार्यान्वयन के लिए है। विकसित की गई रणनीतियों को सफल संचालन के लिए MATLAB आधारित वातावरण में सिमुलेटेड किया जाता है, और विभिन्न प्रयोगों के साथ सिमुलेशन परिणाम को मान्य करने के लिए प्रयोगशाला प्रोटोटाइप का निर्माण किया जाता है।

यह शोध कार्य मुख्य रूप से वितरण नेटवर्क से जुड़े सौर पीवी सिस्टम पर ध्यान केंद्रित करता है। इस काम में संबोधित विभिन्न समस्याओं को वर्गीकृत किया गया है- (i) तीन चरण ग्रिड में बिजली की गुणवत्ता में सुधार, कमजोर वितरण ग्रिड (ii) के तहत सौर पीवी प्रणाली में कम वोल्टेज की सवारी के माध्यम से डबल स्टेज सौर पीवी प्रणाली में लोड क्षतिपूर्ति क्षमताओं को सक्षम करने की रणनीति (iii) बिजली की गुणवत्ता में सुधार की सुविधाओं के साथ ग्रिड-इंटरफ़ेयर ट्रांसफार्मर-कम पीवी सिस्टम में रिसाव वर्तमान दमन। सेंसर की खराबी के तहत सौर पीवी प्रणाली के लचीले संचालन के लिए अनजाने द्वितीय घटनाओं (v) नियंत्रण डिजाइन के तहत जड़ता सौर सौर प्रणाली और इसके निर्बाध संक्रमण का अनुकरण किया। घटनाओं और साइबर हमलों। दो-चरण पीवी प्रणाली के मामले में, पहला चरण एक बढ़ावा कनवर्टर है जो एमपीपीटी (अधिकतम पावर प्वाइंट ट्रैकिंग) के लिए कार्य करता है और दूसरा चरण एक ग्रिड बंधा हुआ वीएससी (वोल्टेज स्रोत कनवर्टर) है।

प्रारंभ में, ग्रिड-करियर संतुलन, ग्रिड हार्मोनिक-धाराओं शमन और असामान्य ग्रिड परिदृश्यों के तहत प्रतिक्रियाशील-शक्ति मुआवजे के लिए तीन-चरण ग्रिड-बाधित दो-चरण सौर पीवी प्रणाली के लिए एक कार्यप्रणाली पर विचार किया जाता है। यह प्रणाली शिखा शक्ति निष्कर्षण, तटस्थ वर्तमान क्षतिपूर्ति क्षमता, वोल्टेज स्रोत कनवर्टर (VSC) नुकसान को कम करने के लिए भी सुनिश्चित करती है, यहां तक कि वितरण प्रणाली में दूर के रेडियल सिरों पर होने वाले विकृत ग्रिड वोल्टेज के दौरान भी। उसके बाद, डबल स्टेज सोलर पीवी एरे सिस्टम के लिए एक लो-वोल्टेज राइड-थ्रू विधि प्रस्तावित है जो कि अंतर्निहित वीएससी ओवरक्रेक संरक्षण को सक्षम करती है और संशोधित ग्रिड कोड के अनुसार प्रतिक्रियाशील बिजली मुआवजे की आपूर्ति करती है। ग्रिड-करंट संतुलन, ग्रिड हार्मोनिक-धाराओं और दायित्व जैसे विद्युत गुणवत्ता सुधार सुविधाओं से समझौता किए बिना, सौर-पीवी सरणी प्रणाली के जीवन-काल को बेहतर बनाने के लिए, दो-चरण पीवी प्रणाली में रिसाव वर्तमान उन्मूलन के लिए एक पद्धति विकसित की गई है। -शक्ति मुआवजा। इसके बाद, तीन-चरण ग्रिड-बाधित और ऑफ-ग्रिड वितरित पीढ़ी प्रणाली के लिए एक सामान्यीकृत भविष्य कहनेवाला नियंत्रण आधारित हार्मोनिक-वोल्टेज नियंत्रक। सटीक आउटपुट वोल्टेज ट्रेकिंग प्रदर्शन को प्राप्त करने और आउटपुट हार्मोनिक वोल्टेज को नियंत्रित करने के लिए सामान्यीकृत भविष्य कहनेवाला नियंत्रक में एक न्यूनतमकरण मानदंड का उपयोग किया जाता है, और इस तरह, ग्रिड में प्रवेश करने वाले हार्मोनिक धाराओं को ग्रिड बाधित ऑपरेशन में विनियमित किया जाता है। इसके अलावा, एक वितरित पीढ़ी के स्रोत आधारित वर्चुअल सिंक्रोनस जनरेटर के निर्बाध संक्रमण के लिए एक विधि की जांच की जाती है, जहां अलग-अलग सिंक्रोनाइजिंग टूल या अलग-अलग टापींग डिटेक्शन एल्गोरिदम की आवश्यकता के बिना निर्बाध संक्रमण का एहसास होता है। यह समर्पित सिंक्रोनाइज़ेशन इकाइयों से संकेत पर निर्भरता के बिना, अपने भीतर ग्रिड-सिंक्रोनाइज़ेशन और आइलैंडिंग का पता लगाता है। सिस्टम अनजाने में टापू की घटनाओं के दौरान द्वीप का पता लगाने में देरी की संभावना नहीं है। अंत में, ग्रिड-

इंटरफेयर सोलर पीवी सिस्टम के निर्बाध संचालन के लिए एक कार्यप्रणाली विकसित की गई है, जो वर्तमान-सेंसर की खराबी की घटनाओं और विभिन्न झूठे डेटा इंजेक्शनों के तहत लचीला संचालन प्रदान करता है। यह नियंत्रण तकनीक खराबी / हमले के संकेत को प्रभावी ढंग से पहचानती है और सुधारात्मक कार्रवाई उत्पन्न करती है। विभिन्न पूर्वोक्त कार्यप्रणाली का प्रदर्शन मूल्यांकन व्यावहारिक परिचालन स्थितियों के तहत किया गया है। यह कार्य बहुक्रियाशील क्षमताओं के साथ वितरण नेटवर्क में लचीला सौर पीवी सिस्टम विकसित करने के लिए एक अच्छा प्रदर्शन प्रदान करने की उम्मीद है।

TABLE OF CONTENTS

	Page No.
Certificate	i
Acknowledgements	ii-iv
Abstract	v-vii
Table of Contents	viii-xiv
List of Figures	xv-xx
List of Tables	xxi
List of Abbreviations	xxii-xxiii
List of Symbols	xxiv-xxvi

CHAPTER—I INTRODUCTION

1.1	General	1
1.2	State of Art	4
1.3	Objectives of the Thesis	8
1.4	Thesis Organization	9

CHAPTER—II LITERATURE REVIEW

2.1	General	16
2.2	Literature Survey	16
2.2.1	Grid-Interfaced and Off-Grid Distributed Power Systems	17
2.2.2	Grid Parity for Solar PV Power Generating Systems	20
2.2.3	Review of MPPT Techniques for Solar PV Power Generation	21
2.2.4	Review of Control Strategies for Power Quality Improvement in Grid interfaced Solar PV Systems	22
2.2.5	Low-Voltage Ride-Through Challenges in Grid-Interfaced Solar PV Systems	27
2.2.6	Review of Control Strategies for Off-Grid Solar PV Systems	28
2.2.7	Leakage Current Problem in Grid Interfaced Solar PV Systems	30
2.2.8	Cyber Attacks in Grid Interfaced Solar PV Systems	31
2.4	Identified Research Areas	32
2.5	Conclusions	33

CHAPTER -III POWER QUALITY IMPROVEMENT IN THREE PHASE GRID INTERFACED PHOTOVOLTAIC SYSTEM UNDER WEAK DISTRIBUTION GRIDS

3.1	General	34
3.2	System Configurations	35
3.2.1	Circuit Configuration of Two-Stage Three-Wire Solar PV System	35
3.2.2	Circuit Configuration of Two-Stage Four-Wire Solar PV System	35
3.3	Design, Modeling and Selection of Two-stage Solar PV System	37
3.3.1	Selection of DC Bus Voltage	37
3.3.2	Design and Selection of DC Bus Capacitor	37
3.3.3	Design and Selection of Devices for VSC	38
3.3.4	Design and Selection of Interfacing Inductors	39
3.3.5	Design and Selection of Ripple Filter	39
3.3.6	Design and Selection of PV Array	39
3.3.7	Design and Selection of Boost Inductor	40
3.4	Control Strategy for Two-Stage Solar PV System	41
3.4.1	DC-DC Boost Converter Control	41
3.4.2	Generation of VSC Gating Pulses	45
3.4.2.1	Adaptive Observer Based Harmonic Extraction Technique	45
3.4.2.2	Assigning Load Current Weights	51
3.4.2.3	DC Link Voltage Regulation	53
3.4.2.4	PV Feed-forward Compensation and Generation of Switching Pulses	54
3.4.2.5	Neutral Current Compensation in Three-Phase Four-Wire Topology	55
3.4.3	Tuning strategy for control parameters	56
3.5	System Simulation in Matlab®/Simulink Environment	60
3.6	Experimental System Description	61
3.6.1	The DSP-dSPACE DS1202 Microlab-box Controller	63
3.6.2	Interfacing Circuit for Hall Effect Current Sensors	66
3.6.3	Interfacing Circuit for Hall Effect Voltage Sensors	67
3.6.4	Interfacing Circuit for Gate Driver	68
3.7	Results and Discussion	69
3.7.1	Simulated Results	69
3.7.1.1	System Response under Load Variations	70

3.7.1.2	System Response under Solar Insolation Variations	70
3.7.1.3	System Response under sag/swell in PCC Voltages	70
3.7.1.4	Neutral Current Compensation Capability of Three-Phase Four-Wire System	72
3.7.1.5	System Response under Distorted Grid Voltages	75
3.7.1.6	Effectiveness of PV Feed-Forward Term	77
3.7.1.7	UPF Operation and Harmonic Tracking Capability	79
3.7.1.8	Comparative analysis with state-of art techniques	80
3.7.2	Experimental Results	83
3.7.2.1	Steady-state Behavior of Solar PV System	83
3.7.2.2	System Behavior under Solar Insolation Variations	86
3.7.2.3	System Behavior under Load Variations	86
3.7.2.4	System Behavior under sag/swell in PCC Voltages	88
3.7.2.5	System Behavior under Distorted Grid Voltages	89
3.7.2.6	Neutral Current Compensation Capability under Different Operating Conditions	90
3.7.2.7	Comparative Performance with State-of-art Technique	92
3.8	Conclusions	93

CHAPTER—IV LOW-VOLTAGE RIDE-THROUGH STRATEGY IN DOUBLE-STAGE SOLAR PV SYSTEM ENABLING LOAD COMPENSATION CAPABILITIES

4.1	General	95
4.2	System Configuration	96
4.3	Design, Modeling and Selection of Circuit parameters for Two-Stage Solar PV System	97
4.4	Control Approach for LVRT Operation	97
4.4.1	Kalman Filtering Scheme for Load Currents Processing	99
4.4.2	Assigning Load Current Weights	104
4.4.3	DC Link Voltage Regulation and PV Feed-Forward Compensation	106
4.4.4	Low-Voltage Ride-Through Control	106
4.4.5	Generation of Inverter Gating Pulses	110
4.5	System Simulation in Matlab®/Simulink Environment	113
4.6	Experimental System Description	114

4.6.1	The DSP-dSPACE DS1202 Microlab-box Controller	115
4.6.2	Interfacing Circuit for Hall Effect Current Sensors	115
4.6.3	Interfacing Circuit for Hall Effect Voltage Sensors	115
4.6.4	Interfacing Circuit for Gate Driver	116
4.7	Results and Discussion	116
4.7.1	Simulated Results	116
4.7.2	Experimental Results	120
	4.7.2.1 Steady-state Response of the System	120
	4.7.2.2 System Performance under Dynamic Loads	121
	4.7.2.3 System Performance under Changes in Solar Insolation	122
	4.7.2.4 Transitions between Grid-Interfaced PV Operation and DSTATCOM Operation	123
	4.7.2.5 System Performance under Voltage Sag Faults	124
4.7.3	Comparative Study with Existing Algorithms	125
4.8	Conclusions	126

CHAPTER—V LEAKAGE CURRENT SUPPRESSION IN GRID-INTERFACED TRANSFORMERLESS PV SYSTEM WITH POWER QUALITY IMPROVEMENT FEATURES

5.1	General	128
5.2	System Configuration	128
5.3	Design, Modeling and Selection of Circuit Parameters for Two-Stage PV System	129
5.4	Control Approach for Leakage Current Suppression with Power Quality Improvement Features	130
	5.4.1 Leakage Current Path in Three-Phase Three-Wire System	131
	5.4.2 Control strategy for leakage current mitigation	133
	5.4.3 Incorporation of power quality improvement features	134
	5.4.4 Generation of gating pulses	136
5.5	System Simulation in Matlab®/Simulink Environment	137
5.6	Test System Description	138
5.7	Results and Discussion	138
	5.7.1 Simulated Results	138
	5.7.2 Comparative Study with Existing Algorithms	142
	5.7.3 Experimental Results	144

5.8	Conclusions	146
-----	-------------	-----

CHAPTER—VI A UNIVERSAL HARMONIC CONTROL APPROACH FOR GRID INTERFACED AND OFF-GRID SOLAR PV SYSTEMS

6.1	General	148
6.2	System Description and Modeling	150
6.3	Design, Modelling and Selection of Circuit Parameters	152
6.3.1	Selection of DC Bus Voltage	152
6.3.2	Design and Selection of Devices for VSC	152
6.3.3	Design and Selection of LC Filter	153
6.4	Control Approach	154
6.4.1	Generalized Predictive Control	154
6.4.2	Harmonic Control Strategy with GPC	159
6.5	System Simulation in Matlab®/Simulink Environment	163
6.6	Experimental System Description	165
6.6.1	The DSP-dSPACE DS1202 Microlab-box Controller	166
6.6.2	Interfacing Circuit for Hall Effect Current Sensors	166
6.6.3	Interfacing Circuit for Hall Effect Voltage Sensors	167
6.6.4	Interfacing Circuit for Gate Driver	167
6.7	Results and Discussion	167
6.7.1	Simulated Results	168
6.7.1.1	Effectiveness of Proposed Controller in Tracking Reference Output Voltages	168
6.7.1.2	Harmonic Control in Grid-Interfaced and Off-Grid modes	169
6.7.2	Experimental Results	173
6.8	Conclusions	175

CHAPTER—VII VIRTUAL SYNCHRONOUS GENERATOR BASED SOLAR PV SYSTEM AND ITS SEAMLESS TRANSITION UNDER UNINTENTIONAL ISLANDING EVENTS

7.1	General	176
7.2	System Description	177
7.3	Design, Modelling and Selection of Circuit Parameters	178
7.3.1	Selection of DC Bus Voltage	178
7.3.2	Design and Selection of Devices for VSC	178

7.3.3	Design and Selection of LC Filter	178
7.4	Control Approach	179
7.4.1	Evaluation of Self Synchronization Signal and Islanding Detection Command	184
7.4.2	Stability Analysis of the Controller	187
7.5	System Simulation in Matlab®/Simulink Environment	191
7.6	Experimental System Description	188
7.6.1	The DSP-dSPACE DS1202 Microlab-box Controller	192
7.6.2	Interfacing Circuit for Hall Effect Current Sensors	193
7.6.3	Interfacing Circuit for Hall Effect Voltage Sensors	193
7.6.4	Interfacing Circuit for Gate Driver	193
7.7	Results and Discussion	194
7.7.1	Simulation Results	194
7.7.1.1	System Response during DG Synchronization with the Grid and its Islanding	194
7.7.1.2	System Response During Synchronization of new DG into Existing Microgrid and their Grid Synchronization	198
7.7.1.3	Comparative Performance	200
7.7.2	Experimental Results	203
7.7.2.1	Steady-State Performance of System	204
7.7.2.2	Performance during Transition from Stand-Alone Mode to Grid-Connected Mode	205
7.7.2.3	Performance during System Islanding Operation	207
7.8	Conclusions	208

CHAPTER—VIII CONTROL DESIGN FOR RESILIENT OPERATION OF SOLAR PV SYSTEM UNDER SENSOR MALFUNCTIONING EVENTS AND CYBER ATTACKS

8.1	General	210
8.2	System Description	210
8.3	Design, Modelling and Selection Of Circuit Parameters for Single- Stage Solar PV System	211
8.4	Control Approach	212
8.4.1	The Resilient Control Approach	212

8.4.2	Generation of Nominal Control Signal	213
8.4.3	The Reference Voltage Generation under False Data Injection Attacks	214
8.4.4	Estimation of Sensor Fault Data	216
8.5	System Simulation in Matlab®/Simulink Environment	216
8.6	Experimental System Description	218
7.6.1	The DSP-dSPACE DS1202 Microlab-box Controller	219
7.6.2	Interfacing Circuit for Hall Effect Current Sensors	219
7.6.3	Interfacing Circuit for Hall Effect Voltage Sensors	219
7.6.4	Interfacing Circuit for Gate Driver	220
8.7	Results and Discussion	220
8.7.1	Simulated Results	220
8.7.1.1	Case-A: False data injection in phase-‘A’	220
8.7.1.2	Case-B: False Data Injection in Phases-‘a’ and ‘b’	221
8.7.1.3	Case-C: Random False-Data Injection	222
8.7.1.4	Complete Malfunction of Phase-‘a’ Current Sensor	222
8.7.2	Experimental Results	229
8.8	Conclusions	231
 CHAPTER—IX MAIN CONCLUSIONS AND SUGRESSIONS FOR FURTHER WORK		
9.1	General	232
9.2	Main Conclusions	233
9.3	Scope of Further Work	237
 REFERENCES		238
LIST OF PUBLICATIONS		265
AUTHOR BIO-DATA		267

LIST OF FIGURES

-
- Fig. 3.1 System configuration of two-stage grid interfaced three phase three wire PV system
- Fig. 3.2 System configuration of two-stage grid interfaced three phase four wire PV system
- Fig. 3.3 Working principle of incremental conductance algorithm
- Fig. 3.4 The adaptive harmonic elimination based control algorithm for the three phase GPV system
- Fig. 3.5 Evaluation of balanced positive sequence grid voltages
- Fig. 3.6 Harmonic component extraction from the update law
- Fig. 3.7 Description of the hysteresis controller
- Fig. 3.8 Description of the hysteresis controller
- Fig. 3.9 Dynamics of ‘Int_{Jsin1}’ and ‘Int_{Jcos1}’ along with their reflection in amplitude of estimated fundamental
- Fig. 3.10 Simulation of three-phase three-wire in Matlab®/Simulink environment
- Fig. 3.11 Simulation of three-phase four-wire in Matlab®/Simulink environment
- Fig. 3.12 The MPPT performance at (a) 1000 W/m² and (b) 500 W/m²
- Fig. 3.13 Schematic for current sensor board
- Fig. 3.14 Photograph of (a) Current sensor (b) Voltage Sensor (c) Opto-isolator
- Fig. 3.15 Schematic for voltage sensor board
- Fig. 3.16 Schematic of opto-isolation board
- Fig. 3.17 GPV system performance under load perturbation
- Fig. 3.18 GPV system performance under solar insolation changes
- Fig. 3.19 System behavior under (a) voltage sag conditions and (b) voltage sag conditions
- Fig. 3.20 System behavior under frequency variation
- Fig. 3.21 Neutral current compensation capability during (a) Load perturbation conditions, (b) Solar insolation changes, (c) PCC voltage variations
- Fig. 3.22 Response of the system under distorted grid voltages with conventional method (a) $v_{sab}-v_{sbc}-v_{sca}$, $v_{sa}-v_{sb}-v_{sc}$, V_t , u_{pabc} (b) $i_{La}-i_{Lb}-i_{Lc}$, $i_{vsca}-i_{vsbc}-i_{vscc}$, $i_{ref-a}-i_{ref-b}-i_{ref-c}$, $i_{sa}-i_{sb}-i_{sc}$
- Fig. 3.23 Response of the system under distorted grid voltages using proposed control strategy (a) $v_{sab}-v_{sbc}-v_{sca}$, $v_{sa}-v_{sb}-v_{sc}$, $v_{a\beta}$, v_{pabc} , V_t (b) x_{pabc}^m , i_{Labc} , i_{vsabc} , $i_{ref-abc}$, i_{sabc}

- Fig. 3.24 Performance of system with and without feed-forward component (a) G , V_{DC} , I_{pv} , P_{pv} (b) v_{sabc} , i_{sabc} , i_{la} , i_{vsc} (c) G , V_{DC} , I_{pv} , P_{pv} (d) v_{sabc} , i_{sabc} , i_{la} , i_{vsc}
- Fig. 3.25 (a) fundamental component extraction under load perturbation and (b) UPF operation of the system
- Fig. 3.26 Comparison of the proposed control scheme with LMF based control
- Fig. 3.27 Test results at balanced nonlinear loads (a)–(d) v_{sab} with i_{sa}, i_{La}, i_{VSCa} and harmonic spectra of grid current (e)–(h) grid power, load power, VSC power and harmonic spectra of load current
- Fig. 3.28 Test results at unbalanced nonlinear loads (a)–(d) v_{sab} with i_{sa}, i_{sb}, i_{sc} and harmonic spectra of grid current (e)–(h) v_{sab} with i_{La}, i_{Lb}, i_{Lc} , and harmonic spectra of load current (i)–(l) v_{sab} with $i_{VSCa}, i_{VSCb}, i_{VSCc}$ and harmonic spectra of VSC current (m)–(o) Grid power, load power and VSC power (p) PV array voltage V_{PV} and current I_{PV}
- Fig. 3.29 Illustration of Fig. 3.27 (d) of Fluke model-43B
- Fig. 3.30 (a) Current-probe and voltage-probe connections, (b) illustration of Fig. 3.27 (e)
- Fig. 3.31 Dynamic performance for solar insolation change from 1000 W/m² to 500 W/m² and vice-versa (a) decrease in insolation (b) increase in insolation
- Fig. 3.32 Internal signals of adaptive algorithm under sudden disconnection of load: (a) i_{La} , $\hat{I}_{ILc}$, $\hat{I}_{ILs}$ and $\hat{I}_{ILff}$ (b) tracking error, frequency estimation and W_{pLa} (c) i_{La} , W_{fa} , W_{fb} and W_c (d) W_{pLa} , W_{pvf} and W_{loss} (e) W_{pnet} and x_{pa}, x_{pb}, x_{pc} (f) $i_{sa}, i_{sa}^*, i_{sb}^*$ and i_{sc}^*
- Fig. 3.33 Dynamic performance for nonlinear load perturbation (a)–(b) i_{La}, i_{Lb}, i_{Lc} and V_{DC} (c)–(d) i_{sa}, i_{VSCa}, I_{pv} and v_{sa} (e) Magnified V_{DC}
- Fig. 3.34 Response of the system under variation in PCC voltage (a)–(b) from 400V to 340 V, (c)–(d) from 360V to 400 V
- Fig. 3.35 Behaviour under distorted grid voltages (a) $v_{sab}, v_{pa}, u_{pa}, i_{sa}$ (b) $v_{sab}-i_{sa}$ (c)–(d) THDs of v_{sab} and i_{sa}
- Fig. 3.36 Test results under balanced nonlinear load (a)–(d) v_{sab} with i_{sa}, i_{La}, i_{VSCa} and THD of i_{sa} ; (e)–(h) v_{sab} with i_{sn}, i_{Ln}, i_{VSCn} and THD of i_{La}
- Fig. 3.37 Test results under unbalanced nonlinear load (a)–(d) v_{sab} with i_{sa}, i_{sb}, i_{sc} and i_{sn} ; (e)–(h) v_{sab} with i_{La}, i_{Lb}, i_{Lc} , and i_{Ln} ; (i)–(l) v_{sab} with $i_{VSCa}, i_{VSCb}, i_{VSCc}$ and i_{VSCn}
- Fig. 3.38 Dynamic response for nonlinear load perturbation (a) i_{sa} with i_{sa}^*, i_{sb}^* and i_{sc}^* (b) i_{La}, i_{Lb}, i_{Lc} and V_{dc} (c) $v_{sab}, i_{sa}, i_{VSCa}$ and I_{pv} , (d) i_{La}, i_{Ln}, i_{VSCn} and i_{sn}

- Fig. 3.39 Comparative performance of fundamental component magnitude estimation using (a) proposed Lyapunov based strategy (b) adaptive filtering strategy
- Fig. 4.1 Configuration of two-stage grid interfaced PV system
- Fig. 4.2 Control schematic for generation of PV inverter gating pulses
- Fig. 4.3 Implementation of EKF algorithm
- Fig. 4.4 Evaluation of balanced positive sequence grid voltages
- Fig. 4.5 De-rated operation of PV inverter during fault ride-through operation
- Fig. 4.6 Control schematic for generation of boost converter gating pulses
- Fig. 4.7 Simulation in Matlab®/Simulink Environment
- Fig. 4.8 System response under L-G and L-L-G faults depicting fault ride-through operation of PV inverter
- Fig. 4.9 System response under L-G and L-L-G faults depicting fault ride-through operation of PV inverter
- Fig. 4.10 System response under unbalanced grid voltages
- Fig. 4.11 Test results under nonlinear loads (a) v_{sab} - i_{sa} (b) v_{sab} - i_{vsca} (c) v_{sab} - i_{La} (d) THD of i_{La} (e) Grid Power (f) Inverter Power (g) Load Power (h) THD of i_{sa}
- Fig. 4.12 System behaviour under load balancing (a) v_{sab} , i_{sa} , i_{vsca} , i_{La} (b) v_{sbc} , i_{sb} , i_{vsca} , i_{Lb} (c) V_{DC} , V_{pv} , I_{pv} , P_{pv}
- Fig. 4.13 Salient internal signals of the controller-(a) W_{loss} , W_{PV} , W_{eq} , W_{net} and (b) reference currents - i_{sa}^* , i_{sa} , i_{sb}^* , i_{sb}
- Fig. 4.14 System behavior under solar insolation change from 500W/m² to 1000 W/m² (a) v_{sab} , i_{sa} , i_{vsca} , i_{La} (b) V_{DC} , V_{pv} , I_{pv} , P_{pv}
- Fig. 4.15 Behavior under transitions between grid-interfaced PV operation and DSTATCOM operation (a) v_{sab} , i_{sa} , i_{vsca} , i_{La} (b) V_{DC} , V_{pv} , I_{pv} , P_{pv} ; and vice-versa (c) v_{sab} , i_{sa} , i_{vsca} , i_{La} (d) V_{DC} , V_{pv} , I_{pv} , P_{pv}
- Fig. 4.16 Behavior under voltage-sag fault (a) v_{sa} , v_{sb} and v_{sc} (b) V_{PV} , I_{PV} and I_{VSCa}
- Fig. 5.1 Configuration of two-stage grid interfaced PV system for leakage current mitigation
- Fig. 5.2 Configuration of two-stage grid interfaced PV system

- Fig. 5.3 Equivalent model for grid interfaced solar power generating system (a) step-1 (b) step-2
- Fig. 5.4 Equivalent model for grid interfaced solar power generating system (a) step-3 (b) step-4
- Fig. 5.5 Equivalent model for grid interfaced solar power generating system
- Fig. 5.6 Control schematic for generation of PV inverter gating pulses
- Fig. 5.7 Simulation in Matlab®/Simulink Environment
- Fig. 5.8 (a)-(b) System response under load balanced nonlinear loads
- Fig. 5.9 (a)-(b) System response under load unbalancing conditions
- Fig. 5.10 System response under balanced nonlinear loads without leakage current mitigation feature
- Fig. 5.11 Comparative performance depicting the salient signals of v_g , i_g , i_L and i_{leak}
- Fig. 5.12 Bar chart depicting the comparative analysis between the proposed strategy and conventional strategies
- Fig. 5.13 Experimental performance of the system (a) v_{sab} with i_{sa} , i_{vsca} and i_{La} , (b) V_{DC} with V_{PV} , I_{PV} and P_{PV} (c) $i_{leakage}$ and V_{CMV}
- Fig. 6.1 System Configuration
- Fig. 6.2 Control schematic of harmonic-voltage controller
- Fig. 6.3 The generalized predictive control schematic
- Fig. 6.4 Equivalent circuit of single DG-VSC system in grid-interfaced mode
- Fig. 6.5 Algorithm for online tuning of harmonic gains - λ_{ak} , λ_{bk} and λ_{ck}
- Fig. 6.6 Simulation in Matlab®/Simulink Environment
- Fig. 6.7 Output voltage tracking capability of GPC
- Fig. 6.8 Performance of single DG-VSC system in grid-interfaced mode of operation (a) without harmonic voltage control and (b) with harmonic voltage control
- Fig. 6.9 THD Values of Grid-Interfaced DG-VSC System with and without Harmonic Control
- Fig. 6.10 Effect of step-sizes (μ_a , μ_b , μ_c) on convergence of harmonic gains
- Fig. 6.11 Performance of double DG-VSC system in stand-alone mode of operation (a) without harmonic voltage control and (b) with harmonic voltage control
- Fig. 6.12 THD Values of Stand-Alone DG-VSC System with and without Harmonic Control

- Fig. 6.13 Performance under GI mode with harmonic compensation enabled (a) v_{gab} with i_{ga} and i_{Lb} (b) Internal signals- $v_{o\alpha}^{ref}$, $v_{o\beta}^{ref}$, $v_{c\alpha}^{ref}$ and $v_{c\beta}^{ref}$
- Fig. 6.14 (a) THD of v_{gab} (b) THD of i_{La} (c) THD of i_{ga}
- Fig. 7.1 System Configuration
- Fig. 7.2 VSC based microgrid depicting virtual stator impedance and fictitious voltage terminal
- Fig. 7.3 Control schematic
- Fig. 7.4 Evaluation of synchronizing signal (S_g)
- Fig. 7.5 Closed loop control of the system (7.30)
- Fig. 7.6 Eigen value plot for closed loop system (7.30)
- Fig. 7.7 Simulation in Matlab®/Simulink Environment
- Fig. 7.8 System response during DG synchronization with the grid and its islanding
- Fig. 7.9 Synchronization gain signal during transition from islanded mode to grid-connected mode
- Fig. 7.10 System response during DG synchronization without voltage magnitude pre-synchronization
- Fig. 7.11 System response during synchronization of new DG into existing microgrid and their grid synchronization
- Fig. 7.12 Comparison of the proposed control strategy with synchronverter strategy during synchronization process prior to grid-connection
- Fig. 7.13 Comparison of the (a) proposed control with (b) PLL-based control during unintentional islanding
- Fig. 7.14 Performance of the system under balanced linear load (a) v_{oab} - i_{oa} (b) v_{obc} - i_{ob} (c) v_{oca} - i_{oc} (d) VSC output active power (e) harmonic spectrum of v_{oab} (f) THD of i_{oa} (g) V_{DC} and i_{oa}
- Fig. 7.15 Performance of the system under nonlinear loads (a) v_{oab} - i_{oa} (b) v_{obc} - i_{ob} (c) v_{oca} - i_{oc} (d) VSC output active power (e) harmonic spectrum of v_{oab} (f) THD of i_{oa} (g) V_{DC} and i_{oa}
- Fig. 7.16 Experimental results depicting pre-synchronization process (a) v_{gab} and v_{oab} along with i_{oa} and synchronization gain (b) v_{gab} , v_{oab} along with their respective phase angles

- Fig. 7.17 Experimental results under grid synchronization process (a) v_{gab} , v_{oab} along with i_{ga} and synchronization gain (b) v_{gab} and v_{oab} along with $|V_o|$ and i_{oa}
- Fig. 7.18 Experimental results under islanding process (a) v_{gab} and v_{oab} along with i_{ga} and synchronization gain (b) v_{gab} and v_{oab} along with $|V_o|$ and i_{oa}
- Fig. 8.1 System Configuration
- Fig. 8.2 Schematic for (a) estimation of fault signal and (b) Generation of control action corresponding to fault signal
- Fig. 8.3 Simulation in Matlab®/Simulink Environment
- Fig. 8.4 (a-d) System response during false data injection in phase-‘a’
- Fig. 8.5 (a-c) System response during false data injection in both phases-‘a’ and ‘b’
- Fig. 8.6 (a-c) System response during random false data injections
- Fig. 8.7 (a-c) System response during malfunction in phase-‘a’
- Fig. 8.8 (a-c) Experimental response during false data injection in d-axis and q-axis currents
- Fig. 8.9 (a-d) Experimental response during false data injection along with DC bias in d-axis and q-axis currents

LIST OF TABLES

Table-3.1	Simulation System Parameters
Table-3.2	Parameters of PV Module
Table-3.3	Experimental System Specifications
Table-3.4	Detailed Specifications of DSP-DSPACE DS1202 Micro-Lab-Box
Table-3.5	System THD Report under Nonlinear Load
Table-3.6	Comparative Study of Different Control Schemes
Table-4.1	Simulation System Parameters
Table-4.2	Parameters of PV Module
Table-4.3	Experimental System Parameters
Table-4.4	Comparative Study with Fault Ride Through Algorithms
Table-5.1	Simulation System Parameters
Table-5.2	Possible switching states of (5.5)
Table-5.3	The complete switching sequence corresponding to group-4
Table 5.4	Test System Parameters
Table-6.1	Simulation System Parameters
Table-6.2	Experimental System Specifications
Table-7.1	Simulation System Parameters
Table-7.2	Experimental System Specifications
Table-8.1	Simulation System Parameters

Table-8.2 Experimental System Parameters

LIST OF ABBREVIATIONS

AC	Alternating Current
ADC	Analog to Digital Converter
DAC	Digital to Analog Converter
DC	Direct Current
DSP	Digital Signal Processor
D-STATCOM	Distribution Static Compensator
FACTS	Flexible Alternating Current Transmission Systems
FRT	Fault Ride Through
GPC	Generalized Predictive Control
GPV	Grid Interfaced Photo Voltaic
IGBTs	Insulated Gate Bipolar Transistors
InC	Incremental Conductance
LMF	Least Mean Fourth
LMS	Least Mean Squares
LPF	Low Pass Filter
LVRT	Low Voltage Ride Through
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
PCC	Point of Common Coupling

PI	Proportional Integral
PLL	Phase Locked Loop
P&O	Perturb and Observe
PV	Photo Voltaic
PWM	Pulse Width Modulation
SOGI	Second Order Generalized Integrator
SECS	Solar Energy Conversion System
SPV	Solar Photo Voltaic
SRFT	Synchronous Reference Frame Theory
VSC	Voltage Source Converter

LIST OF SYMBOLS

C_{DC}	DC bus capacitance of the VSC
C_r	Capacitance for ripple filter
D	Duty ratio of boost converter
D_{ref}	Reference duty ratio of boost converter
f_s	Switching frequency
I_{sc}	Short circuit current of single solar cell
I_{mppC}	MPP current of single solar cell
I_{SCA}	Short circuit current of SPV array
ΔI_{in}	Ripple current in the input current of boost converter
I_{PV}	PV array current
I_{mppA}	MPP current of SPV array
I_{VSC}	VSC current in single-phase system
I_{VSCmax}	Maximum current for VSC
I_{VSCp}	Peak current for VSC
I_{VSCr}	Peak ripple current for VSC
I_{SW}	Current rating of IGBT switch
W_{PVFF}	PV array feed forward contribution
W_{Lp}	Magnitude of active power component of load current
W_{gp}	Amplitude of reference grid current

i_g	Sensed grid current in single-phase system
$i_{ga}, i_{gb}, i_{gc}, i_{gn}$	Sensed grid currents in three-phase system
i_{gref}	Reference grid current in single-phase system
$i_{garef}, i_{gbref}, i_{gceref}$	Reference grid currents in three-phase system
i_L	Sensed load current in single-phase system
i_{Lh}	Harmonics component in sensed load current
$i_{La}, i_{L\beta}$	Estimated fundamental currents by notch filter algorithm
$i_{La}, i_{Lb}, i_{Lc}, i_{Ln}$	Sensed load currents in three-phase system
$I_{VSCa}, i_{VSCb}, i_{VSCc}, i_{VSCn}$	VSC currents in three-phase system
K_p	Proportional constant for PI controller
K_i	Integral constant for PI controller
L_B	Inductor for boost converter
L_{VSC}	Interfacing inductor for VSC
L_{VSCn}	Interfacing inductor for neutral leg of VSC
m	Modulation index
n_p	Number of parallel solar cells
n_s	Number of series solar cells
P_{maxA}	MPP power of SPV array
P_{PV}	Power supplied by the PV array
P_{VSC}	Power supplied by the VSC
R_r	Resistance for ripple filter

T_s	Switching time period
v_{DC}	DC bus voltage
V_{DCref}	Reference DC link voltage
V_{DCmin}	Minimum DC bus voltage
V_{DCmax}	Maximum DC bus voltage
V_{mppC}	MPP voltage of single solar cell
V_{mppA}	MPP voltage of SPV array
V_{oc}	Open circuit voltage of single solar cell
V_{OCA}	Open circuit voltage of SPV array
V_{PV}	PV array voltage
V_{PVref}	Reference PV array voltage
V_m	Estimated amplitude of single-phase PCC voltage
V_z	Estimated amplitude of three-phase PCC voltage
V_{SW}	Voltage rating of IGBT switch
x_{pa}, x_{pb}, x_{pc}	In-phase unit templates for phase-‘a’, ‘b’ and ‘c’
x_{qa}, x_{qb}, x_{qc}	Quadratic unit templates for phases ‘a’, ‘b’ and ‘c’
μ	Scaling factor in an adaptive DC link voltage control