

**DESIGN, CONTROL AND IMPLEMENTATION OF GRID
INTERACTIVE SOLAR PV ARRAY AND BATTERY
ENERGY STORAGE BASED MICROGRIDS**

SHAILENDRA KUMAR



**DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
HAUZ KHAS, NEW DELHI-110016, INDIA.**

MAY 2019

© Indian Institute of Technology Delhi (IITD), New Delhi, 2019

**DESIGN, CONTROL AND IMPLEMENTATION OF
GRID INTERACTIVE SOLAR PV ARRAY AND
BATTERY ENERGY STORAGE BASED MICROGRIDS**

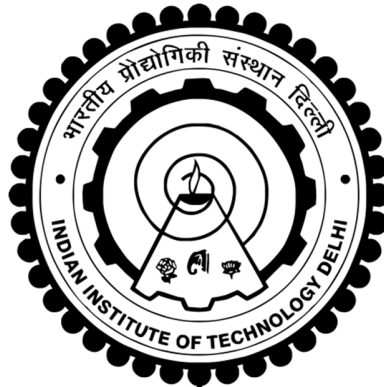
by

SHAILENDRA KUMAR
Electrical Engineering Department

Submitted

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

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

MAY 2019

**DESIGN, CONTROL AND IMPLEMENTATION OF
GRID INTERACTIVE SOLAR PV ARRAY AND
BATTERY ENERGY STORAGE BASED MICROGRIDS**

by

SHAILENDRA KUMAR
Electrical Engineering Department

Submitted

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

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

MAY 2019

CERTIFICATE

It is certified that the thesis entitled “**Design, Control and Implementation of Grid Interactive Solar PV Array and Battery Energy Storage Based Microgrids,**” being submitted by **Mr. Shailendra Kumar** 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: May 16, 2019

(Prof. Bhim Singh)
Electrical Engineering Department
Indian Institute of Technology Delhi
Hauz Khas, New Delhi-110016, India

ACKNOWLEDGEMENTS

I wish to express my deepest gratitude and indebtedness to **Prof. Bhim Singh** 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** have been the inspiration for me to complete this work. His 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 his 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. Sukumar Mishra, Prof. B. K. Panigrahi and Prof. T.S. Bhatti**, 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. B. P. Singh, Prof. G. Bhuvaneshwari, Late Prof. K. R. Rajagopal, Prof. M. Veerachary, Prof. Amit K. Jain, Prof. R. K. Maheshwari and Prof. Anandarup Das** for their valuable inputs during my course work, which made the foundation for my research work. I am grateful to IIT Delhi for providing me the research facilities. 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)**” project. I wish to express my sincere thanks to the government of India for helping financially under the project ministry of electronics and information technology (MEITY). Thanks are due to Sh. Srichand, Sh. Puran Singh, Sh. Jagbir Singh, Mr. Amit Kumar and Mr. Jitendra of PG Machines

Lab, UG Machines Lab and Power Electronics Lab., IIT Delhi for providing me facilities and assistance during this work.

I would like to thank all my seniors, Dr. Ashish Shrivastava, Dr. V. Sandeep, Dr. Rajashekhar Reddy, Dr. Shailendra Sharma, Dr. Jeevanand, Dr. Sumit Ghatak Choudhuri, Dr. Sanjeet Dwivedi, Dr. Sanjeev Singh, Dr. Sabharaj Arya, Dr. Rajesh Mutharath, Dr. Ram Niwas, Dr. Ujjwal Kalla, Dr. Arun Kumar Verma, Dr. M. Sandeep, Dr. N. K. Swami Naidu Dr. Chinmay Jain, Dr. Vashist Bist, Dr. Shikha Singh, Dr. Swati Narula, Dr. Raj Kumar Garg, Dr. Manoj Badoni, Dr. Geeta Pathak, Dr. Aman Jha, Dr. Shailendra Tiwari Dr. Stuti Shukla, Mr. Saurabh Mangalik and Mr. Sachin Devassy to motivate me in the starting of my research work. I would like to use this opportunity to thank Dr. Chinmay Jain, Dr. Ikhlq Hussain, Dr. Rajan Sonkar, Mr. Anshul Varshney, Mr. Utkarsh Sharma and Mr. Rahul Pandey who have constantly helped me on all technical and non-technical issues. My sincere thanks are due to for co-operation and informal support Ms. Nidhi Mishra, Mr. Aniket Anand, Mr. Sai Pranith Girimaji, Mr. Mohd. Junaid, Mr. Nishant Kumar, Ms. Shatakshi Sharma, Mr. Deepu Vijay and Mr. Saurabh Shukla in pursuing this research work. I would like to thank Mr. Piyush Kant, Mr. Anjaneesh Mishra, Mr. Shadab Murshid, Mr. Vineet P. Chandran, Mr. Tipurari Nath Gupta, Ms. Radha Kushwaha, Ms. Seema, Ms. Vanadana Jain, Dr. Amresh Kumar Singh, Ms. Nupur Saxena, Mr. Somnath Pal and all other colleges for their valuable aid and co-operation. Moreover, I would like to thank, Mr. Sreejith R. Mr. Gurmeet Singh, Mr. Anjeet Verma, Mr. Debasish Mishra, Ms. Subarni Pradhan, Ms. Tabish Mir, Mr. Praveen Kumar Singh, Mr. K. P. Tomar, Mr. Sunil Kumar Pandey, Mr. Niranjana Devela, Mr. G. K. Taneja, Mr. Khusro Khan, Ms. Yashi Singh, Ms. Shubhra, Ms. Farheen Chisti, Ms. Rohini Sharma, Ms. Pavitra Shukl, Mr. P. Sambasivaiah, Mr. Priyank Shah, Mr. V.L. Srinivas, Mr. Munesh Kumar Singh, Ms.

Aakanksha Rajput, Ms. Hina Parveen, Ms. Rashmi Rai, Mr. Yalavarthi Amarnath, Mr. Arayadip Sen, Mr. Kashif, Mr. Gaurav Modi, Mr. Sudip Bhattacharya, Mr. Bilal Naqvi, Mr. Jitendra Gupta, Mr. Utsav Sharma, Mr. Sandeep Kumar Sahoo, Ms. Shalvi Tyagi, Mr. Souvik Das, Mr. Vivek Narayanan, Mr. Suri Praneeth, Mr. Priyvratt Vats, Mr. Sayandev Ghosh, Saran Chaurashiya, Mr. Sharan Shastri, Mr. Shivam Yadav, Mr. Rahul Kumar, Mr. Deepak Saw, Ms. Kousalya V, Ms. Chandrakala Devi, Mr. Saurabh Mishra, Mr. Subir Karmakar, Mr. Girja Shankar and all PG Machines lab group for their valuable support. How could I forget my hostel mates Mr. Kapil Shukla, Dr. Srikanth Reddy, Mr. Nikhil Krishna, Mr. Rishi Kant Sharma and Mr. Nikhil Singh, who supported and inspired me during my stay in 'Zanskar' house. I would also like to thank Mr. Yatindra, Mr. Satish, 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.

I would like to thank my mother, Mrs. Raj Kumari and my father Mr. R. P. Dwivedi for their dreams, blessings and constant encouragement. Moreover, I would like to thank my wife Ms. Neha Dwivedi and my little daughter Kavya Dwivedi for giving me the inner strength and wholehearted support. I would like to thank my elder brother Dheerendra Dwivedi and younger brothers Yogendra Dwivedi and Kavendra Dwivedi for their continuous support and encouragement. Their trust in my capabilities had been a key factor to all my achievements.

At last, I am beholden to almighty for their blessings to help me to raise my academic level to this stage. I pray for their benediction in my future endeavors. Their blessings may be showered on me for strength, wisdom and determination to achieve in future.

Date: May 16, 2019

Shailendra Kumar

ABSTRACT

This work presents dual mode reconfigurable residential photovoltaic (PV)-battery energy storage (BES) based microgrid for rural electrification. The proposed microgrids address the problems related to the electrification of remote/ rural areas along with the systems/ loads that are running on diesel generators and suffering from the outage of electricity. Both these problems can be resolved by using renewable energy resources and storage to feed the remote locations and to reduce the fuel consumptions and outage of electricity. Moreover, due to protection reasons, conventional solar inverters are mandatory to shut down automatically at loss of the grid. However, proposed multitasking residential microgrids are developed to provide uninterrupted energy to consumer load even under outage of utility grid. It is also configured as utility interactive inverters and islanding inverters.

The microgrids have renewable energy sources (wind, solar and small hydro etc.), which works in synchronicity to the utility for bidirectional active power flow as well to supply the power to local consumer loads. The dispatchability of the system should be enough to produce the power when it is required by the consumers. However, in night time, the PV power is not available. In order to achieve dispatchability of the microgrid, the energy storage devices are required. Therefore, BES is an important part to make the microgrid dispatchable means under outage of PV power and the utility, BES dispatches the energy to the loads. The PV array with BES is integrated close to the consumers load rather than using long transmission lines for providing the power to the consumers. Moreover, the microgrid becomes reliable when it is operated in islanding mode by maintaining the voltage source converter (VSC) output voltage and frequency within the boundary under loss of utility grid. It is transferred to other operating mode under recovery of the utility. In utility integrated mode, the load voltage and frequency are decided by the utility. The VSC works as a power conditioner unit to supply the harmonics current as well as reactive power required by the nonlinear loads. Moreover, the current technology of solar inverter is not multi-functional also not able to provide uninterrupted power. However, in this work, it improves the utilization factor of microgrid as it is capable of saving substantially capital investment, and maintenance cost on behalf of multi-functional features. However, in islanding mode, BES and PV array (depending upon the availability) must take care of loads.

The substantial power electronics converter based nonlinear loads are used in the domestic applications, which have given rise to serious power quality problems such as poor power factor, harmonics in grid current, neutral current, voltage distortion etc. in the distribution network. This pollution in the grid, causes mal-operation of appliances, increased losses, reactive power burden on the grid, and it also deteriorates the power factor. Therefore, fast and accurate control algorithms are required to mitigate these load harmonics current.

This research work aims at the design, control and implementation of various single-phase and three-phase for PV-BES microgrids. All the proposed microgrids are simulated in MATLAB platform and the laboratory prototypes of them are developed to validate the topology, control algorithms and developed simulation model. This research work mainly focuses on the grid interactive PV-BES microgrids, which provides power to local emergency nonlinear load even under outage of utility grid and PV generation. In order to deal with the problem of electricity outage and power quality issues of distribution network, the various configurations of PV-BES microgrids are developed in this work, which are classified based on their type of battery connection, type of utility grid (single-phase or three-phase) and number of power conversion stages (single-stage or two-stage). In case of two-stage PV-BES microgrids, the first stage is a boost converter, which is used for MPPT and the second stage is a grid interactive VSC. However, in single stage microgrid systems, the bidirectional converter is used to achieve extraction of peak energy from the PV array as well control the charging/discharging of the battery bank. In grid interactive mode, A PV feed-forward (PVFF) loop is incorporated in current control for injection of active power to the utility grid as well as to improve the dynamic behavior of the PV-BES microgrid. The three phase microgrids are further classified in three phase three wire and three phase four wire configurations. The three phase four wire microgrids are capable of performing neutral current mitigation along with functionalities furnished by three-phase three-wire PV-BES microgrid. Therefore, the selection of type of microgrid, depends on the requirements of the consumers. The problem of utility outage is quite common in the rural areas. Therefore, simple, autonomous and intelligent control techniques for grid interactive PV-BES microgrid, are developed such that the PV-BES microgrid is capable of operating under outage and recovery of utility grid and PV array and provides uninterrupted power to the end users.

सार

यह कार्य ग्रामीण विद्युतीकरण के लिए दोहरी मोड रेकोंफ़िगुरबल रेजिडेंशियल फोटोवोल्टिक (पीवी) -बैटरी एनर्जी स्टोरेज (बीईएस) आधारित माइक्रोग्रिड प्रस्तुत करता है। प्रस्तावित माइक्रोग्रिड सिस्टम / भार के साथ सुदूर / ग्रामीण क्षेत्रों के विद्युतीकरण से संबंधित समस्याओं को संबोधित करते हैं जो डीजल जनरेटर पर चल रहे हैं और बिजली के आउटेज से पीड़ित हैं। दूरदराज के स्थानों को ईंधन की खपत और बिजली की कमी को कम करने के लिए अक्षय ऊर्जा संसाधनों और भंडारण का उपयोग करके इन दोनों समस्याओं का समाधान किया जा सकता है। इसके अलावा, सुरक्षा कारणों से, ग्रिड के नुकसान पर पारंपरिक सौर इनवर्टर को स्वचालित रूप से बंद करना अनिवार्य है। हालाँकि, प्रस्तावित मल्टीटास्किंग आवासीय माइक्रोग्रिड्स को यूटिलिटी ग्रिड के बाहर भी उपभोक्ता भार को निर्बाध ऊर्जा प्रदान करने के लिए विकसित किया गया है। यह उपयोगिता इंटरैक्टिव इनवर्टर और आइलैंडिंग इनवर्टर के रूप में भी कॉन्फ़िगर किया गया है।

माइक्रोग्रिड्स में नवीकरणीय ऊर्जा स्रोत (पवन, सौर और छोटे हाइड्रो आदि) हैं, जो द्विदिश सक्रिय ऊर्जा प्रवाह के लिए उपयोगिता के साथ-साथ स्थानीय उपभोक्ता भार को बिजली की आपूर्ति करने के लिए उपयोगिता में काम करता है। उपभोक्ताओं द्वारा आवश्यक होने पर बिजली का उत्पादन करने के लिए सिस्टम की डिस्पैचबिलिटी पर्याप्त होनी चाहिए। हालांकि, रात के समय में, पीवी पावर उपलब्ध नहीं है। माइक्रोग्रिड के डिस्पैचबिलिटी को प्राप्त करने के लिए, ऊर्जा भंडारण उपकरणों की आवश्यकता होती है। इसलिए, बीईएस पीवी पावर और यूटिलिटी के आउटेज के तहत माइक्रोग्रिड डिस्पैचेबल साधनों को बनाने के लिए एक महत्वपूर्ण हिस्सा है, बीईएस ऊर्जा को भार में भेज देता है। बीईएस के साथ पीवी सरणी उपभोक्ताओं को बिजली प्रदान करने के लिए लंबी ट्रांसमिशन लाइनों का उपयोग करने के बजाय उपभोक्ताओं के लोड के करीब एकीकृत है। इसके अलावा, माइक्रोग्रिड विश्वसनीय हो जाता है जब यह उपयोगिता स्रोत के नुकसान के तहत सीमा के साथ वोल्टेज स्रोत कनवर्टर (वीएससी) आउटपुट वोल्टेज और आवृत्ति को बनाए रखकर द्वीप के मोड में संचालित होता है। यह उपयोगिता की वसूली के तहत अन्य ऑपरेटिंग मोड में स्थानांतरित किया जाता है। उपयोगिता एकीकृत मोड में, लोड वोल्टेज और आवृत्ति उपयोगिता द्वारा तय की जाती है। वीएससी एक पावर कंडीशनर इकाई के रूप में काम करता है जो हार्मोनिक्स करंट के साथ-साथ भार द्वारा आवश्यक प्रतिक्रियाशील शक्ति की आपूर्ति करता है। इसके अलावा, सौर इनवर्टर की वर्तमान तकनीक बहुआयामी नहीं है, जो निर्बाध शक्ति प्रदान करने में सक्षम नहीं है। हालांकि, इस काम में, यह माइक्रोग्रिड के उपयोग के कारक को बेहतर बनाता है क्योंकि यह बहु-कार्यात्मक सुविधाओं की ओर से पर्याप्त पूंजी निवेश और रखरखाव लागत को बचाने में सक्षम है। हालांकि, आइलैंडिंग मोड में, बीईएस और पीवी सरणी (उपलब्धता के आधार पर) को भार का ध्यान रखना चाहिए। घरेलू अनुप्रयोगों में पर्याप्त पावर इलेक्ट्रॉनिक्स कनवर्टर आधारित नानालिनीयर लोड का उपयोग किया जाता है, जिसने वितरण नेटवर्क में खराब बिजली का कारक, ग्रिड करंट में हार्मोनिक्स, न्यूट्रल करंट, वोल्टेज विरूपण आदि जैसी गंभीर गुणवत्ता की समस्याओं को जन्म दिया है। ग्रिड में यह प्रदूषण, उपकरणों के खराब संचालन, घाटे में वृद्धि, ग्रिड पर प्रतिक्रियाशील बिजली के बोझ का कारण

बनता है, और यह शक्ति कारक को भी खराब करता है। इसलिए, इन लोड हार्मोनिक्स करंट को कम करने के लिए तेज और सटीक नियंत्रण एल्गोरिदम की आवश्यकता होती है।

यह शोध कार्य पीवी-बीईएस माइक्रोग्रिड के लिए विभिन्न एकल-चरण और तीन-चरण के डिजाइन, नियंत्रण और कार्यान्वयन के उद्देश्य से है। सभी प्रस्तावित माइक्रोग्रिड MATLAB प्लेटफॉर्म में सिमुलेटेड हैं और उनमें से प्रयोगशाला प्रोटोटाइप को टोपोलॉजी, नियंत्रण एल्गोरिदम को मान्य करने और सिमुलेशन मॉडल विकसित किया गया है। यह शोध कार्य मुख्य रूप से ग्रिड इंटरैक्टिव पीवी-बीईएस माइक्रोग्रिड पर केंद्रित है, जो उपयोगिता ग्रिड और पीवी ऊर्जा के आउटपुट के तहत स्थानीय आपातकालीन नानलिनीयर लोड को भी शक्ति प्रदान करता है। वितरण नेटवर्क की बिजली की आउटपुट और बिजली की गुणवत्ता की समस्याओं की समस्या से निपटने के लिए, इस काम में पीवी-बीईएस माइक्रोग्रिड के विभिन्न विन्यास विकसित किए जाते हैं, जिन्हें अनेक प्रकार के बैटरी कनेक्शन, उपयोगिता ग्रिड के प्रकार (एकल चरण या तीन-चरण) के आधार पर वर्गीकृत किया जाता है। और बिजली रूपांतरण चरणों की संख्या (एकल-चरण या दो-चरण)। दो रूपांतरण चरणों पीवी-बीईएस माइक्रोग्रिड्स के मामले में, पहला रूपांतरण चरण एक बूस्टर कनवर्टर है, जिसका उपयोग एमपीपीटी के लिए किया जाता है और दूसरा रूपांतरण चरण ग्रिड इंटरैक्टिव वीएससी है। हालांकि, सिंगल स्टेज माइक्रोग्रिड सिस्टम में, पी.वी. सरणी से पीक एनर्जी के निष्कर्षण को प्राप्त करने के लिए द्विदिशीय कनवर्टर का उपयोग किया जाता है और साथ ही बैटरी बैंक के चार्जिंग / डिस्चार्जिंग को नियंत्रित करता है। ग्रिड इंटरैक्टिव मोड में, पीवी फीड-फॉरवर्ड (पीवीएफएफ) लूप को उपयोगिता ग्रिड को सक्रिय शक्ति के इंजेक्शन के साथ-साथ पीवी-बीईएस माइक्रोग्रिड के गतिशील व्यवहार में सुधार करने के लिए वर्तमान नियंत्रण में शामिल किया गया है। तीन चरण माइक्रोग्रिड को तीन चरण तीन तार और तीन चरण चार तार विन्यास में वर्गीकृत किया गया है। तीन चरण चार तार माइक्रोग्रिड तीन-चरण तीन-तार पीवी-बीईएस माइक्रोग्रिड द्वारा सुसज्जित कार्यक्षमताओं के साथ तटस्थ करंट शमन करने में सक्षम हैं। इसलिए, माइक्रोग्रिड के प्रकार का चयन, उपभोक्ताओं की आवश्यकताओं पर निर्भर करता है। यूटिलिटी आउटपुट की समस्या ग्रामीण क्षेत्रों में काफी आम है। इसलिए, ग्रिड इंटरैक्टिव पीवी-बीईएस माइक्रोग्रिड के लिए सरल, स्वायत्त और बुद्धिमान नियंत्रण तकनीकों को ऐसे विकसित किया गया है कि पीवी-बीईएस माइक्रोग्रिड उपयोगिता ग्रिड और पीवी सरणी के आउटपुट और रिकवरी के तहत संचालित करने में सक्षम है और अंत उपयोगकर्ताओं को निर्बाध शक्ति प्रदान करता है।

TABLE OF CONTENTS

	Page No.
Certificate	i
Acknowledgements	ii
Abstract	v
Table of Contents	vii
List of Figures	xxi
List of Tables	xxx
List of Abbreviations	xxxii
List of Symbols	xxxii
CHAPTER-I INTRODUCTION	1-16
1.1 General	1
1.2 Classification of PV-BES Based Microgrid Systems	3
1.3 State of Art on PV-BES Based Microgrid Systems	4
1.4 MPPT Techniques for PV-BES Based Microgrid Systems	6
1.5 Islanding Detection, and Synchronization Schemes of PV-BES Based Microgrid Systems	7
1.6 Power Quality Improvements in Microgrid Systems	8
1.7 Objectives and Scope of Work	9
1.8 Outline of the Chapters	14
CHAPTER -II LITERATURE REVIEW	17-31
2.1 General	17
2.2 Literature Survey	17
2.2.1 Standalone and Grid Interactive PV-BES Microgrid Systems	18
2.2.2 Review of MPPT Control of PV-BES Microgrid Systems	19
2.2.3 Review of Islanding Detection and Synchronization Algorithms	21
2.2.4 Review of Control of BES for PV-BES Microgrid Systems	24
2.2.5 Power management in Grid Interactive Microgrids	24
2.2.6 Power Quality Issues in Microgrid Systems	25
2.2.7 Compensating Devices for Power Quality improvement in Microgrid Systems	26
2.3 Identified Research Areas	28
2.4 Conclusions	31
CHAPTER – III CLASSIFICATION AND CONFIGURATIONS OF PV-BES BASED MICROGRID SYSTEMS	32-42
3.1 General	32

3.2	Classification of PV-BES Based Microgrid Systems	32
3.3	System Configurations and Features of PV-BES Based Microgrid Systems	33
3.3.1	System Configurations and Features of Single Phase and Three Phase Standalone PV-BES Microgrid	33
3.3.2	System Configurations and Features of Single Phase and Three Phase Grid Interactive PV Based Microgrid Systems	35
3.3.3	System Configurations and Features of Two-Stage Single-Phase PV-BES Microgrid without and with Buck-Boost Converter Controlled BES	36
3.3.4	System Configurations and Features of Single-Stage Single-Phase PV-BES Microgrid with Buck-Boost Converter Controlled BES	38
3.3.5	System Configurations and Features of Two-Stage Three-Phase Three Wire and Three-Phase Four Wire PV-BES Microgrid without and with Buck-Boost Converter Controlled BES	39
3.3.6	System Configurations and Features of Single-Stage Three-Phase Three Wire and Three Phase Four Wire PV-BES Microgrid with Buck-Boost Converter Controlled BES	41
3.5	Conclusions	42
CHAPTER-IV CONTROL AND IMPLEMENTATION OF SINGLE PHASE AND THREE PHASE STANDALONE PV-BES MICROGRIDS		43-67
4.1	General	43
4.2	Circuit Configurations of Standalone PV-BES Microgrids	43
4.2.1	Circuit Configuration of Single Phase Standalone PV-BES Microgrid	44
4.2.2	Circuit Configuration of Three Phase Standalone PV-BES Microgrid	44
4.3	Design of Standalone PV-BES Microgrids	45
4.3.1	Design of Single Phase Standalone PV-BES Microgrid	45
4.3.2	Design of Three Phase Standalone PV-BES Microgrid	45
4.4	Control Approaches of Standalone PV-BES Microgrids	46
4.4.1	Control Approach of Single Phase Standalone PV-BES Microgrid	47
4.4.1.1	MPPT Control Algorithm	47
4.4.1.2	Control Approach for Single Phase VSC	49
4.4.2	Control Approach of Three Phase Standalone PV-BES Microgrid	50
4.4.2.1	MPPT control technique	50
4.4.2.2	Control approach for Three Phase VSC	50
4.4.3	Control Approach of Bidirectional DC-DC Buck-Boost converter	53
4.5	MATLAB Based Modeling of Standalone PV-BES Microgrids	54
4.5.1	MATLAB Based Modeling of Single Phase Standalone PV-BES Microgrid	54
4.5.2	MATLAB Based Modeling of Three Phase Standalone PV-BES	54

	Microgrid	
4.6	Hardware Implementation of Single Phase and Three Phase Standalone PV-BES Microgrid	55
4.6.1	Hardware Configuration of DSP d-SPACE-1103 Controller	55
4.6.2	Interfacing Circuit for Hall Effect Current Sensors	56
4.6.3	Interfacing Circuit for Hall Effect Voltage Sensors	56
4.6.4	Interfacing Circuit for Gate Driver	56
4.7	Results and Discussion	56
4.7.1	Simulated Performances	56
4.7.1.1	Simulated Steady State Performance of Single Phase Standalone PV-BES Microgrid	57
4.7.1.2	Simulated Dynamic Performance of Single Phase Standalone PV-BES Microgrid	57
4.7.1.3	Simulated Steady State Performance of Three Phase Standalone PV-BES Microgrid	59
4.7.1.4	Simulated Dynamic Performance of Three Phase Standalone PV-BES Microgrid	59
4.7.2	Experimental Performances	62
4.7.2.1	Experimental Steady State Performance of Single Phase Standalone PV-BES Microgrid	62
4.7.2.2	Experimental Dynamic Performance of Single Phase Standalone PV-BES Microgrid	64
4.7.2.3	Experimental Steady State Performance of Three Phase Standalone Microgrid	65
4.7.2.4	Experimental Dynamic Performance of Three Phase Standalone PV-BES Microgrid	66
4.8	Conclusions	66
CHAPTER-V	CONTROL AND IMPLEMENTATION OF GRID INTERACTIVE PV BASED MICROGRID SYSTEMS WITHOUT BATTERY STORAGE	68-108
5.1	General	68
5.2	Circuit Configurations of Grid Interactive PV Based Microgrid Systems	69
5.2.1	Circuit Configuration of Single Phase Grid Interactive PV Based Microgrid	69
5.2.2	Circuit Configuration of Three Phase Grid Interactive PV Based Microgrid	70
5.3	Design of Grid Interactive PV Based Microgrids	70
5.3.1	Design of Single Phase Grid Interactive PV Based Microgrid	71
5.3.2	Design of Three Phase Grid Interactive PV Based Microgrid	71
5.4	Control Approaches of Grid Interactive PV Based Microgrids	71
5.4.1	Current Control Approach of Single Phase Grid Interactive PV Based Microgrids	73
5.4.2	Current Control Approach of Three Phase Grid Interactive PV Based Microgrids	75

5.4.3	Voltage Control Approach of Single Phase Grid Interactive PV Based Microgrid	79
5.4.4	Voltage Control Approach of Three Phase Grid Interactive PV Based Microgrid	80
5.4.5	Synchronization Scheme and Mode Transfer Controller for Grid Interactive PV Based Microgrid	80
5.5	MATLAB Based Modeling for Grid Interactive PV Based Microgrid	81
5.5.1	MATLAB Based Modeling of Single Phase Grid Interactive PV Based Microgrid	81
5.5.2	MATLAB Based Modeling of Three Phase Grid Interactive PV Based Microgrid	82
5.6	Hardware Implementation of Grid Interactive PV Based Microgrid	82
5.6.1	Hardware Configuration of DSP d-SPACE 1103 Controller	83
5.6.2	Interfacing Circuit for Hall Effect Current Sensors	83
5.6.3	Interfacing Circuit for Hall Effect Voltage Sensors	84
5.6.4	Interfacing Circuit for Gate Driver	86
5.7	Results and Discussion	87
5.7.1	Simulated Performances	88
5.7.1.1	Simulated Performance of Single Phase Grid Interactive PV Based Microgrid	88
5.7.1.1.1	Simulated Results of Single Phase PV Based Microgrid without BES at Outage of Utility Grid	88
5.7.1.1.2	Simulated Results of Single Phase PV Based Microgrid without BES at Recovery of Utility Grid	88
5.7.1.1.3	Simulated Performance under Variation of Solar PV Insolation	89
5.7.1.2	Simulated Performance of Three Phase PV Based Microgrid without BES	91
5.7.1.2.1	Simulated Results of Three Phase PV Based Microgrid without BES at outage of Utility Grid	91
5.7.1.2.2	Simulated Results of Three Phase PV Based Microgrid without BES at Recovery of Utility Grid	91
5.7.1.2.3	Simulated Performance of Three Phase PV Based Microgrid at Unbalanced Nonlinear Loads	92
5.7.1.2.4	Simulated Performance under Variation of Solar PV Insolations	93
5.7.2	Experimental Performances	93
5.7.2.1	Experimental Performance of Single Phase Grid	94

	Interactive PV Based Microgrid	
	5.7.2.1.1 Experimental Performance of Single Phase PV Based Microgrid without BES at Outage of Utility Grid	95
	5.7.2.1.2 Experimental Performance of Single Phase PV Based Microgrid without BES at Recovery of Utility Grid	96
	5.7.2.1.3 Steady State Performance of Single Phase PV Based Microgrid at Utility Tied and Islanded Modes	97
	5.7.2.1.4 Performance under Variation of PV Insolations	97
	5.7.2.1.5 Intermediate Signals of Adjustable Step Based Control Approach	100
5.7.2.2	Experimental Performance of Three Phase Grid Interactive PV Based Microgrid	100
	5.7.2.2.1 De-synchronization of PV Based Three Phase Microgrid without BES at outage of Grid	101
	5.7.2.2.2 Synchronization of PV Based Microgrid without BES at Recovery of Grid	102
	5.7.2.2.3 Steady State Performance of Three Phase PV Based Microgrid at Utility Tied and Islanded Modes	103
	5.7.2.2.4 Experimental Performance under Variation of Solar PV Insolations	104
	5.7.2.2.5 Experimental Intermediate Signals of LWDF Control Approach	106
5.8	Conclusions	108
CHAPTER-VI	CONTROL AND IMPLEMENTATION OF TWO-STAGE SINGLE-PHASE PV-BES MICROGRID WITHOUT AND WITH BUCK-BOOST CONVERTER CONTROLLED BES	109-146
6.1	General	109
6.2	Circuit Configurations for Two-Stage Single-Phase PV-BES Microgrid without and with Buck-Boost Converter Controlled BES	109
6.3	Design of Two-Stage Single-Phase PV-BES Microgrid without and with Buck-Boost Converter Controlled BES	111
6.4	Control Approaches for Two-Stage Single-Phase PV-BES Microgrid without and with Buck-Boost Converter Controlled BES	112
	6.4.1 MPPT Control Approach for Two-Stage Single-Phase PV-BES Microgrid	113

6.4.2	Control Approaches for Single Phase PV-BES Microgrid	114
6.4.2.1	Control of PV-BES Microgrid in Current Control Mode	114
6.4.2.2	Control of PV-BES Microgrid in Islanded Mode	119
6.4.3	Control Approach for Bidirectional Buck-Boost Converter	120
6.4.4	Control Approach for Seamless Transition Between Two Modes	121
6.5	MATLAB Based Modeling for Two-Stage Single-Phase PV-BES Microgrid with and without Buck-Boost Converter Controlled BES	123
6.6	Hardware Implementation of Two-Stage Single-Phase PV-BES Microgrid with and without Buck-Boost Converter Controlled BES	124
6.6.1	Hardware Configuration of DSP d-SPACE 1103 Controller	124
6.6.2	Interfacing Circuit for Hall Effect Current Sensors	125
6.6.3	Interfacing Circuit for Hall Effect Voltage Sensors	125
6.6.4	Interfacing Circuit for Gate Driver	125
6.7	Results and Discussion	125
6.7.1	Simulated Performances	125
6.7.1.1	Simulated Performance for Two-Stage Single-Phase PV-BES Microgrid without Buck-Boost Converter Controlled BES	126
6.7.1.1.1	Simulated Performance under Sudden Outage of Utility Grid	126
6.7.1.1.2	Simulated Performance under Sudden Recovery of Utility Grid	126
6.7.1.1.3	Simulated Performance under Constant Power Feeding to the Utility with Nonlinear load	127
6.7.1.1.4	Simulated Performance Evaluation under Outage of PV Source	127
6.7.1.2	Simulated Performance for Two-Stage Single-Phase PV-BES Microgrid with a Buck-Boost Converter Controlled BES	129
6.7.1.2.1	Simulated Performance under Sudden Outage of Utility Grid	129
6.7.1.2.2	Simulated Performance under Sudden Recovery of Utility Grid	129
6.7.1.2.3	Simulated Performance under Constant Power Feeding to the Utility with Nonlinear load	131
6.7.1.2.4	Simulated Performance Evaluation under Outage of PV Source	131
6.7.2	Experimental Performances	132
6.7.2.1	Experimental Performance for Two-Stage Single-Phase PV-BES Microgrid without Buck-Boost Converter	133

	Controlled BES	
	6.7.2.1.1	Experimental Performance under Sudden Outage of Utility Grid 133
	6.7.2.1.2	Experimental Performance under Sudden Recovery of Utility Grid 134
	6.7.2.1.3	Experimental Performance under Constant Power Feeding to the Utility Nonlinear load 135
	6.7.2.1.4	Experimental Performance under Outage of PV Source and Utility Grid 136
	6.7.2.1.5	Intermediate Signals of Proposed Control 137
6.7.2.2	Experimental Performance for Two-Stage Single-Phase PV-BES Microgrid with Buck-Boost Converter Controlled BES	138
	6.7.2.2.1	Experimental Performance under Sudden Outage of Utility Grid 139
	6.7.2.2.2	Experimental Performance under Sudden Recovery of Utility Grid 140
	6.7.2.2.3	Experimental Performance under Constant Power Feeding to the Utility with Nonlinear load 141
	6.7.2.2.4	Experimental Performance under Outage of PV Source and Utility Grid 142
	6.7.2.2.5	Intermediate Signals of Proposed Control 144
6.7.3	Comparative Analysis of Proposed and conventional Synchronization Schemes	145
6.8	Conclusions	145
CHAPTER-VII	CONTROL AND IMPLEMENTATION OF SINGLE-STAGE SINGLE-PHASE PV-BES MICROGRID WITH BUCK-BOOST CONVERTER CONTROLLED BES	147-166
7.1	General	147
7.2	Circuit Configuration of Single-Stage Single-Phase PV-BES Microgrid with Buck-Boost Converter Controlled BES	147
7.3	Design of Single-Stage Single-Phase PV-BES Microgrid with Buck-Boost Converter Controlled BES	148
7.4	Control Approaches of Single-Stage Single-Phase PV-BES Microgrid with Buck-Boost Converter Controlled BES	148
7.4.1	MPPT Control Approach for Single-Stage Single-Phase PV-BES Microgrid	149
7.4.2	Control Approaches for PV-BES Microgrid	150

	7.4.2.1	Control of PV-BES Microgrid in Current Control Mode	150
	7.4.2.2	Control of PV-BES Microgrid in Islanded Control Mode	152
	7.4.3	Control Approach for Bidirectional Buck-Boost Converter	153
	7.4.4	Control Approach for Seamless Transition Between Two Modes	153
7.5		MATLAB Based Modeling for Single-Stage Single-Phase PV-BES Microgrid with Buck-Boost Converter Controlled BES	154
7.6		Hardware Implementation of Single-Stage Single-Phase PV-BES Microgrid with Buck-Boost Converter Controlled BES	155
	7.6.1	Hardware Configuration of DSP d-SPACE 1103 Controller	155
	7.6.2	Interfacing Circuit for Hall Effect Current Sensors	156
	7.6.3	Interfacing Circuit for Hall Effect Voltage Sensors	156
	7.6.4	Interfacing Circuit for Gate Driver	156
7.7		Results and Discussion	156
	7.7.1	Simulated Performances	156
	7.7.1.1	Performance under Sudden Outage of Utility Grid	157
	7.7.1.2	Performance under Sudden Recovery of Utility Grid	157
	7.7.1.3	Performance under Constant Power Feeding to the Utility with Balanced and Unbalanced Nonlinear load	157
	7.7.1.4	Simulated Performance under Outage of PV Source and Utility Grid	158
	7.7.2	Experimental Performances	160
	7.7.2.1	Performance under Sudden Outage of Utility Grid	160
	7.7.2.2	Performance under Sudden Recovery of Utility Grid	161
	7.7.2.3	Performance under Constant Power Feeding to the Utility with Balanced and Unbalanced Nonlinear load	162
	7.7.2.4	Performance under Outage and recovery of PV Source	164
	7.7.2.5	Intermediate Signals of Proposed Frequency Observer based Current Control	164
7.8		Conclusions	166
CHAPTER-VIII CONTROL AND IMPLEMENTATION OF TWO-STAGE THREE-PHASE THREE WIRE AND THREE-PHASE FOUR WIRE PV-BES MICROGRID WITHOUT AND WITH A BUCK-BOOST CONVERTER CONTROLLED BES			167-241
8.1		General	167
8.2		Circuit Configurations	168
	8.2.1	Circuit Configuration of Two-Stage Three-Phase PV-BES Microgrid without and with Buck-Boost Converter Controlled BES	168
	8.2.2	Circuit Configuration of Two-Stage Three-Phase Four Wire PV-BES Microgrid With Buck-Boost Converter Controlled BES	168
8.3		Design of Two-Stage Three-Phase PV-BES Microgrid without and with Buck-Boost Converter Controlled BES	170

8.3.1	Design of Two-Stage Three-Phase PV-BES Microgrid without and with Buck-Boost Converter Controlled BES	171
8.3.2	Design of Two-Stage Three-Phase Four Wire PV-BES Microgrid with Buck-Boost Converter Controlled BES	172
8.4	Control Approaches of Two-Stage Three-Phase Three-Wire PV-BES Microgrid without and with Buck-Boost Converter Controlled BES	173
8.4.1	MPPT Control Approach for Two-Stage Three-Phase PV-BES Microgrid	174
8.4.2	Control Approaches for PV-BES Microgrid	175
	8.4.2.1 Control of Three Phase PV-BES Microgrid in Current Control Mode	176
	8.4.2.2 Control of PV-BES Microgrid in Islanded Control Mode	184
8.4.3	Control Approach for Bidirectional Buck-Boost converter	185
8.4.4	Control Approach for Seamless Transition Between Two Modes	186
8.4.5	Detection of Fundamental Positive Sequence Voltages at Polluted Grid Conditions	187
8.5	Control Approach of Two-Stage Three-Phase Four Wire PV-BES Microgrid with Buck-Boost Converter Controlled BES	189
8.5.1	MPPT Control Approach for Two-Stage Three-Phase Four Wire PV-BES Microgrid	190
8.5.2	Control Approaches for PV-BES Microgrid	190
	8.5.2.1 Control of Three-Phase four Wire PV-BES Microgrid in Current Control Mode	190
	8.5.2.2 Control of Three-Phase four Wire PV-BES Microgrid in Islanded Control Mode	195
8.5.3	Control Approach for Seamless Transition Between Two Modes	196
8.6	MATLAB Based Modeling for Two-Stage Three-Phase Three Wire PV-BES Microgrid without and with Buck-Boost Converter Controlled BES	196
8.7	MATLAB Based Modeling for Two-Stage Three-Phase Four Wire PV-BES Microgrid with Buck-Boost Converter Controlled BES	196
8.8	Hardware Implementation of Two-Stage Three-Phase Three Wire and Three-Phase Four Wire PV-BES Microgrid without and with Buck-Boost Converter Controlled BES	198
8.8.1	Hardware Configuration of DSP d-SPACE 1103 Controller	198
8.8.2	Interfacing Circuit for Hall Effect Current Sensors	199
8.8.3	Interfacing Circuit for Hall Effect Voltage Sensors	199
8.8.4	Interfacing Circuit for Gate Driver	199
8.9	Results and Discussion	200
8.9.1	Simulated Performances	200
	8.9.1.1 Simulated Performance for Two-Stage Three-Phase PV-BES Microgrid without a Buck-Boost Converter Controlled BES	200

	8.9.1.1.1	Simulated Performance under Sudden Outage of Utility Grid	200
	8.9.1.1.2	Simulated Performance under Sudden Recovery of Utility Grid	202
	8.9.1.1.3	Simulated Performance under Constant Power Feeding to the Utility with Balanced and Unbalanced Nonlinear load	203
	8.9.1.1.4	Simulated Performance Evaluation under Outage of PV Source	204
8.9.1.2		Simulated Performance for Two-Stage Three-Phase PV-BES Microgrid with Buck-Boost Converter	206
	8.9.1.2.1	Simulated Performance under Sudden Outage of Utility Grid	206
	8.9.1.2.2	Simulated Performance under Sudden Recovery of Utility Grid	206
	8.9.1.2.3	Simulated Performance under Constant Power Feeding to the Utility with Balanced and Unbalanced Nonlinear load	208
	8.9.1.2.4	Simulated Performance Evaluation under Outage of PV Source	210
8.9.1.3		Simulated Performance for Two-Stage Three-Phase Four Wire PV-BES Microgrid with Buck-Boost Converter Controlled BES	212
	8.9.1.3.1	Simulated Performance under Sudden Outage of Utility Grid	212
	8.9.1.3.2	Simulated Performance under Sudden Recovery of Utility Grid	212
	8.9.1.3.3	Simulated Performance of Three-Phase Four-Wire Microgrid with Balanced and Unbalanced Nonlinear load	213
	8.9.1.3.4	Simulated Performance Evaluation under Outage of PV Source and Utility Grid	216
8.9.2		Experimental Performances	218
	8.9.2.1	Experimental Performance for Two-Stage Three-Phase Three-Wire PV-BES Microgrid without Buck-Boost Converter Controlled BES	218
	8.9.2.1.1	Experimental Performance under Sudden Outage of Utility Grid	219
	8.9.2.1.2	Experimental Performance under Sudden Recovery of Utility Grid	220
	8.9.2.1.3	Experimental Performance under	221

		Constant Power Feeding to the Utility with Nonlinear Load	
	8.9.2.1.4	Experimental Performance Evaluation under Insulations Change	221
	8.9.2.1.5	Intermediate Signals of Proposed Current Control	223
	8.9.2.2	Experimental Performance for Two-Stage Three-Phase Three Wire PV-BES Microgrid with Buck-Boost Converter Controlled BES	224
	8.9.2.2.1	Experimental Performance under Sudden Outage of Utility Grid	225
	8.9.2.2.2	Experimental Performance under Sudden Recovery of Utility Grid	227
	8.9.2.2.3	Experimental Performance under Constant Power Feeding to the Utility Nonlinear load	228
	8.9.2.2.4	Experimental Performance Evaluation under Outage of PV Source and Utility	228
	8.9.2.2.5	Intermediate Signals of Proposed Current Control	230
	8.9.2.3	Experimental Performance for Two-Stage Three-Phase Four Wire PV-BES Microgrid with Buck-Boost Converter Controlled BES	231
	8.9.2.3.1	Experimental Performance under Sudden Outage of Utility Grid	232
	8.9.2.3.2	Experimental Performance under Sudden Recovery of Utility Grid	233
	8.9.2.3.3	Experimental Performance under Constant Power Feeding to the Utility at Balanced and Unbalanced Nonlinear load	234
	8.9.2.3.4	Experimental Performance Evaluation under Outage of PV Source and Utility	237
	8.9.2.3.5	Intermediate Signals of Proposed Current Control	238
	8.9.4	Assessment of Phase and Frequency using Conventional PLL and Proposed Controller at Grid Synchronization	239
8.10		Conclusions	241

CHAPTER-IX	CONTROL AND IMPLEMENTATION OF SINGLE-STAGE THREE-PHASE THREE WIRE AND THREE PHASE FOUR WIRE PV-BES MICROGRIDS WITH BUCK-BOOST CONVERTER CONTROLLED BES	242-283
9.1	General	242
9.2	Circuit Configurations	243
	9.2.1 Circuit Configurations of Single-Stage Three-Phase Three Wire PV-BES Microgrid with Buck-Boost Converter Controlled BES	243
	9.2.2 Circuit Configurations of Single-Stage Three-Phase Four Wire PV-BES Microgrid with Buck-Boost Converter Controlled BES	244
9.3	Design of Single-Stage Three-Phase Three Wire and Three Phase Four Wire PV-BES Microgrid with Buck-Boost Converter Controlled BES	245
	9.3.1 Design of Single-Stage Three-Phase Three Wire PV-BES Microgrid with Buck-Boost Converter Controlled BES	245
	9.3.2 Design of Single-Stage Three-Phase Four Wire PV-BES Microgrid with Buck-Boost Converter Controlled BES	246
9.4	Control Approaches of Single-Stage Three-Phase Three Wire PV-BES Microgrid with Buck-Boost Converter Controlled BES	246
	9.4.1 MPPT Control Approach for Single-Stage Three-Phase PV-BES Microgrid	247
	9.4.2 Control Approaches for Single-Stage Three-Phase PV-BES Microgrid	247
	9.4.2.1 Control of PV-BES Microgrid in Current Control Mode	247
	9.4.2.2 Control of PV-BES Microgrid in Islanded Control Mode	252
	9.4.3 Control Approach for Bidirectional Buck-Boost converter	252
	9.4.4 Control Approach for Seamless Transition Between Two Modes	253
9.5	Control Approaches of Single-Stage Three-Phase Four-Wire PV-BES Microgrid with Buck-Boost Converter Controlled BES	255
	9.5.1 Control of Single-Stage Three-Phase Four Wire PV-BES Microgrid in Current Control Mode	255
	9.5.2 Control of Single-Stage Three-Phase Four Wire PV-BES Microgrid in Islanded Control Mode	258
9.6	MATLAB Based Modeling for Single-Stage Three-Phase Three Wire PV-BES Microgrid with Buck-Boost Converter Controlled BES	258
9.7	MATLAB Based Modeling for Single-Stage Three-Phase Four Wire PV-BES Microgrid with Buck-Boost Converter Controlled BES	259
9.8	Hardware Implementation of Single-Stage Three-Phase Three Wire and Four Wire PV-BES Microgrid with Buck-Boost Converter Controlled BES	260
9.9	Energy Management Scheme For Proposed PV-BES Microgrid	260
9.10	Results and Discussion	262
	9.10.1 Simulated Performances	262
	9.10.1.1 Simulated Performance of Single-Stage Three-Phase Three Wire PV-BES Microgrid	262

	9.10.1.1.1	Simulated Performance under Sudden Outage of Utility Grid	262
	9.10.1.1.2	Simulated Performance under Sudden Recovery of Utility Grid	263
	9.10.1.1.3	Simulated Performance of Single-Stage Three-Phase Three-Wire Microgrid with Balanced and Unbalanced Nonlinear load	264
	9.10.1.1.4	Simulated Performance under Outage of PV Source	264
9.10.1.2		Simulated Performance of Single-Stage Three-Phase Four Wire PV-BES Microgrid	265
	9.10.1.2.1	Simulated Performance under Sudden Outage of Utility Grid	266
	9.10.1.2.2	Simulated Performance under Sudden Recovery of Utility Grid	266
	9.10.1.2.3	Simulated Performance under Constant Power Feeding to the Utility with Balanced and Unbalanced Nonlinear load	267
	9.10.1.2.4	Simulated Performance under Outage of PV Source and Utility Grid	267
9.10.2		Experimental Performances	269
	9.10.2.1	Experimental Performance of Single-Stage Three-Phase Three Wire PV-BES Microgrid	269
	9.10.2.1.1	Experimental Performance under Sudden Outage of Utility Grid	270
	9.10.2.1.2	Experimental Performance under Sudden Recovery of Utility Grid	270
	9.10.2.1.3	Experimental Performance of Three-Phase Three-Wire PV-BES Microgrid at Balanced Nonlinear load	272
	9.10.2.1.4	Experimental Performance under Outage of PV Source and Utility Grid	272
	9.10.2.1.5	Intermediate Signals of Proposed Control	274
9.10.2.2		Experimental Performance of Single-Stage Three-Phase Four Wire PV-BES Microgrid	275
	9.10.2.2.1	Performance under Sudden Outage of Utility Grid	275
	9.10.2.2.2	Performance under Sudden Recovery of Utility Grid	277
	9.10.2.2.3	Performance under Constant Power Feeding to the Utility with Balanced and	277

		Unbalanced Nonlinear load	
	9.10.2.2.4	Performance under Outage of PV and Utility Grid	280
	9.10.3	Experimental Comparative Assessment of Proposed current Control Algorithm With Conventional Controllers	282
9.11		Conclusions	283
CHAPTER-X	MAIN CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK		284-288
10.1		General	284
10.2		Main Conclusions	285
10.3		Suggestion for Future Work	288
		REFERENCES	289-302
		LIST OF PUBLICATIONS	303-305
		BIO-DATA	306

LIST OF FIGURES

- Fig. 1.1 Classification of different PV-BES based microgrids in grid connected mode
- Fig. 1.2 Classification of different PV-BES based microgrids in standalone mode
- Fig. 3.1 Classification of PV-BES microgrids
- Fig. 3.2 Circuit Configuration of single phase standalone microgrid
- Fig. 3.3 Circuit Configuration of three phase standalone PV-BES microgrid
- Fig. 3.4 System configuration of single-phase grid interactive PV based microgrid.
- Fig. 3.5 System configuration for three phase grid interactive PV based microgrid.
- Fig. 3.6 Single Phase two stage Grid Interactive PV-BES Microgrid System without Bidirectional converter
- Fig. 3.7 Single Phase two stage Grid Interactive PV-BES Microgrid System with Bidirectional converter
- Fig. 3.8 Single Stage Single Phase Grid Interactive PV-BES Microgrid Systems
- Fig. 3.9 Two stage three Phase Grid Interactive PV-BES Microgrid Systems without bidirectional DC-DC converter
- Fig. 3.10 Two stage three Phase three wire Grid Interactive PV-BES Microgrid Systems with bidirectional DC-DC converter
- Fig. 3.11 Two stage three Phase four wire Grid Interactive PV-BES Microgrid Systems with bidirectional DC-DC converter
- Fig. 3.12 Single stage three Phase three wire Grid Interactive PV-BES Microgrid Systems with bidirectional DC-DC converter
- Fig. 3.13 Single stage three Phase four wire Grid Interactive PV-BES Microgrid Systems with bidirectional DC-DC converter
- Fig. 4.1 Circuit Configuration of single phase standalone microgrid
- Fig. 4.2 Circuit Configuration of three phase standalone microgrid
- Fig. 4.3 MPPT curve
- Fig. 4.4 Flow chart of MPPT control
- Fig. 4.5 Control approach for single phase VSC
- Fig. 4.6 Signal control model of three phase VSC in voltage control mode
- Fig. 4.7 Islanded control: signal control model of VSC including all variables
- Fig. 4.8 Stability analysis of voltage controller (a) Pole-zero plot analysis (b) frequency response using Bode plot
- Fig. 4.9 Generation of reference load voltages
- Fig. 4.10 Control technique of a bidirectional converter
- Fig. 4.11 MATLAB model of single phase standalone microgrid
- Fig. 4.12 MATLAB model of three phase standalone microgrid
- Fig. 4.13 Simulated steady state performance of single phase standalone microgrid

- Fig. 4.14 Simulated dynamic performance of single phase standalone microgrid
- Fig. 4.15 (a)-(b) Harmonics analysis of load current and load voltage
- Fig. 4.16 Simulated steady state performance of three phase standalone microgrid.
- Fig. 4.17 Simulated dynamic performance of three phase standalone microgrid
- Fig. 4.18 (a)-(b) Harmonics analysis of load current and load voltage
- Fig. 4.19 PV array characteristics and MPPT performance at 1000 W/m^2 of single phase standalone microgrid
- Fig. 4.20 PV array characteristics and MPPT performance at 1000 W/m^2 of three phase standalone microgrid
- Fig. 4.21 (a)-(h) Load voltage, load current, load power, VSC current, VSC power, THD of load voltage and load current, battery voltage and current and battery power
- Fig. 4.22 (a) - (d) Dynamic Performance at outage and restoration of PV array
- Fig. 4.23 (a)-(h) Three phase load voltages, load currents, load power, THD of load voltage and load current, battery voltage and current and battery power
- Fig. 4.24 (a)-(b) Dynamic Performance at outage and restoration of PV array
- Fig. 5.1 System configuration of single-phase grid interactive PV based microgrid
- Fig. 5.2 System Configuration for three phase grid interactive PV based microgrid.
- Fig. 5.3 VSC control
- Fig. 5.4 Self adjustable step-based control to extract peak load current.
- Fig. 5.5 LWDF based current control approach
- Fig. 5.6 Basic Diagram of LWDF
- Fig. 5.7 All pass first order
- Fig. 5.8 All pass second order classic section
- Fig. 5.9 (a)-(b) mode shifting control and decision control signal for STS
- Fig. 5.10 MATLAB modeling for single phase grid interactive PV based microgrid.
- Fig. 5.11 MATLAB modeling for three phase grid interactive PV based microgrid.
- Fig. 5.12 Schematic of d-SPACE 1103 with its photograph
- Fig. 5.13 (a)-(b) Schematic for current sensor board.
- Fig. 5.14 Schematic for voltage sensor board.
- Fig. 5.15 Schematic of Opto isolation board.
- Fig. 5.16 Performance of single phase PV based microgrid at outage of utility grid
- Fig. 5.17 Performance of single phase PV based microgrid at recovery of utility grid
- Fig. 5.18 Performance of single phase PV based microgrid at change in insolation from 1000 W/m^2 to 500 W/m^2
- Fig. 5.19 Harmonics analysis of single phase PV based microgrid (a) grid current (b) load current
- Fig. 5.20 Performance of single phase PV based microgrid at outage of utility grid

- Fig. 5.21 Performance of single phase PV based microgrid at recovery of utility grid
- Fig. 5.22 Simulated results of three phase PV based microgrid at unbalanced nonlinear loads
- Fig. 5.23 Simulated results of three phase PV based microgrid at Sudden change in solar insolation
- Fig. 5.24 Harmonics analysis of three phase PV based microgrid (a) grid current (b) load current
- Fig. 5.25 MPPT performance of single phase PV based microgrid (a) Under 1000 W/m² (b) off-MPPT mode
- Fig. 5.26 (a)-(c) Performance of single phase PV based microgrid without BES under outage of grid
- Fig. 5.27 (a)-(d) Performance of single phase PV based microgrid without BES under restoration of grid
- Fig. 5.28 Behaviour of single phase PV based microgrid at utility integrated mode (a)-(c) Grid Voltage v_s with i_s , i_L and i_{VSC} (d) Utility Power (P_g), (e) VSC power (P_{VSCa}) (f) load power (g)-(j) THDs of v_{sa} , i_{sa} and i_{La}
- Fig. 5.29 Performance of single phase PV based microgrid in islanded mode (a)-(b) load voltage (v_{La}), load current (i_{La}) and load power (c)-(d) THDs of i_{La} , v_{La} (e)-(f) VSC current and VSC power (g)-(h) PV voltage, PV current and PV power
- Fig. 5.30 (a)-(d) Response of the proposed configuration under decrease and increase in insolation condition
- Fig. 5.31 (a)-(f) Intermediate signals of the adjustable step based control algorithm
- Fig. 5.32 MPPT performance (a) Under 1000 W/m² (b) off-MPPT mode of operation
- Fig. 5.33 (a)-(d) Performance of PV based microgrid without BES under restoration of grid
- Fig. 5.34 (a)-(d) Performance of PV based microgrid without BES under recovery of grid
- Fig. 5.35 Experimental results of three phase PV based microgrid in grid tied mode (a)-(c) v_{sa} with i_{sa} , i_{La} and i_{VSCa} (d)-(f) grid, load and VSC power. (g)-(j) Harmonic spectra of i_{sa} , v_{sa} , i_{La} and i_{VSCa} (k)-(l) PV voltage, PV current and PV power
- Fig. 5.36 Performance of PV based microgrid in islanded mode (a)-(b) load voltage (v_{La}), load current (i_{La}) and load power (c)-(d) THDs of i_{La} , v_{La} (e)-(f) VSC current and VSC power (g)-(h) PV voltage, I_{pv} and PV power
- Fig. 5.37 (a)-(d) Response of the proposed configuration under decrease and increase in insolation condition
- Fig. 5.38 Various intermediate signals (a)-(d) at sudden disconnection of load (e)-(h) at sudden connection of load
- Fig. 6.1 Two-stage single-phase PV-BES microgrid without bidirectional converter controlled BES
- Fig. 6.2 Two-stage single-phase PV-BES microgrid with DC-DC bidirectional converter controlled BES
- Fig. 6.3 Boost converter control using MPPT algorithm
- Fig. 6.4 LQ based current control and Voltage control for VSC
- Fig. 6.5 Circular normalized filter (CNF) control and Islanded control
- Fig. 6.6 Control technique of bidirectional converter

- Fig. 6.7 Estimation of θ_L and θ_g using windowing factor scheme
- Fig. 6.8 Seamless transition controller
- Fig. 6.9 MATLAB model of PV-BES microgrid without bidirectional converter controlled BES
- Fig. 6.10 MATLAB model of PV-BES microgrid with bidirectional converter controlled BES
- Fig. 6.11 Simulated behavior of microgrid without buck-boost controlled BES at sudden outage of grid
- Fig. 6.12 Simulated behavior of microgrid without buck-boost controlled BES at recovery of grid
- Fig. 6.13 Harmonics analysis of (a) grid current (b) load current
- Fig. 6.14 Steady state response under nonlinear load
- Fig. 6.15 Simulated Response at outage of PV source
- Fig. 6.16 Simulated behavior of microgrid with buck boost controlled BES at sudden outage of grid
- Fig. 6.17 Simulated behavior of microgrid with buck-boost controlled BES at sudden recovery of grid
- Fig. 6.18 Harmonics analysis of (a) grid current (b) load current
- Fig. 6.19 Simulated behavior of microgrid with buck boost controlled BES at steady state conditions
- Fig. 6.20 Simulated behavior of microgrid with buck-boost controlled BES at sudden outage of PV array
- Fig. 6.21 The I_{pv} - V_{pv} and P_{pv} - V_{pv} MPPT characteristics along with percentage of MPPT Tracking
- Fig. 6.22 Response at sudden outage of utility grid (a) utility voltage (v_s), load voltage (v_L), utility voltage phase angle (θ_s) and load voltage phase angle (θ_L), (b) v_L , v_s , battery current (I_{batt}) and PV current (I_{pv}), (c) v_s , battery current (V_{batt}), utility current (i_s) and nonlinear load current (i_L)
- Fig. 6.23 Response at sudden recovery of utility grid (a) utility voltage (v_s), load voltage (v_L), utility voltage phase angle (θ_s) and load voltage phase angle (θ_L), (b) v_L , v_s , battery current (I_{batt}) and PV current (I_{pv}), (c) v_s , battery current (V_{batt}), utility current (i_s) and nonlinear load current (i_L)
- Fig. 6.24 Response of microgrid in grid connected mode (a)-(c) grid current, grid power and THD of grid current, (d)-(f) VSC current, VSC power and BES voltage and current, (g)-(i) v_s with i_L , load power and THD of i_L
- Fig. 6.25 (a) Performance of PV-BES system under outage PV source, PV current (I_{pv}), BES current (I_{batt}), utility current (i_s) and nonlinear load current (i_L) (b)-(c) Performance of PV-BES system under outage of utility
- Fig. 6.26 Performance of LQ based current controller under change of load (a)-(b) load current (i_L) and extracted components of load current (I_{L1} , I_{L2} , I_{L3}) at load dynamic conditions, (c)-(d) load current (i_L), in-phase unit templates derived from utility voltage and extracted active component (I_{pL})
- Fig. 6.27 PV array characteristic
- Fig. 6.28 (a)-(c) Behavior of microgrid at disappearance of utility grid

- Fig. 6.29 (a)-(c) Behavior of microgrid at recovery of utility
Experimental results in utility tied operation (a) utility voltage and currents (b) utility powers and power factor (c) VSC current (d) VSC powers (e) load current (f) load powers (g-h) power quality Indices of utility and load currents (i) DC link voltage and PV current
- Fig. 6.30 (a)-(f) Behaviour at outage and recovery of PV array followed by sudden disappearance of utility grid
- Fig. 6.31 (a)-(d) Performance of circular normalized filter (CNF) algorithm at disconnection and injection of load
- Fig. 6.32 (a)-(b) Frequency and phase jump and dip by using PLL and windowing factor based scheme
- Fig. 6.33 Configuration of single-stage single-phase PV-BES microgrid with buck-boost converter controlled BES
- Fig. 7.1 Flow-chart of P & O MPPT approach
- Fig. 7.2 Frequency observer based current control and dq based voltage control
- Fig. 7.3 Control of DC-DC bidirectional converter
- Fig. 7.4 LTI-EPLL for phase and frequency estimation
- Fig. 7.5 Mode transition controller
- Fig. 7.6 MATLAB model of single-stage single-phase PV-BES microgrid
- Fig. 7.7 Simulated behavior of single stage single phase microgrid at sudden outage of utility
- Fig. 7.8 Simulated behavior of single stage single phase microgrid at recovery of grid
- Fig. 7.9 Simulated behavior of single stage single phase microgrid at load connection and disconnection
- Fig. 7.10 Simulated behavior of single stage single phase microgrid at outage of PV array
- Fig. 7.11 (a)-(b) Harmonics analysis of single phase PV-BES microgrid
- Fig. 7.12 tracking efficiency at (a) 1000 W/m² (b) 600 W/m²
- Fig. 7.13 (a)-(c) Experimental performance of single stage single phase microgrid at sudden outage of utility grid
- Fig. 7.14 (a)-(c) Experimental results of single stage single phase microgrid at sudden recovery of utility grid
Response of microgrid in grid connected mode (a)-(d) grid current, grid power and THD of grid current and voltage, (e)-(g) VSC current, VSC power and Harmonics in VSC current, (h)-(j) v_s with i_L , load power and THD of i_L , (k) PV voltage and current, (m)-(n) BES voltage and current in charging and discharging modes
- Fig. 7.15 (a) - (d) Performance of single stage PV-BES microgrid at outage and recovery of PV
- Fig. 7.16 (a)-(f) various intermediate signals of frequency observer based current control at load perturbation
- Fig. 7.17 Circuit Configuration of Two-Stage Three-Phase Three Wire PV-BES Microgrid without Buck-Boost Controlled BES
- Fig. 7.18 Circuit Configuration of Two-Stage Three-Phase Three Wire PV-BES Microgrid with Buck-Boost Controlled BES

- Fig. 8.3 Circuit Configuration of Two-Stage Three-Phase Four Wire PV-BES Microgrid with Buck-Boost Controlled BES
- Fig. 8.4 Slope of (P_{pv}) versus (V_{pv}) curve
- Fig. 8.5 Grid tied and islanded control of three phase three wire PV-BES microgrid without buck boost converter controlled BES
- Fig. 8.6 Grid tied and islanded control of three phase three wire PV-BES microgrid with buck boost converter controlled BES
- Fig. 8.7 Detailed structure of the paralleled sub-filter
- Fig. 8.8 Detailed structure of the paralleled sub-filter
- Fig. 8.9 Phase angle matching and generation of reference load voltage
- Fig. 8.10 Mode shifting control and decision control signal for STS
- Fig. 8.11 (a)-(c) Graphical illustration of synchronization of islanded mode and grid connected mode
- Fig. 8.12 Structure of PL-EPLL based control
- Fig. 8.13 Estimation of positive sequence component using PL-EPLL control under grid voltage distortion
- Fig. 8.14 DMSI based current control and dq based islanded control technique
- Fig. 8.15 The developed MATLAB model for two-stage three phase three wire PV-BES microgrid without bidirectional controlled BES
- Fig. 8.16 The MATLAB model for two-stage three phase three wire PV-BES microgrid with bidirectional converter controlled BES
- Fig. 8.17 The developed MATLAB model for two-stage three phase four wire PV-BES microgrid
- Fig. 8.18 Schematic of hardware interfacing circuit
- Fig. 8.19 Behavior of two stage three phase three wire PV-BES microgrid without bidirectional converter controlled BES at sudden outage of utility
- Fig. 8.20 Behavior of two stage three phase three wire PV-BES microgrid without bidirectional converter controlled BES at sudden utility restoration (b) utility outage
- Fig. 8.21 Simulated performance under constant power feeding to the utility with nonlinear load
- Fig. 8.22 Harmonics Analysis of three phase three wire microgrid without buck boost converter (a) THD of grid current (b) THD of load current
- Fig. 8.23 Dynamic performance of PV-BES microgrid under sudden outage of PV source
- Fig. 8.24 Behavior of three phase three wire microgrid with bidirectional converter at sudden outage of utility
- Fig. 8.25 Behavior of two stage three phase three wire microgrid with bidirectional converter at recovery of utility
- Fig. 8.26 Simulated performance of three phase three wire PV-BES microgrid with bidirectional converter controlled BES under constant power feeding to the utility with balanced and unbalanced nonlinear load
- Fig. 8.27 Harmonics Analysis of three phase three wire microgrid with buck boost converter (a) THD of grid current (b) THD of load current
- Fig. 8.28 Simulated performance of three phase three wire PV-BES microgrid with

- bidirectional converter controlled BES under outage of PV array
- Fig. 8.29 Behavior of two stage three phase four wire PV-BES microgrid with bidirectional converter controlled BES at sudden outage of utility grid
- Fig. 8.30 Behavior of two stage three phase four wire PV-BES microgrid with bidirectional converter controlled BES at sudden recovery of utility grid
- Fig. 8.31 Simulated performance of three phase four wire PV-BES microgrid with bidirectional converter controlled BES under constant power feeding to the utility with 3P4W balanced and unbalanced nonlinear load
- Fig. 8.32 Harmonics Analysis of three phase four wire microgrid with buck boost converter (a) THD of grid current (b) THD of load current
- Fig. 8.33 Simulated performance of three phase four wire PV-BES microgrid with bidirectional converter controlled BES under outage of PV array
- Fig. 8.34 Experimentally recorded MPPT performance in steady state condition at (a) 1000W/m², (b) 500W/m².
- Fig. 8.35 (a)-(d) Performance of microgrid under grid outage conditions
- Fig. 8.36 (a)-(d) Performance of microgrid under restoration of grid
- Fig. 8.37 Response of microgrid in grid connected mode (a)-(c) grid voltage and current, grid power and THD of grid current, (d)-(f) VSC current, VSC power and harmonics analysis of VSC current (g)-(i) v_{sa} with i_{La} , load power and THD of i_{La} (j) grid voltage THD (k) battery voltage and battery current (l) PV voltage and current
- Fig. 8.38 (a)-(d) Response of microgrid under sudden change in PV insulations
- Fig. 8.39 (a)-(d) Performance of proposed current controller at load perturbation
- Fig. 8.40 Distorted grid voltages, load currents and respective THD in grid voltages and load currents at adverse grid conditions
- Fig. 8.41 Experimentally recorded MPPT performance in steady state condition at (a) 1000W/m², (b) 500W/m².
- Fig. 8.42 (a)-(d) Experimental behavior of two stage three phase three wire PV-BES microgrid at outage of grid
- Fig. 8.43 (a)-(d) Experimental behavior of two stage three phase three wire microgrid at recovery of grid
- Fig. 8.44 Behavior of microgrid for feeding constant power at weak grid conditions (a) distorted grid voltages (v_s) and load current (i_{La}), (b) Grid voltages (v_s) and grid currents (i_s) after compensation (c) VSC currents (i_{VSC}) (d) THD of v_{sa} and i_{sa} before compensation (e) THD of v_{sa} and i_{sa} after the compensation (f) surplus PV power injected to the utility (g) Net power carries by VSC (h) Load power
- Fig. 8.45 (a)-(f) Behavior of microgrid at outage and recovery of PV generation and utility
- Fig. 8.46 (a)-(h) Performance of SNE based current control with intermediate parameters under sudden disconnection and connection of loads
- Fig. 8.47 Experimentally recorded MPPT performance in steady state condition at (a) 1000W/m², (b) 500W/m².
- Fig. 8.48 (a)-(d) Experimental behavior of two stage three phase four wire PV-BES microgrid at outage of grid
- Fig. 8.49 (a)-(d) Experimental behavior of three phase three wire PV-BES microgrid at recovery of grid

- Fig. 8.50 Performance of three phase four wire microgrid at balanced nonlinear load (a) v_{sab} with i_{La} , i_{Lb} , i_{Lc} and i_{Ln} (b) Grid power (c) THD analysis of v_{sa} and i_{sa} (d) v_{sab} with i_{La} , i_{Lb} , i_{Lc} and i_{Ln} (e) load power (f) THD analysis of i_{La} (g) v_{sab} with i_{VSCa} , i_{VSCb} , i_{VSCc} and i_{VSCn} (h) VSC power (i) Phasor diagram of grid voltages and currents
- Fig. 8.51 Performance of grid tied three phase four wire microgrid at unbalanced nonlinear load (a) v_{sab} with i_{La} , i_{Lb} , i_{Lc} and i_{Ln} (b) Power required by load (c) Harmonic analysis of i_{La} (d) v_{sab} with i_{sa} , i_{sb} , i_{sc} and i_{sn} (e) power fed to grid (f) Harmonic analysis of i_{sa} (g) v_{sab} with i_{VSCa} , i_{VSCb} , i_{VSCc} and i_{VSCn} (h) VSC power (i) Phasor representation of grid voltages and currents
- Fig. 8.52 (a)-(f) Behavior of microgrid at outage and recovery of PV generation and utility
- Fig. 8.53 (a)-(h) Intermediate signals of the proposed DMSI control technique
- Fig. 8.54 Simulated assessment of proposed controller and conventional PLL structure at sudden recovery of grid
- Fig. 8.55 (a) - (b) Frequency and phase variation through PLL and proposed PL-EPLL based control technique (c) variation in phase error and frequencies at sudden recovery of utility
- Fig. 9.1 Circuit configuration of single-stage three-phase three wire PV-BES microgrid
- Fig. 9.2 Circuit configuration of single-stage three-phase four wire PV-BES microgrid
- Fig. 9.3 Instantaneous characteristic based adaptive filter for three phase three wire microgrid
- Fig. 9.4 Extraction of fundamental component by using instantaneous characteristic based adaptive filter
- Fig. 9.5 Control technique of bidirectional converter
- Fig. 9.6 State space based mode transition approach
- Fig. 9.7 Structure of LTI-EPLL
- Fig. 9.8 Variable learning based adaptive current controller and voltage control for three phase four wire microgrid
- Fig. 9.9 The developed MATLAB model for single-stage three phase three wire PV-BES microgrid
- Fig. 9.10 The developed MATLAB model for single-stage three phase four wire PV-BES microgrid
- Fig. 9.11 Energy management scheme
- Fig. 9.12 Simulated behavior of single stage three phase three wire microgrid at outage of utility
- Fig. 9.13 Simulated behavior of single stage three phase three wire microgrid at recovery of grid
- Fig. 9.14 Simulated behavior of single stage three phase three wire microgrid at load perturbation
- Fig. 9.15 Simulated behavior of single stage three phase three wire microgrid at outage of PV array
- Fig. 9.16 (a) - (b) Harmonics analysis of single stage three phase three wire microgrid
- Fig. 9.17 Simulated behavior of single stage three phase four wire microgrid at outage of utility
- Fig. 9.18 Simulated behavior of single stage three phase four wire microgrid at recovery of grid

- Fig. 9.19 Simulated behavior of single stage three phase four wire microgrid at load perturbation
- Fig. 9.20 Simulated behavior of single stage three phase four wire microgrid at outage of PV array
- Fig. 9.21 (a)-(b) Harmonics analysis of single stage three phase four wire microgrid
- Fig. 9.22 Experimentally recorded MPPT performance in steady state condition at (a) 1000W/m², (b) 500W/m².
- Fig. 9.23 (a)-(d) Experimental results under transition from utility tied mode to Islanding
- Fig. 9.24 (a)-(d) Experimental results under transition from Islanded to utility tied mode
- Fig. 9.25 Experimental results in utility tied operation (a) utility voltages (v_{sa} , v_{sb} , v_{sc}) and currents (i_{sa} , i_{sb} , i_{sc}) (b) utility powers (P_s , Q_s) and power factor (c) harmonics graph of v_{sa} and i_{sa} (d) load voltages (v_{La} , v_{Lb} , v_{Lc}) and currents (i_{La} , i_{Lb} , i_{Lc}) (e) load Powers (P_L , Q_L) (f) harmonics graph of v_{La} and i_{La} (g) utility voltages (v_{sa} , v_{sb} , v_{sc}) and VSC currents (i_{vsc_a} , i_{vsc_b} , i_{vsc_c}) (h) VSC powers (i) BES voltage and current (j)-(k) phasor representation of utility, VSC and load parameters
- Fig. 9.26 (a) - (b) Response of microgrid at disconnection of PV array and outage of utility
- Fig. 9.27 (a)-(f) Performance of instantaneous characteristic based adaptive filter under variation of load
- Fig. 9.28 (a)-(f) Response of PV-BES microgrid at sudden outage of utility grid
- Fig. 9.29 (a)-(f) Response of PV-BES microgrid at sudden recovery of utility grid
- Fig. 9.30 Experimental results in utility tied operation (a) utility voltages (v_{sa} , v_{sb} , v_{sc}) and currents (i_{sa} , i_{sb} , i_{sc}) (b) utility powers (P_s , Q_s) (c) harmonics graph of v_{sa} and i_{sa} (d) v_{sa} , v_{sb} , v_{sc} and VSC currents (i_{vsc_a} , i_{vsc_b} , i_{vsc_c}) (e) VSC powers (f-g) load voltages (v_{La} , v_{Lb} , v_{Lc}) and currents (i_{La} , i_{Lb} , i_{Lc}) load Powers (P_L , Q_L) (h) harmonics graph of v_{La} and i_{La}
- Fig. 9.31 Experimental results in utility tied operation at unbalanced nonlinear load (a) v_{La} , v_{Lb} , v_{Lc} with i_{La} , i_{Lb} , i_{Lc} and i_{Ln} (b) load powers (c) harmonics spectrum of load current (d) v_{sa} , v_{sb} , v_{sc} with i_{sa} , i_{sb} , i_{sc} and i_{sn} (e) grid power with PF (f) Harmonics analysis of v_{sa} and i_{sa} (g) v_{sa} , v_{sb} , v_{sc} with i_{vsc_a} , i_{vsc_b} , i_{vsc_c} , i_{vsc_n} (h) VSC powers
- Fig. 9.32 (a)-(d) Response of microgrid at outage and recovery of PV array
- Fig. 9.33 (a)-(b) Response of 3P4W microgrid at recovery of utility and PV array curve with MPPT Tracking
- Fig. 9.34 Experimental comparative assessment of proposed controller

LIST OF TABLES

Table 4.1	Design specifications of single phase standalone PV-BES microgrid for experimental implementation
Table 4.2	Design specifications of three phase standalone PV-BES microgrid for experimental implementation
Table 5.1	Design parameters of single-phase grid interactive PV based microgrid for experimental implementation
Table 5.2	Design parameters of three-phase grid interactive PV based microgrid for experimental implementation
Table 6.1	Design of two-stage single-phase microgrid without buck-boost converter controlled BES for experimental implementation
Table 6.2	Design of two-stage single-phase microgrid with buck-boost converter controlled BES for experimental implementation
Table 7.1	Design of single-stage single-phase microgrid with buck-boost converter controlled BES for experimental implementation
Table 8.1	Design specifications of two-stage three-phase three-wire PV-BES microgrid without bidirectional converter controlled BES for experimental implementation
Table 8.2	Design specifications of two-stage three-phase three-wire PV-BES microgrid with bidirectional converter controlled BES for experimental implementation
Table 8.3	Design specifications of two-stage three-phase three-wire PV-BES microgrid with bidirectional converter controlled BES for experimental implementation
Table 9.1	Design specifications of single-stage three-phase three-wire PV-BES microgrid for experimental implementation
Table 9.2	Design specifications of single-stage three-phase four-wire PV-BES microgrid for experimental implementation

LIST OF ABBREVIATIONS

RES	Renewable Energy Sources
PV	Photo Voltaic
BES	Battery Energy Storage
MPPT	Maximum Power Point Technique
P & O	Perturb & Observe
INC	Incremental Conductance
DC	Direct Current
AC	Alternating Current
PCC	Point of Common Coupling
DSTATCOM	Distribution Static Compensator
IGBT	Insulated Gate Bipolar Transistor
PQ	Power Quality
VSC	Voltage Source Converter
PLL	Phase Locked Loop
STS	static transfer switch
NDZ	Non-Detection Zone
3P4W	three phase four wire
LWDF	lattice wave digital filter
DSP	Digital Signal Processor
DAC	Digital to Analog Converter
ADC	Analog to Digital Converter
PI	Proportional Integral
LQ	Learning Quantization
CNF	Circular Normalized Filter
PVFF	PV Feed-Forward
DMSI	Digital Multistage Interpolation
LTI-EPLL	Linear Time Invariant-Enhanced Phase Locked Loop

LIST OF SYMBOLS

P_{pv}	PV array power
I_{pv}	PV array current
V_{pv}	PV array voltage
V_{pv}^*	Reference PV array voltage
V_{mpp}	MPP voltage
I_{mpp}	MPP current
P_{mpp}	MPP power
V_{oc}	Open circuit PV voltage
I_{sc}	Short circuit PV current
V_{dc}	DC link voltage
V_{dc}^*	Reference DC link voltage
V_{dcer}	DC link voltage error
C_{dc}	DC link capacitor of VSC
L_b	Boost inductance
L_{bb}	Buck-boost inductance
D_{bb}	Duty ratio of buck boost converter
V_{batt}, I_{batt}	BES voltage and BES current
I_{battf}	Estimated component of battery
L_f	Interfacing inductor
R, C	Ripple filter
i_s	Grid current for single phase microgrid
i_s^*	Reference grid current for single phase microgrid
v_s	Grid voltage for single phase microgrid
$v_{s\alpha}, v_{s\beta}$	Orthogonal voltages
u_p, u_q	In phase and quadrature unit template for single phase microgrid
i_L	Load current for single phase microgrid
v_L	Load voltage for single phase microgrid

v_L^*	Reference load voltage for single phase microgrid
i_{vsc}	VSC current for single phase microgrid
i_{vsc}^*	Reference VSC current for single phase microgrid
i_{sa}, i_{sb}, i_{sc}	Grid currents for three phase microgrid
$i_{sa}^*, i_{sb}^*, i_{sc}^*$	Reference grid current for three phase microgrid
$i_{VSCa}, i_{VSCb}, i_{VSCc}$	VSC currents for three phase microgrid
$i_{VSCa}^*, i_{VSCb}^*, i_{VSCc}^*$	Reference VSC currents for three phase microgrid
i_{La}, i_{Lb}, i_{Lc}	Load currents for three phase microgrid
v_{sa}, v_{sb}, v_{sc}	Grid voltages for three phase microgrid
v_{La}, v_{Lb}, v_{Lc}	Load voltages for three phase microgrid
u_{pa}, u_{pb}, u_{pc}	In-phase unit template for three phase microgrid
u_{qa}, u_{qb}, u_{qc}	Quadrature unit templates for three phase microgrid
i_{sn}, i_{Ln}, i_{VSCn}	Grid, load and VSC neutral currents
i_{sn}^*	Reference grid neutral current for three phase four wire microgrid
$i_{esa}, i_{esb}, i_{esc}$	Error between the fundamental and load current component
f_s, f_L	Grid and load frequency components
θ_s, θ_L	Grid and load voltage angles
G_1, G_2	Gains of frequency observer based control
m	Modulation index
a	Over loading factor
V_{SW}, I_{SW}	VSC switch voltage and current
V_t	Estimated Amplitude of grid voltage
k_p, k_i	PI controller gains for islanded control
k_{pv} and k_{iv}	PI controller gains for DC link voltage and bidirectional converter control
ε, τ, ρ	Gains of self-adjustable step-based control
γ_p	Phase neuron learning rate
I_{Lp}	Fundamental active component of grid current
$e(k)$	Error between the load current and fundamental component
I_{pLt}	Net active component of load current
I_{loss}	Output of DC link voltage PI controller

I_{pvff}	PV feed forward term
$L_1(z)$ and $L_2(z)$	All pass functions for LWDF control
$\mu_1, \mu_2, \mu_3, \mu_4$	Filter coefficients for LWDF control
$m_1(n), w_2(n), y_2(n), T_2(n),$	Extracted components of load current using LWDF
$T_n(n)$	Overall transfer function of using LWDF
$i_{fla}, i_{flb}, i_{flc}$	Fundamental components of load current
$I_{pLa}, I_{pLb}, I_{pLc}$	Active power current components of all three phases
$I_{qLa}, I_{qLb}, I_{qLc}$	Reactive power current components of all three phases
I_{Lpeq}	Equivalent active component of load current
γ	Learning coefficient
$I_{L1}, I_{L2}, I_{L3}, I_{L4}$	Extracted components of load current
k	Battery utilization factor
R_p, C_p	Battery components
V_{rms}, I_{rms}	RMS grid voltage and current
V_{pk}, I_{pk}	Peak grid voltage and current
n	The number of samples in CNF control
σ	Error circular coefficient
β	Mixing normalized variable
i_{Lerr}	Output of comb filter
$k_I \gamma$	Intermediate variable of SNE based control
$i_{L1}(r)$	Output of the first section of DMSI based control
$\sigma_1, \sigma_2, \sigma_3, \sigma_4, \sigma_5, \sigma_6$	Filter coefficients of DMSI based control
α	Instantaneous characteristic factor
ρ	is the learning rate
$f_{LPLL}, f_{gPLL}, f_{gw}, f_{Lw}$	Frequency components estimated through the PLL and windowing factor based control
$\theta_{LPLL}, \theta_{gPLL}, \theta_{gw},$ $\theta_{Lw}, \theta_{SPLL}, \theta_{ePL-PLL}$	Frequency components estimated through the PLL and PL-EPLL based control
I_{VSCR}	Peak ripple current for VSC
I_{VSCP}	Peak current for VSC